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JET PROPULSION LABORATORY

CALIFORNIA INSTITUTE OF TECHNOLOGY

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INTRODUCTION

This volume contains a review of all supporting research and technology in progress at the Jet Propulsion Laboratory during the period January 1 to June 30, 1969, under the direction of the JPL Office of Research and Advanced Development, for the NASA Office of Advanced Research and Technology.

The work units are arranged in numerical sequence by NASA code in each subject section. To locate a desired unit, refer to the Table of Contents under the appropriate subject heading.

JPL research and advanced development results published during this report period are listed under each work unit.

PREFACE

This document has been prepared under the direction of the Office of Research and Advanced Development of the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California.

The Semiannual Review of Research and Advanced Development is published in two* volumes directed to the appropriate NASA funding offices:

Volume I	Supporting Research and Technology for the Office of Space Sciences and Applications
Volume II	Supporting Research and Technology for the Office of Advanced Research and Technology

Previous issues were published as follows:

Fiscal Year	
1965	TM 33-243
1966	TM 33-272 TM 33-296
1967	TM 33-322 TM 33-353
1968	701-6
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1969	701-23

* Previous issues included a third volume directed to the Office of Tracking and Data Acquisition (New Systems and Spacecraft Subsystems).

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SPACE POWER AND ELECTRIC PROPULSION SYSTEM SRT(120)

ELECTRIC ENGINE SYSTEMS (120-26)

RESEARCH ON MAGNETIC CONTAINMENT ION THRUSTERS

NASA Work Unit 120-26-02-03

JPL 320-61701-0-3830

D. J. Kerrisk

OBJECTIVE

The objective of this work unit was to conduct research and advanced development on electron bombardment ion engines of the magnetic containment ion chamber configuration in order to seek higher total effeciencies than are currently available. Further, the objective was to identify problems and characteristics of such engines as might affect their integration into spacecraft systems. It was planned that this work would be conducted under contract rather than at JPL.

STATUS

This contract was not executed as a result of redefining overall priorities within the solar electric propulsion system technology program.

PUBLICATIONS

None

ELECTRIC PROPULSION POWER CONDITIONING

NASA Work Unit 120-26-04-05

JPL 320-60301-2-3420

E. Costogue

OBJECTIVE

The electric-propulsion power-conditioning activities are directed toward the accomplishment of two tasks. The first task, SEPST II involves the evaluation testing of a power-conditioner supply with two oxide-cathode ion engines. A switching module is utilized to switch power to either engine by command. The second task, SEPST III, is to be operational in late 1969. This task will involve the design, fabrication and evaluation testing of the complete power-conditioning subsystem of the electric propulsion system. The power-conditioning subsystem will consist of: (1) a breadboard and two experimental power-conditioning supplies of improved designs with an expected average efficiency of 92 per cent and specific weight of 8.6 lb/kW at the operating level, (2) a switching unit that will be utilized to switch power-conditioning units to available ion engines, (3) a maximum power point-monitor to detect the maximum power point of the solar-panel source, and determine the power margins and available power to the system, and (4) a solar-array simulator to simulate the solar-panel output of 15 kW and voltage-current characteristics for 1 AU to 5 AU. Items (1) and (4) will be developed under contracts. Items (2) and (3) will be designed and fabricated at JPL.

PROGRESS

The SEPST II power conditioner, a modified unit built earlier for the SERT II program, was delivered by the contractor in December. Integration testing with the thruster was initiated, and a number of minor modifications had to be introduced, mainly in the control-logic-and-sensing circuits, to obtain the desired operational characteristics. The modifications introduced were in the following areas:

(1) Overload Circuits

The response and the tripping levels of the high-voltage supplies were adjusted to tolerable limits for improved thruster operation and power-conditioner protection.

(2) Thruster Closed-Loop Operational Amplifier

The characteristics of the closed-loop operational amplifier were adjusted to achieve stability and desired operational levels of thruster mass utilization.

(3) Soft Recovery from Arcing

The recovery after temporary shutdown of the thruster to interrupt a sustained arc was improved by reducing the magnet current to a minimum during thruster restart.

At the completion of the integration tests, all functional characteristics of the power conditioners had been verified and the satisfactory operation of the thruster over the total range of thrust was established.

The switching unit was designed in-house and was delivered to the system on schedule. The unit has performed satisfactorily in all the tests conducted with the power conditioner and the ground power supplies.

At the beginning of April, the SEPST II pre-endurance test was initiated. The pre-endurance test was terminated after approximately 400 hours. The performance of the power conditioner was considered satisfactory although a number of marginal areas were uncovered. The marginal areas were mostly in the logic circuits. Modification was introduced to correct the logic-circuit deficiency of operating randomly on either the main or the standby units of the accelerator and arc supply. Additional override circuitry was introduced to improve the soft recovery of the system after a temporary shutdown to interrupt a sustained arc. The endurance test was initiated, and is progressing satisfactorily.

In the SEPST III program, functional specifications of all the power-systems units have been generated and issued. The activities at Hughes Aircraft Company — the contractor to design, develop, fabricate, and qualify the power-conditioner supplies — are progressing on schedule. A preliminary circuit design, physical layout, mounting configuration, and over-all electrical-thermal detail evaluation design review has been held. A problem in meeting the design goal efficiency of 93 percent has been reported. The problem was attributed to poor switching characteristics of the proposed power transistor. The designs were based on switching the power transistors at the frequency of 12.5 kHz. The high switching losses experienced forced modifications in the drive circuitry and reduction in switching frequencies from 12.5 kHz to 10.0 kHz. New power transistors are being evaluated and will be considered for substitution to improve the efficiency.

The design of the switching matrix unit is progressing on schedule. A design review is scheduled for the first week of June.

The design of the maximum power-point monitor was initiated and is progressing. A laboratory-type solar-array simulator is being fabricated and assembled to test the breadboard unit. The design review of the unit is scheduled for the end of June. The detail specification of the solar-array simulator unit has been issued. The request-for-proposal cycle has been initiated and the selection of the contractor is expected to be completed by July, 1969.

PUBLICATIONS

None

LIQUID MERCURY CATHODE RESEARCH

NASA Work Unit 120-26-04-08

JPL 320-61301-0-3830

D. J. Kerrisk

OBJECTIVE

The objective of this work unit is to provide an analytical and experimental evaluation of mercury-fed cathodes of liquid and vapor types for use as both main-thruster and neutralizer cathodes in ion engines. Steady-state performance of thrusters so equipped will be determined to allow meaningful performance comparison with state-of-the-art devices.

PROGRESS

A sole-source contract for this study has been initiated with the Hughes Aircraft Company. The effort began February 5, 1968. Accomplishments to date include:

(1) A breadboard flow system, that included a single-capillary flow impedance, EM pump, and high voltage isolator, was assembled and demonstrated proper operation and mutual compatibility with a LM cathode thruster.

(2) A 30-cm thruster, employing LM cathode for both thruster electron source and neutralizer, has been tested for a range of discharge chamber geometry. Thruster performance competitive with existing hollow-cathode thrusters was obtained.

(3) A modified 20-cm thruster has been operated over a 2:1 range in output power. Performance mapping of this thruster has been completed. High-performance operation was obtained with both axial and radial magnetic fields.

(4) Vapor-fed and liquid-fed cathodes, including slit and annular geometries, have been investigated over a wide range of operation. The liquid-fed annular geometry was demonstrated to be superior to the other types.

(5) A high-temperature LM cathode has been thermally integrated with a 30-cm diameter thruster. Satisfactory operation was demonstrated.

Work on this contract was completed in April, 1969. The final report has been submitted for approval. A follow-on contract has also been negotiated and work will begin early in the next reporting period. Under the new contract, a complete propulsion module will be integrated and tested. This will include a thermally-integrated, high-temperature LM cathode. The effort will be concentrated on a 20-cm thruster, compatible in power requirements, size, and mounting dimensions with the thruster used in the present JPL program, and which will serve as a backup to that thruster. The propellant feed system will be an integral portion of this thruster.

PUBLICATIONS

Meeting and Symposia Papers

1. Hyman, J., Jr., Eckhardt, W. O., Bayless, J. R., and Snyder, J. A., "LM Cathode Electron Bombardment Thrusters," AIAA Paper No. 69-302, 7th Electric Propulsion Conference, Williamsburg, Va., March 1969.

ATTITUDE CONTROL ACTUATOR SYSTEM FOR CLUSTERED ION ENGINE ARRAY

NASA Work Unit 120-26-04-10

JPL 320-60401-X-3440

J. D. Ferrera
G. S. Perkins

OBJECTIVE

The long-term objective of this work unit is to develop a new multi-engine array and actuation system to support the development of solar-powered electric propulsion systems suitable for interplanetary spacecraft application. Gimballing of the engines provides roll attitude control. Translation of the multi-engine array in the X-Y directions plus and minus 13 inches aligns the resultant thrust vector through the center of gravity of the spacecraft for pitch and yaw attitude control.

The immediate objective of this task is to complete the system testing of the breadboard, which consists of a two-engine array with each engine supported in gimbals and controlled by a gimbal actuator. The two-engine array is translated in one axis and controlled by a translation actuator. Figures 1 and 2 of SPS 37-54, Vol. III, "Actuator Development for a Clustered Ion Engine Array," show this assembly as it is mounted in the test chamber. All major components needed to fly a typical solar electric spacecraft attitude control and primary propulsion thruster system are present in the total system breadboard.

PROGRESS

Two-Engine Array

A detail description and functional test results on the gimbal and translation actuators for the two-engine breadboard array were included in the previous report. In this reporting period, these actuators and the translation structure have been incorporated into the complete system and the 1000-hour endurance test initiated. All the endurance test objectives on the actuators have been met as follows:

(1) The actuator response is compatible with the system functional requirements.

(2) Sufficient thermal protection has been provided in the actuator design to prevent malfunction due to thermal buckling and to protect the internal actuator electronics against high ion engine operating temperatures ($\approx 260°C$). The worst case temperature recorded by thermistors inside the actuator is $100°C$ which is a safe environment for the electronics.

(3) Step life endurance has been verified. The design requirements for both actuators is to demonstrate a maximum capability of one million cycles. As of June 1, 1969, the gimbals have been tested over eleven million cycles and the translator over four million. No malfunctions have occurred.

Multi-Engine Array

During this reporting period, the detail design of the flight prototype multi-engine array was completed. Special attention was given to the following areas:

(1) Space and flight environmental compatibility.

(2) Minor design problems highlighted during the two-engine array 1000-hour endurance test were corrected in the prototype design.

(3) Significant weight reduction over breadboard model.

Detail prints are now available on the translation and gimbal actuators and the multi-engine array. A detailed structural analysis is currently being performed on the array. With the exception of a weight reduction and the use of a size 15 stepper motor (rather than size 11) in the translation actuator, the multi-engine array actuators are functionally very similar to the two-engine array actuators.

PLANS

Multi-Engine Array

The multi-engine actuators and array will be committed to production early in the next reporting period. The system will then be fabricated, assembled and bench tested such that system integration for the 10,000 hour endurance test can begin on January 1, 1970. Also, in the next reporting period the design, building and testing of the electrical and mechanical feed systems, necessary for moving power, telemetry, and propellant across an X-Y moving interface, will be completed.

PUBLICATIONS

Meeting and Symposia Papers

1. Pawlik, E. V., Macie, T. W., Ferrera, J. D., "Electric Propulsion System Performance Evaluation," AIAA 7th Electric Propulsion Conference, March 3-5, 1969.

2. Macie, T. W., Pawlik, E. V., Ferrera, J. D., Costogue, E. N., "Solar-Electric Propulsion System Evaluation," AIAA 5th Propulsion Joint Specialist Conference, June 9-13, 1969.

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ELECTRIC PROPULSION SYSTEM PERFORMANCE ANALYSIS AND TRAJECTORY PROGRAMMING

NASA Work Unit 120-26-07-01

JPL 320-60501-0-3830

D. J. Kerrisk

OBJECTIVE

The objective of this work unit is to provide mission performance analysis support to electric propulsion research and development. The close inter-relationships between the mission and spacecraft parameters, and the development of components and subsystems require continuous tradeoff study. This includes weight, reliability, cost, flight constraints, power profile, thrust vectoring, and systems integration.

From R&D studies, estimates are made of electric propulsion component and subsystem parameters such as, specific mass, efficiency, reliability, etc. These elements are then evaluated with respect to potential missions of interest to JPL. Particular emphasis is given to tradeoffs of greatest importance for mission performance and system simplicity. Results of such analyses are fed back into R&D tasks to improve the capabilities of electric propulsion. Iterative mission and spacecraft feasibility studies are conducted to the point where significant mission potential is shown to exist, at which time the analysis effort is transferred to other cognizance within JPL.

PROGRESS

Due to priority effort on other solar electric spacecraft studies under OSSA sponsorship, there was no activity under this work unit this half of the fiscal year other than preparation of the listed paper.

PUBLICATIONS

Meeting and Symposia Papers

1. Wrobel, J. R. and Kerrisk, D. J., "Early Exploration of the Asteroids Region by Solar Powered Electrically Propelled

Spácecraft," presented at the American Astronautical Society and Operations Research Society Joint National Meeting, Denver, Colorado, June 17-20, 1969.

LOW THRUST TRAJECTORY ANALYSIS

NASA Work Unit 120-26-07-03

JPL 320-60201-1-3910
JPL 320-60202-1-3920

T. H. Elconin
J. F. Jordan
W. Kizner
C. G. Sauer
W. Stavro

OBJECTIVE

The objectives of this task are to provide an efficient and versatile trajectory performance computational capability, and to carry out parametric studies of the trajectory-related properties of specified advanced propulsion missions.

PROGRESS

Trajectory Analysis

The work being performed in the low-thrust area during the last six months may be divided into the mission/trajectory analysis and program development/conversion for the Univac 1108 computer system.

In the mission analysis area, most of the work has been concentrated on a nuclear-electric-propulsion Jupiter orbiter mission. Most of the results of this investigation appear in a preliminary document* published by and for the use of the OART nuclear-electric systems analysis working group. This Jupiter mission included data for both capture in an elliptical orbit (2 x 38 radii) and a circular orbit (15 x 15 radii). The missions so far investigated have been for a high thrust injection to escape at the earth using one of three possible launch vehicles. A deboost maneuver with a chemical retro-propulsion

*Trajectory data on nuclear-electric missions to Jupiter, Saturn, Uranus and Neptune.

system was used for the elliptical orbit capture and a captural low-thrust spiral trajectory was used for the circular orbit. Still to be investigated are missions using escape spiral trajectories from the earth for the analysis.

The mission analysis in the solar-electric-propulsion area has been fairly minimal the past half year. One mission currently being investigated is that of an anti-solar probe. The object of this mission being to get a spacecraft into an eccentric orbit with a semi-major axis of 1 AU and on the opposite side of the sun from the earth.

A Fortran V version is now operating and being checked out on the Univac 1108. This version of the low-thrust program includes most of the capability of the original IBM 7094 version except for the (unconstrained) variable-thrust program. Most of the transversality conditions used to optimize vehicle and path parameters are in the 1108 program and are being checked out.

The Univac 1108 program also has the capability to run n-body low-thrust trajectories, although optimization of spacecraft power and specific impulse and departure and arrival energy for the planetocentric phases is not yet possible for this option since the partial derivatives needed for the transversality condition have not yet been included. In addition the two-body optimization of low-thrust trajectories having low-thrust departure or arrival spiral trajectories has been included.

Low Thrust Trajectory Accuracy Studies

(1) Low Thrust Navigation Analysis

The Continuous Estimation Program (CEP) and other matrix manipulator programs have been applied to the orbit determination problem associated with a continuously thrusting spacecraft. Recent studies have emphasized sensitivity to process noise correlation time.

(2) Grand Tour Navigation Analysis

Application of the low-thrust techniques have been applied to the Grand Tour as a possible solar electric leg (earth-Jupiter) of a 1977 Grand Tour Mission. Results will appear shortly in Section II of a forthcoming JPL Grand Tour Mission Study Report.

(3) <u>Grand Tour Low Thrust Vehicle Guidance and Control</u>

Studies have been conducted in the area of control of low-thrust vehicles. Application of the present theories are being performed on the Grand Tour trajectory. The current control strategy is a fixed time strategy which minimizes the integral of a quadratic in control derivations. Results will appear in the Grand Tour Study Report.

Efforts are underway to generalize the control program to include other control methods. The Second Variation method and Variable Final Time Control will be among those considered. Internal and external reports will be forthcoming.

Projected efforts for the next reporting period include new inherent estimation accuracy studies relating to low-thrust planetary missions. A more reliable process noise model than used in previous analyses will be formulated and employed. The studies will investigate the inherent O. D. accuracies for various missions and various methods of processing data for real-time tracking (sequential estimation, batch processing, adaptive filtering). Possible applications will include trajectory error analysis and navigation accuracy analysis of outer planet orbiter and flyby missions in the 1980's, both solar-electric and nuclear-electric.

Work is being carried out on the reliability models for arrays of thrusters of ion propulsion engines. The problem can be broken into two parts, one consisting of the system being driven by white noise, and the other the system being driven by noise which is highly correlated, stemming from the failure of thrusters. The white noise aspects can be handled by standard methods of analysis, such as Kalman filters. However, special techniques are required for the correlated noise. One model has been analyzed and an analytic expression for the autocovariance function for the noise has been obtained. Some of the standard deviations for the quantities of interest have been obtained. It is anticipated that the programming to finish this problem will be completed in a few weeks, at which time a report will be issued.

Computer Program Development

Work on the ASTRAL program has continued in this time period. An activity was undertaken to analyze and compare several optimization methods to be used in the optimizing subroutine of ASTA, the first version of ASTRAL. This activity was completed and the decision made to incorporate the direct search optimization method as a primary optimizer with the complex method as a back-up.

The checkout of ASTRAL with comparisons to Sauer's integrating program were continued. Reference 1 was a progress report showing the results of some comparison cases.

At present the main activity is in the documentation and conversion of ASTA. The new set of JPL astronomical constants has now been incorporated in ASTA.

An attempt is now being made to use ASTA as a mission analysis tool. A test of the utility of ASTRAL as an aid to the use of Sauer's program was carried out. The test case chosen was a Saturn fly-by and ASTRAL did provide useful parameter estimates even though the two programs used somewhat different models of the spacecraft low thrust acceleration level.

A low-thrust Saturn orbiter mission in the early 80's is currently being investigated using ASTRAL. Results will be compared to similar ballistic missions and publication of the results will follow in the near future.

The AIAA 7th Electric Propulsion Conference in Williamsburg in March 1969 was attended in connection with these studies.

REFERENCES

1. Alderson, D. J., "ASTRAL Checkout Progress (III)," ION 315.21/643, March 7, 1969.

PUBLICATIONS

Journal Articles

1. Jordan, J. F., "Orbit Determination for Powered Flight Space Vehicles on Deep Space Missions", Journal of Spacecraft and Rockets, June 1969.

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ELECTRIC PROPULSION APPLICATIONS

NASA Work Unit 120-26-08-01

JPL 320-60101-0-3830

D. J. Kerrisk

OBJECTIVE

The objective of this task is to bring the technology of solar-powered electric propulsion to a flight-ready status. To demonstrate the flight-readiness of the technology a series of tests has been planned. These include an open-loop test of a partial thrust subsystem during FY 69, and a closed-loop test of a complete breadboarded thrust subsystem during FY 71.

PROGRESS

The effort during the past six months has concentrated on the open-loop subsystem test. Also, work continued on the installation of the 7 1/2' vacuum chamber, in which the closed-loop test will be conducted, and on preliminary work for the closed loop system test. Each of these will be considered separately.

Open-Loop Test

The open-loop subsystem test activities are divided into three major areas: integration testing, an initial 300-hour shakedown test, and a 300-hour test run. The major findings of each of these phases will be reviewed.

Integration testing of the power conditioning unit and the oxide cathode thruster started late in December, 1968. A detailed description of this test subsystem is given in Pub. 2. The prinicpal problem area encountered was during thruster turnoff and restart. Ion engines are subject to intermittent arcing between the high voltage extraction grids, which can cause large transients in the power conditioning unit. In order to protect the electronic circuitry from these undesirable transients, the power conditioner is programmed to shut down when over-currents are demanded in any of the supplies, and to automatically restart after a short interval. During the integration phase it was found that the power conditioner was frequently shutting off with no indication of thruster arcing, and that it was having a great deal of difficulty in restarting the thruster. An investigation of the causes of power conditioner shut down revealed a great deal of noise was getting into the logic circuitry. By adjusting the over-current shut-off levels and the times required for shut-down, the problem of "nuisance" shut-down was eliminated. The problem of thruster restart was more difficult. After thruster shut-down, the particle density in the thruster chamber increases. When thruster operation is re-established, a large burst of current occurs, which is seen by the power conditioner as an over-current and will cause the power conditioner to shut down again. This leads to a continuous cycling between on and off conditions.

A detailed investigation of thruster restart procedures was made to try to minimize these turn-on transients. The alternative, to increase the over-current capability of the various power supplies to withstand the turn-on transients, was considered unacceptable because of the weight penalty attendant on this approach. The investigation led to a turn-on sequence that utilized a cut-back in the thruster magnetic field and a slow ramp to its normal value in order to provide a reliable restart capability.

In April, 1969, a shake-down run of the open-loop subsystem was started. This test, which is described in detail in Pub. 3, revealed several incipient problem areas. These included noise sensitivity of several of the subsystem elements, the variation in performance of "identical" thrusters when operated from the same power conditioner, and weaknesses in the power conditioning logic. It was also found that further work on the turn-on sequence for the thruster was required. This was again modified to reduce the propellant flow to the thruster during the time the thruster was trying to restart. A major problem was encountered in the coating of all exposed surfaces in the vacuum chamber with back-sputtered material. By the end of the shake-down run it was felt that sufficient data had been accumulated to permit the starting of a system test following the incorporation of the power conditioner modifications indicated by the shake-down test and the improvement of the protection of in-tank exposed surfaces from sputtering contamination.

The test run commenced during May, 1969, and ran for 300 hours. During this time the system was found to perform well, recycling reliably at all output power levels. Several minor problems were encountered, mostly either in the power-conditioner logic circuitry, which had been extensively re-worked, or in facility equipment. Back-sputtered material remained a problem, and after approximately 200 hours, caused the failure of one engine by shorting the cathode to the thruster housing. The power conditioner was switched to the second thruster and the test continued. The test was stopped at 300 hours because of the failure, due to overheating, of a transformer mounted in the vacuum chamber. While testing could have been resumed within a short period, it was decided that all major test objectives had been met, and further testing should be concentrated on the new power conditioning unit just delivered.

The Open Loop Test showed the ability of a thrust subsystem to operate in an extremely hostile environment. All major subsystem elements were operated, and accelerated life testing of gimbal and translator actuators was performed. Over ten million steps were put on these actuators. This is about four times the nominal number required on a 10,000 hour mission. Switching was demonstrated to be problem-free, and power conditioner-thruster interactions have been defined and their effects on subsystem operation have been minimized.

<u>7 1/2' x 15' Vacuum Chamber</u>

Installation of the main vacuum chamber was completed early in April, 1969, and the system was pumped down to below 10^{-7} torr. The power conditioning test chamber was installed during June, 1969, and it is presently being wired into the facility control console. This will be completed during July, 1969. Meanwhile, testing of thrusters has already started in the main chamber.

<u>Closed-Loop Test</u>

During this reporting period, a major design effort was started on all subsystem elements. Preliminary testing of thrusters in the new vacuum chamber commenced, and the test setup for evaluation of the new power conditioner breadboard was completed. Acceptance of the breadboard was made late in June, 1969, and evaluation of this unit will take place early in the next reporting period.

PLANS

During the next six months, most of the hardware for the closed-loop test will be fabricated. Power conditioner evaluation will be completed by December, and assembly of the closed loop system will start in January, 1970. Installation of the experiment control console will be completed during this period.

PUBLICATIONS

Meeting and Symposia Papers

1. Pawlik, E. V., Macie, T. W., and Ferrera, J. D., "Electric Propulsion System Performance Evaluation," AIAA Paper No. 69-236, AIAA 7th Electric Propulsion Conference, Williamsburg, Virginia, March 1969.

2. Macie, T. W., Pawlik, E. V., Ferrera, J. D., and Costogue, E., "Solar Electric Propulsion System Evaluation," AIAA Paper No. 69-498, AIAA 5th Propulsion Joint Specialist Conference, U. S. Air Force Academy, Colorado, June 1969.

3. Masek, T. D., "Plasma Properties and Performance of Mercury Ion Thrusters," AIAA Paper No. 69-256, AIAA 7th Electric Propulsion Conference, Williamsburg, Virginia, March 1969.

4. Mueller, P. A., and Pawlik, E. V., "Control Analysis of an Ion Thruster with Programmed Thrust," AIAA Paper No. 69-239, AIAA 7th Electric Propulsion Conference, Williamsburg, Virginia, March 1969.

EVALUATION OF ELECTRIC PROPULSION BEAM DIVERGENCE AND EFFECTS ON SPACECRAFT

NASA Work Unit 120-26-08-02

JPL 320-61501-0-3830

D. J. Kerrisk

OBJECTIVE

The objective of this work unit is to evaluate analytically and experimentally the interactions effects of an ion engine exhaust beam on external surfaces of electric propulsion spacecraft to provide design data for advanced propulsion spacecraft development.

PROGRESS

The first phase of this program was completed in August 1968. The rough draft of the Final Report for Phase I has been reviewed and revision is almost complete. Release of the Final Report is expected by the end of FY69. AIAA Paper No. 69-271 summarizing the knowledge gained in Phase I was given at the AIAA 7th Electric Propulsion Conference.

A contract for the second phase of this program was negotiated and formally let February 10, 1969 (JPL Contract No. 952350). The following accomplishments summarize the results of this effort to date:

1. Priorities of experiments and a preliminary schedule of the experimental activities have been established. First priority has been given jointly to the surface thermal and chemistry experiments.
2. Fabrication of the necessary experimental fixtures to be used in the surface-thermal erosion (sputtering) experiments has been essentially completed.
3. Procurement and preparation of all samples to be used in the surface-thermal, chemistry, and erosion (sputtering) experiments has been essentially completed.

4. Six organic spacecraft materials, which are representative of the chemical structures making up the organic matrices of spacecraft materials under study in this program were selected for cesium immersion tests. Materials selected were Sylgard 182, Delrin, GT 100, SMRD 745, Teflon FEP, and Kapton H-Film. Initial tests on most of these materials have been completed and the chemical effects evaluated. Results of these initial tests indicate that after a 48-hr exposure at room temperature:

   (a) The compatibility of Kapton with liquid cesium is questionable.

   (b) Teflon FEP is seriously degraded at the surface.

   (c) Sylgard 182 may be degraded.

   (d) Delrin and SMRD 745 are stable toward cesium.

   Analysis of all six spacecraft materials will be continued and completed and conclusions drawn, after which similar tests and analyses of these materials in mercury will be performed.

5. Initial metallurgical tests of silver in mercury, solder in mercury, and solder in cesium have been made and evaluated. Test results to data indicate that

   (a) after six weeks exposure of soft solder to mercury, a large quantity of solder constituents is dissolved and that the remaining structure has little or no mechanical strength,

   (b) mercury reacts rather slowly with silver (4 week exposure).

   Further tests of cesium/solder and mercury/silver are planned. In addition, mechanical properties tests are to be performed.

6. Final modifications to the experimental facility have been completed.

7. Gravimetric boiler calibration runs using mercury have been made.

The first in-tank experiments will be to determine effects of mercury neutrals from the thruster on the surface thermal properties of various materials. This experiment will be started by the end of FY 69.

PUBLICATIONS

Meeting and Symposia Papers

1. Hall, D. F., Newman, B. E., and Womack, J. R., "Electrostatic Rocket Exhaust Effects on Solar-Electric Spacecraft Subsystems," AIAA Paper No. 69-271, presented at the AIAA 7th Electric Propulsion Conference, Williamsburg, Virginia, March 1969.

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ELECTRIC PROPULSION SPACECRAFT PLASMAS AND FIELDS INTERACTIONS

NASA Work Unit 120-26-08-04

JPL 320-61001-0-3830

D. J. Kerrisk

OBJECTIVE

The objective of this work unit is to investigate possible interactions between electric propulsion systems and scientific data collection on unmanned interplanetary spacecraft. Such interactions could influence data collection in several ways; the fields associated with electric propulsion systems could influence the science instruments themselves, giving false readings; second, the fields could influence the space plasma, disturbing it to such an extent that the measurements taken give little indication of the undisturbed condition; third, the particles associated with the electric propulsion system, particularly the electrons and slow ions, could themselves be detected by the particles measuring devices, thereby giving spurious readings. The severity of each type of interaction must be investigated.

PROGRESS

A contract was initiated with TRW Systems in February 1969. This is a continuation of a previous study (NAPO Contract NAS-7-564) directed toward identifying the expected major problem areas. During the first months of this contract, attention has been primarily directed to the problem of magnetic contamination, particularly as associated with large area solar arrays. A detailed examination of the General Electric roll-out solar array was made to determine the magnitude of the residual magnetic fields at various locations on a hypothetical spacecraft employing such an array. With the present configuration, the analysis showed contaminant fields on the order of one to two gamma can be expected at a distance of two meters from the solar array. Simple reconfiguration of the array wiring could reduce this field level by an order of magnitude. Analysis of these contaminant fields will be extended to include contributions from the thruster array during the next reporting period.

A second area of study has been the examination of electrostatic contamination of a solar-electric spacecraft. During this reporting period, an experimental setup of a plasma wind tunnel was completed to evaluate the dynamic resistance between the spacecraft and the space plasma. Principal emphasis during the next period will be given to the evaluation of the electron interchange between the thrust beam and the space plasma, and its effect on the floating potential of the spacecraft. This will allow an evaluation of the anticipated electrostatic effects on spacecraft science.

PUBLICATIONS

Contractor Reports

1. Sellen, J. M., Jr., "Study of Electric Spacecraft Plasmas and Fields Interactions," AIAA Paper 69-276, March 1969.

2. Ogawa, H. S., Colè, R. K., and Sellen, J. M., Jr., "Measurements of Equilibration Between a Plasma 'Thrust' Beam and a Dilute 'Space' Plasma," AIAA Paper 69-263, March 1969.

ION ENGINE THRUST VECTOR STUDY

NASA Work Unit 120-26-08-05

JPL 320-61101-0-3830

D. J. KERRISK

OBJECTIVE

The objective of this work unit is to evaluate the probable uncertainty in the magnitude and direction of the thrust vector of an array of ion thrusters to provide information for use in spacecraft systems analysis and in navigation and guidance analysis.

PROGRESS

Work was started on this contract by the Hughes Aircraft Company during January, 1968. The contract was modified during October to include experimental determination of the thrust vector. Progress on this study to date includes:

(1) Analysis of both the effects on ion optics and the causes of grid misalignments has been completed. The beam direction has been found to be moderately sensitive to grid displacements.

(2) A lightweight 30-cm diameter thruster complete with grid displacing actuators has been fabricated and tested. Satisfactory thruster operation was obtained.

(3) The parts for the thrust stand have been fabricated and are in final assembly. The position sensors and electronics to drive the balancing motors have been completed.

(4) Design information on the spring constants of the thrust stand wiring has been obtained experimentally.

Much of the effort on this program has been delayed because of internal HAC problems with both personnel scheduling and vacuum facility modifications. An analysis, conducted during the program, indicated a sensitivity of the thrust stand to vacuum tank mechanical vibrations. A vacuum tank is being reinstalled in a vertical position. Suitable mounts, to eliminate vibrations, have been added to make this facility compatible with the thrust vector program. A no-cost extension to this effort has been requested to provide testing time in this modified facility.

PUBLICATIONS

Meeting and Symposia Papers

1. Seliger, R. L., Nudd, G. R., Brewer, G. R., and Amboss, K., "Analysis of the Expected Thrust Misalignment of Kaufman Thrusters," AIAA Paper No. 69-303, 7th Electric Propulsion Conference, Williamsburg, Va., March 1969.

Contract Reports, Interim

1. Ion Engine Thrust Vector Study, Quarterly Report No. 2, April 1969, Contract No. 952129.

ELECTRIC THRUSTER POWER CONVERSION AND CONTROLS

NASA Work Unit 120-26-08-06

JPL 320-61201-0-3830

D. J. Kerrisk

OBJECTIVE

This work unit is directed toward the development of lightweight, efficient, and reliable power conditioning units for use in solar powered electric propulsion systems. Its technical goals are demonstration of 9 lb/kw, 92% efficiency, and 96% reliability (for 10,000 hours) for a 2.5 kw power conditioning unit.

PROGRESS

A contract was released to Hughes Aircraft Co. in June, 1968, for the development of the power conditioning units. The initial schedule called for delivery of a breadboard unit to JPL by 1 January 1969. This date was first modified to 1 April 1969, and later to mid-June 1969, in order to incorporate changes in the logic circuitry found to be desirable during the open-loop system testing discussed under NASA Work Unit 120-26-08-01-55. Acceptance testing of the breadboard commenced during May, 1969, and several minor deviations from the specification were detected. Also, problems in meeting the specified efficiency goal were encountered. This is traceable to the main power transistors, which did not display the switching times guaranteed by the manufacturer. An alternate power transistor has been evaluated, which would increase the efficiency to the desired level; however, for the time being, no plans have been made to incorporate this transistor in the breadboard unit. Acceptance of the breadboard occurred on June 17, 1969, and the unit has been delivered to JPL for integration and testing with a thruster. Delivery of the two experimental units will take place in September, 1969, and November, 1969.

PUBLICATIONS

Contractor Reports

1. "Electric Thruster Power Conditioner," Quarterly Technical Report #3, HAC Document No. 2228/945, April, 1969, JPL Contract 952297.

ELECTRIC PROPULSION ENGINE AND ATTITUDE CONTROL

NASA Work Unit 120-26-08-07

JPL 320-61601-X-3440

P. A. Mueller

OBJECTIVE

The long-range objective of this work unit is to support the Solar Electric Propulsion System Technology (SEPST) effort which is directed toward a system feasibility demonstration scheduled for calendar years 1970-71. The goal of the feasibility demonstration is to conduct a ground test, incorporating all equipment necessary, to prove feasibility for a flight program. The objectives of this period were to continue analysis and simulation of ion thruster control loops and to perform three-axis attitude control (thrust vector control) analysis, simulation and circuit design and initiate breadboarding. Another subtask on stored program thrust control has been transferred to another work unit.

PROGRESS

During this period, work has continued on Phase II and Phase III of SEPST. In the previous period, open-loop electronics for thrust vector control were developed and analysis of the oxide-coated cathode ion thruster was completed. These efforts were in support of Phase II. Since delivery of the thrust vector control electronics, several Phase II system tests (ion thrusters, actuators, power conditioning, etc.) have been conducted in preparation for a 1000-hour endurance run of the system. The control system electronics and stepper motor driven actuators have been operated more than one million steps, thereby demonstrating the necessary stepping lifetime.

The majority of the effort during this period has been in support of Phase III. Preliminary study of the Phase III ion thruster has been initiated. As in Phase II, the study pertains to the analysis and simulation of the control loops used in the thruster power conditioning. Some detailed thrust vector control analysis and simulations have been performed to provide specifications for the electronics system for Phase III. Ion thruster arcing (brief loss of thrust) was investigated to determine its effect on the control loops. The arcing appears to have negligible effect on the total number of actuator steps required. Requirements for minor loop feedback were also investigated. It appears that the minor loop feedback is a critical requirement for the limit cycle mode.

During this period, work on the thrust vector control electronics has progressed from the functional specification of the last period to functional design and breadboarding. Several changes have been made in the functional specifications to eliminate interface conflicts with other subsystems involved with the Phase III effort. SEPST program management has requested the added capability of automatic gimbal failure detection. Several major hardware items have been selected for use in the test operation. Among these are the operational amplifiers (approximately 50 are used), the type of logic elements (chosen for compatibility and noise immunity), and solid-state switches (appropriate for reliability in advanced missions). Breadboarding is about 20% complete.

The JPL central analog computer facility will be used to simulate the spacecraft dynamics in Phase III. Two multichannel cables have been installed between the Phase III site and the computer facility.

During the next period, study of the hollow cathode ion thruster control loops will continue and simulations will be performed on the digital computer. The thrust vector control electronics hardware will proceed into fabrication. It will be tested alone and with the actuators and is scheduled for delivery to the Phase III site early in the following period.

PLANS

During the next six-month period, the most important activity will be the fabrication and test of the complete three-axis control system electronics unit. It will be integrated into the Phase III test program. A ground test of the entire control system will be initiated. In addition, analysis of new engine configurations will continue.

PUBLICATIONS

None

NUCLEAR ELECTRIC POWER SYSTEMS (120-27)

THERMIONIC REACTOR STUDIES

NASA Work Unit 120-27-05-01

JPL 320-71501-0-3830

J. P. Davis
H. G. Gronroos
W. M. Phillips

OBJECTIVE

Thermionic reactors are of major interest as potential space nuclear powerplants, particularly as applied to unmanned electric propulsion. The objectives of the thermionic reactor studies are to define and investigate those aspects of thermionic reactor design, control and dynamics required to further the development of these systems. In addition, the objectives are to evaluate proposed design concepts relative to configuration, materials, static and dynamic characteristics, and to aid in selection of the most promising directions for future development.

PROGRESS

Thermionic Diode Kinetics Experiment

The purpose of the thermionic diode kinetics experiment is to study thermionic reactor dynamics and control by non-nuclear means. The principle components are: (1) a testbank capable of holding six converters (four installed at initial startup) with heat rejected to NaK coolant and enclosed in a 36-inch-diameter vacuum chamber, (2) NaK heat rejection loop with N_2/NaK heat exchanger, EM pump, flowmeters, and an electrical resistance coil for preheating, (3) a coupling unit which permits various patterns of series and parallel connections, and (4) power supplies, controls, power conditioner, and auxiliary systems to support the test program. A separate development effort was necessary for the high-current, low-voltage drop (600 amp., 5 millivolt) switches in the coupling unit, and for the low-voltage power conditioner.

During this period the Kinetics Experiment has been brought to full power operation. The four thermionic diodes have been performance tested and data indicate that the current-voltage characteristics are essentially the same in the NaK-cooled system as determined initially by the vendor in a test employing water cooling.

Several experiments have been made to study the effects of coupling diodes in series and parallel the effects of perturbing one of the diodes in the chosen coupling pattern, and the effects of open and short circuiting. These experiments have been aimed at familiarization with the system behavior. During the initial runs the analog computer reactor simulator has been used on a limited scale on-line.

A specific experiment was conducted to determine if the onset of "thermionic burnout" could be observed. Thermionic burnout is a phenomenon which has been postulated to occur when an increase in heat input to the emitter, for cesium pressure at or below optimum, increases emitter temperature and causes the cesium to desorb from the emitter surface. The emitter temperature increases further due to decreasing electron cooling, which further desorbs cesium etc., resulting in a runaway condition. The final equilibrium attained has a bare emitter at very high temperature with essentially no electric power output. A clear indication of its existence was obtained in this experiment. One technique was by optimizing the cesium reservior temperature at a lower emitter temperature and then increasing the thermal power input in small steps until the diode failed to reach a new equilibrium. The burnout is slow for this case because it starts in a localized area of the emitter and gradually spreads over the whole surface. The second technique and more rapid means by which burnout was induced was by lowering the cesium reservior temperature.

The initial operation of the Thermionic Diode Kinetics Experiment has been highly productive. The equipment has operated very satisfactorily with only minor problems. The assembly has been developed to a point where routine operations and procedures have been established, and useful experimental information is being obtained. The next phase will be the systematic execution of the experimental program.

Uninsulated Thermionic Diode

The computer program developed at JPL for detailed analysis of this diode is now operational. This program couples the Simcon thermionic characteristics to the non-uniform axial thermal distribution which is generated to yield overall diode performance. The temperature perturbations at the diode ends caused by the electrical lead are included, hence an accurately optimized lead can be determined for any set at operating conditions in addition to local temperature, current density, and voltage along the entire emitter surface.

Materials Studies

Among the nuclear fuels considered for nuclear thermionic reactors is uranium dioxide. This fuel has been shown to migrate down a thermal gradient to form a fully dense layer in the coolest portions of a fuel element. In the case of a cylindrical nuclear thermionic fuel element this results in a shell of fuel against the clad and a central void. Gaseous fission products migrate up a thermal gradient and collect in the central void building up pressure as fission continues. The resulting pressure combined with the plasticity of $U0_2$ at thermionic temperatures can result in fuel element swelling. Prevention of fuel swelling requires venting of fission products to reduce the central void pressure buildup. This can be achieved by either insertion of a snorkel vent tube through the clad into the central void or by a peripheral vent hole in the clad. While the peripheral vent would be easier to fabricate, it could plug with $U0_2$ as the fuel redistributes against the fuel element clad.

An experiment was designed to: (1) measure the rates of $U0_2$ redistribution as a function of temperature and thermal gradient, (2) determine the time necessary to plug a peripheral vent hole or a snorkel vent tube, and, if plugged, (3) determine the degree of thermal cycling necessary to crack the $U0_2$ and provide communication between the central void and a peripheral vent hole.

A test capsule was designed to provide a thermal gradient similar to that of a nuclear thermionic fuel element. An electron bombardment heater provides center-line temperatures in excess of 2000°C. Control of the surface temperature and thermal gradient is acheived through the use of an external cylindrical heater and a balance between the power put into the center-line heater and the external heater. An argon pressurization tube allows the injection of argon into the central void to simulate fission gas. Plugging of a peripheral vent hole by redistribution of the $U0_2$ is determined by injection of a small amount of argon into the central void through the argon pressurization tube. If the peripheral vent hole is communicated to the central void a rise in vacuum chamber pressure is produced.

Redistribution of $U0_2$ powder has been determined by radiographic techniques. A central void forms within 24 hours at what are considered moderate temperatures by thermionic standards, approximately 1600°C surface.

Testing has shown that a 0. 005 inch diameter peripheral vent was plugged in less than 200 hours at thermionic conditions. A thermal shock down to a temperature of 500°F was necessary to cause recommunication between the central cavity and the vacuum chamber. Initial post-test examination has also shown $U0_2$-W reaction which results in substantial movement of tungsten within the capsule. Testing is continuing with tungsten capsules, and plans include the fabrication of rhenium test capsules.

PUBLICATIONS

JPL Publications

1. Gronroos, H., Weaver, L. E. and Guppy, J. G., "A Control System Study for an In-Core Thermionic Reactor," TR 32-1355, January 15, 1969.

2. Weaver, L. E., Summa, W. J., and Gronroos, H. G., "A State-Variable Feedback Design for the Control System for an In-Core Thermionic Reactor," SPS 37-55, Vol. III, February 28, 1969, p. 220.

3. Gronroos, H. G., Pellgren, M. L., and Davis, J. P., "Initial Operation of the Thermionic Diode Kinetics Experiment," SPS 37-57, Vol. III, May 31, 1969.

NUCLEAR POWER SYSTEM DEFINITION STUDIES

NASA Work Unit 120-27-06-01

JPL 320-70101-2-3420

R. Campbell
P. Gingo

OBJECTIVE

The inclusion of an RTG on a spacecraft introduces a neutron and gamma radiation environment which will interfere with the normal operation of many instruments onboard the spacecraft, particularly the very sensitive science instruments. The major objectives of this task are to predict, analyze and reduce the RTG radiation field interactions with the space vehicle. The evaluation of source radiation characteristics, the effects of the emitted radiation on scientific instruments and spacecraft subsystems, and the methods of reducing the radiation sensitivity of expected components will be studied.

PROGRESS

The work unit may be divided into two broad tasks; one covering an analytic radiation analysis, the second encompassing an extensive experimental effort.

Radiation Analysis

With the increased emphasis placed on plutonium dioxide as an RTG heat source, it became necessary to study its nuclear characteristics in great detail. Large variations in both experimental and analytical data were found in the literature. After an extensive literature search, and evaluation of existing data for $Pu0_2$ it was possible to:

(1) Identify all gamma-ray source intensities due to primary decay, daughter nuclide decay, fission product decay and 0^{18} $(\alpha, n)Ne^{21}$ transitions. These were grouped into 20 energy intervals extending from 7meV down to 1 keV

(2) Determine the neutron yields and energy distribution from spontaneous fission, the O^{18} $(\alpha, n)Ne^{21}$ reaction, and from the (α, n) reaction in other light elements. These are grouped into 23 energy intervals extending from 10meV down to 0.025 ev in neutron energy.

Following this, the neutron and gamma-ray spectra were determined for three typical RTG fuel capsule designs. Flux values were calculated at the capsule surface and for exterior detector points. The spectrum of the gamma radiation was determined as a function of the age of the fuel for periods up to 18 years. This work was done parametrically with fuel impurity concentration. Photon attenuation in tungsten shields was also determined for shield thicknesses of from 1/4 to 1 inch. Included in this was the neutron capture gamma spectrum generated in the shield.

Contract (PO. NO. GP-505386) for $10,000 was awarded to ART Associates to perform Monte Carlo calculations to predict component response and sensitivity to the RTG radiation.

An investigation, based on preliminary data, analyzed the interaction of several scientific experiments and spacecraft components with an RTG radiation field. Shield weights were developed for a typical configuration and recommendations to minimize shield weights were made.

Experimental Program

RTG Radiation Test Laboratory and Experiments

The structural modification of Building 247 for use as a radiation test laboratory was begun in February and completed for occupancy in early April. A Standard Operating Procedure for the laboratory, which is required for the receipt of an RTG fuel capsule assembly, has been written and appropriate sections have been approved by the AEC OSD/ALO.

Since RTG fuel capsules will not be available at all times, a variety of other radiation sources have been acquired. These include eight Pm-147 heat sources, six SNAP-15A Pu-238 metal heat sources, and a five-curie PuBe source. In addition, a simulated PuO_2 source has been designed which will accurately reproduce the neutron and gamma spectra expected from a fuel capsule, without the use of high activity alpha particle emitters. With this source it will be possible to mockup the changes in the radiation spectrum expected in a PuO_2 fuel capsule over an 18-year period. The existing state license has been amended to allow these sources to be used in our laboratory.

Measurements of gamma spectra from the radiation sources have begun. Both a NaI(Tl) scintillation spectrometer and lithium drifted germanium solid state spectrometer have been calibrated so that absolute gamma intensities may be determined. The Pm-147 and Pu-238 source spectra have been measured with the NaI(Tl) and Ge(Li) spectrometers, respectively. Several codes have been acquired for the stripping analysis of the complex gamma-ray spectrometer data which, by the use of the detector response function, convert the pulse height data as measured with the spectra analyzer back to the actual spectra emitted by the radiation source.

Battelle Northwest Laboratories Experimental Program

An $80, 000 contract (NO. 952559) was awarded to Battelle Northwest Laboratories, Richland, Washington to determine experimentally the absolute efficiency of certain scientific flight instrument components as a function of incident monoenergetic neutron and photon radiation. Typical components under study are totally and partially depleted silicon surface barrier detectors, several miniaturized G-M tubes and the channeltron analyzer. Exposures in monoenergetic gamma fields have begun.

PLANS

Radiation Analysis

For each of the nuclear detectors studies in the experimental program, the intrinsic efficiencies will be calculated for both monoenergetic gamma and neutron radiation incident upon the detector. This will be compared with the results from the Battelle contract. When agreement is good at this point, the response to complex spectra will be calculated and compared to the experimental work done at JPL. It will then be eventually possible to provide semi-empirical equations which predict science instrument interference modes. Calculated fuel capsule spectra will continually be compared with new experimental information and updated as required.

Experimental Effort

Battelle Northwest will determine the response of a wide variety of detectors to monoenergetic neutron and gamma radiation. These same detectors will be exposed to complex, mixed spectra at JPL using several types of radiation sources including Pu-238. Results of both efforts will be compared with each other and with the analytical approach. The measurements will then be extended to include the study of instrument packages containing numerous components. A SNAP-19 or SNAP-27 fuel capsule assembly should be obtained during the next 6-month period for use in the radiation program.

PUBLICATIONS

SPS Contributions

1. Gingo, P. J., "Gamma Radiation Characteristics of Plutonium Dioxide Fuel," SPS 37-56, Vol. III, April 1969.

2. Dore, M., "Required Gamma Ray Shielding for Science Instruments on Radioisotope Powered Spacecraft," SPS 37-57, Vol. III, June 1969.

3. Gingo, P. J., "Nuclear Power System Definition Studies," SPS 37-57, Vol. III, June 1969.

NUCLEAR REACTOR AND LIQUID METAL SYSTEMS ENGINEERING

NASA Work Unit 120-27-06-02

JPL 320-70201-0-3830

J. P. Davis
G. M. Kikin
H. G. Gronroos
M. L. Peelgren
W. M. Phillips

OBJECTIVE

The objective of this work is to further the understanding of the dynamic and steady-state characteristics of high-temperature Rankine cycle powerplants with nuclear reactor heat sources. A two-loop (lithium-boiling potassium) test loop was designed, fabricated, and operated at JPL. The test loop contained all of the essential components of a Rankine cycle powerplant, including an analog computer for simulation of neutron kinetics. The loop operated with velocities, temperatures, pressures, transient times, and many other important parameters in the range of actual system interest.

PROGRESS

Lithium-Boiling Potassium Rankine Cycle Test Loop

This work has been completed, and the results of examination of the loop submitted as a paper for presentation at the Liquid Metals Corrosion 1969 Fall Meeting. It has been found that yttrium hot trapping of lithium, and zirconium hot trapping of potassium have been effective means of minimizing attack in a Cb-1Zr system.

Alkali Metal - Stainless Steel Corrosion Studies

The results of work on additions of various gettering elements to an alkali liquid metal have been summarized in a report presently in preparation. This work will be continued under the thermionics program with the fabrication and testing of a thermal loop using materials applicable to thermionics. Active metal oxygen scavengers, e.g., yttrium, has resulted in increased temperature suitability of stainless steel up to 1400°F in lithium.

ANTICIPATED PUBLICATIONS

1. Phillips, W. M., "Some Effects of Flow Stream Gettering on Alkali Metal Corrosion," to be published as JPL Technical Report.

2. Phillips, W. M., "Some Alkali Metal Corrosion Effects in a Rankine Cycle Test Loop," submitted to the Metallurgical Society of AIME, Liquid Metals Meeting, Philadelphia, Pa., Fall of 1969.

PUBLICATIONS

None

MHD CONVERSION SYSTEMS

NASA Work Unit 120-27-06-03

JPL 320-70301-0-3830

D. G. Elliott
D. J. Cerini
L. G. Hays

OBJECTIVE

Liquid-metal magnetohydrodynamic (MHD) power conversion is being investigated as a power source for nuclear-electric propulsion. A liquid-metal MHD system would have no moving mechanical parts and would operate at heat-source temperatures between 1600°F and 2000°F. The system has the potential of high reliability and long lifetime using readily-available containment materials such as Nb-1%Zr. Liquid lithium would be heated at about 150 psia in the reactor or reactor-loop heat exchanger; mixed with liquid cesium at the inlet of a two-phase nozzle, causing the cesium to vaporize; accelerated by the cesium to about 500 ft/s at 15 psia; separated from the cesium; decelerated in an alternating-current MHD generator; and returned through a diffuser to the heat source. The cesium would be condensed in a radiator or radiator-loop heat exchanger and returned to the nozzle by an MHD pump.

PROGRESS

NaK-Nitrogen Conversion System

The conversion system assembly consisting of the nozzle, separator, generator housing and NaK return lines has been completed. The flow tests with NaK and nitrogen will provide hydraulic and electrical characteristics of a conversion system directly relatable to a Cs-Li space power plant. The NaK supply system has been completed and helium leak checked prior to NaK fill. The core losses were measured for the generator to be used in the first test, and as a result of using 4% silicon-iron were found to be approximately 10 times less than previously measured using iron-cobalt laminations. Coils and stator blocks have been assembled and are being prepared for final installation and measurement of winding loss when installed in the generator housing.

Induction Generator Studies

The end losses, consisting of the eddy current and shunt end losses, in an MHD induction generator were analyzed. The fluid eddy currents, which occur in the vaned inlet and exit regions because of the rms compensating field, were treated as rectangular current loops taking into account the flow-wise resistance to current flow. The losses predicted for the previously-tested 1 kw generator were within 25% of the measured value. The optimum number of vanes considering friction losses and eddy current losses for the 50 kw NaK-nitrogen generator was reduced from 14 to 7, and the predicted output for the NaK-N_2 generator was increased from 42 to 47 kw.

An induction generator has been constructed and is being installed in the NaK blowdown test facility at the Argonne National Laboratory under Contract No. 952453 to the University of Illinois. The generator is designed for studying end losses.

Cesium-Lithium Erosion Loop

The results of the hydraulic tests of the erosion loop nozzle and separator indicate that the cesium flow to the condenser will contain 2 to 7% of the lithium nozzle flow. This represents an additional heat load which is within the capabilities of the heat rejection system. The NaK heat rejection system was operated at a temperature of 920°K at a NaK flowrate of 0.43 kg/s with 25 kw being transferred.

Impinging Nozzle Experiments

Preliminary results from water-nitrogen tests of the impinging nozzle assembly demonstrate the ability to coalesce the two-phase flow from two rectangular nozzles by impinging the jets at 15 deg. to form a single jet which contains most of the liquid and only 25% of the initial gas flow. If applied to a Cs-Li cycle this could raise the cycle efficiency from 6% to 8%.

Multi Stage Cycles

A cycle efficiency improvement to 9-10% was found possible in cycles with several stages. In a multistage system several nozzle-separator-generator-diffuser stages operate in series on the same cesium-lithium flow.

Each stage extracts a fraction of the available power permitting lower velocities and reduced friction losses.

Test Facilities

The 4800-kw DC motor-generator set and control system for heating lithium in future large-scale conversion system tests has been installed. High-voltage power lines are being installed.

PUBLICATIONS

Meeting and Symposia Papers

1. Elliott, D. G., "Effect of Slots on MHD Induction Generator Efficiency," Tenth Symposium on Engineering Aspects of Magnetohydrodynamics, Cambridge, Mass., March 26-28, 1969.

2. Cerini, D. J., and Hays, L. G., "Progress on the Cesium-Lithium MHD Cycle," Tenth Symposium on Engineering Aspects of Magnetohydrodynamics, Cambridge, Mass., March 26-28, 1969.

3. Hays, L. G., "Surface Damage from High.Velocity Flow of Lithium" American Society for Testing and Materials, 72nd Annual Meeting Atlantic City, N. J., June 22-27, 1969.

JPL Publications

1. Hays, L. G., "Analyses of a Multistage Liquid-Metal Magnetohydrodynamic Power Conversion Cycle," Jet Propulsion Laboratory Report TR 32-1371, Pasadena, California, April, 1969.

2. Hays, L. G., "Liquid-Metal MHD Power Conversion," SPS 37-55, Vol. III, pp. 212-213, February 28, 1969.

3. Elliott, D. G., Hays, L. G., Cerini, D. J., "Liquid-Metal MHD Power Conversion," SPS 37-56, Vol. III, April 30, 1969.

4. Hays, L. G., "Liquid-Metal MHD Power Conversion," SPS 37-57, Vol. III, June 30, 1969.

NUCLEAR THERMOELECTRIC POWER SOURCES

NASA Work Unit 120-27-06-08

JPL 320-70801-2-3420

P. Rouklove
G. Stapfer

OBJECTIVE

The objective of the program is the evaluation of state-of-the-art and advanced isotope thermoelectric power sources. The task involves the procurement and evaluation of thermoelectric elements, multi element modules and thermoelectric generators. The units under investigation are subjected to parametric, environmental and life testing. The modes of abnormal behavior are examined.

PROGRESS

The testing of thermoelectric generators and modules reported in the last period was continued. A brief description of each follows.

SNAP 11

Generator Model QN-3 after being subjected to environmental and parametric evaluation in ambient and in vacuum was placed on long-term life testing in an ambient environment.

During this endurance testing the generator was set to operate at a power input of 714 W, with an output voltage of 2.5V corresponding to the point of maximum power. Parametric evaluation after the acceleration and vibration tests indicated an approximate 2.0 W step decrease in power output. Prior to that time the average rate of decrease in output power was determined to be 0.12 W/1000 h. This corresponds to a degradation rate of about 0.72%/1000 h.

SNAP 19

The testing of two SNAP-19 generators, Models SN-20 and 21, was continued. Model SN-20, which produces about 30 W(e) power, was subjected to a simulated mission environment in thermal vacuum. The voltage-current characteristics of the generator are presently being recorded on a monthly basis. The generator has shown a large decrease in the fill gas pressure, which decreased from an original value of 30 psi to 3.6 psi after 13,354 hours of operation. This has not appeared to influence the power output, which has decreased at an average rate of 0.178 W/1000 h (0.69%/1000 h) over this time period with the present rate being about 0.1 W/1000 h. Endurance testing of the generator is continuing.

Model SN-21, assembled with 2P-2N material, but with "cups" at the hot and cold end contacts, has been subjected to endurance testing in ambient with voltage-current characteristics obtained every 1000 hours. During the past 9,622 hours of operation the power output of the generator has decreased at an average rate of 0.33 W/1000 h. This appears to be a 3-fold improvement over the normal 2P-2N generators in which a power degradation of 1.0 W/1000 h appears to be average. The magnetic moment of this generator was also obtained. Endurance testing is still continuing.

Cascaded Generator

The delivery to JPL of a cascaded generator composed of a first stage using silicon germanium thermoelectric elements, and coupled by a sodium-filled heat pipe to a second stage using lead telluride elements (TEM-10 configuration), is delayed until late December, 1969. The generator will be supplied under Contract 952196 with Westinghouse Astro Nuclear. RCA is responsible for building the Si-Ge stage. The silicon germanium stage was assembled on the heat pipe but difficulties in the TEM-10 module postponed the delivery of the completed assembly.

The tests at JPL of the Westinghouse tubular module revealed that under the stress of thermal cycling a misalignment of the internal components and short circuit between individual couples occurs. The deficiency was traced to the end enclosures and Westinghouse is presently in the process of correcting the defect.

PLANS

A SNAP 27 has been received at JPL and in the near future will be subjected to parametric evaluation and long-term life tests.

Module Life and Performance Testing

The tests and performance evaluation of individual modules is continuing. The TEM-8 Westinghouse Tubular Module has exceeded 22,000 h of operation. A recent analysis of the module's performance to date, has shown that the output power has decreased by 61%. This corresponds to an average rate of 2.8%/1000 h. Although the performance degraded rapidly during the periods of initial thermal cycling, performance degradation was noted as well during uninterrupted operating periods.

The two 10-couple lead-telluride modules from the 3-M Company have accumulated a combined operating time of 28,000 h. The units appear to be degrading at the rate of 0.72%/1000 h. The internal pressure of this unit is still decreasing and is presently at 3 psi. The initial pressure at the start of the test was 8.2 psi. The decrease in pressure has not appeared to affect the units' degradation rate. The testing of Module No. 2 has been terminated due to an open circuit which developed after 9000 h of operation.

The 24-couple silicon-germanium module built by RCA has accumulated 8,850 h of operation. Over the initial 7000 h a degradation of 0.36%/1000 h was observed.

The tests of the RCA silicon-germanium module operating in conjunction with a heat pipe, have temporarily been halted, to allow the reinstrumentation of the module. A total of 11,450 h of operation has been logged on this module.

PUBLICATIONS

JPL SPS Contributions

Rouklove, P., "Testing of a Thermoelectric Generator," SPS 37-55 Vol. III, Feb. 1969 pp. 99-101.

JPL Technical Reports

Rouklove, P., "Parametric Tests of a Thermoelectric Generator SNAP-11 - TR-32-1294, Jan. 1969 (Classified).

Contract Reports

"Cascaded Thermoelectric Generator," Phase II Quarterly Report WANL PR (DOD)-0005, Westinghouse, April 1969, Contract No. 952196.

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NUCLEAR THERMIONIC CONVERTER DEVELOPMENT

NASA Work Unit 120-27-06-09

JPL 320-70901-2-3420

P. Rouklove
G. Stapfer

OBJECTIVE

The objective of this program is to support the nuclear reactor thermionic project. It consists of the procurement and evaluation of out-of-pile nuclear thermionic converters developed under several nuclear thermionic programs and studies of different phenomena related to the in-pile operation of thermionic converters. The task involves the design and construction of test equipment, parametric and life testing of the converters, evaluation of converters operating in an abnormal mode, and the examination of the failure modes of the converters.

PROGRESS

Test Equipment Construction

A total of four test stations are planned for the parametric performance and life testing of cylindrical converters. The first of these stations has been assembled and fully checked out with the use of a planar thermionic converter test unit. The assembly of the second and third stations is in progress. All required procurement orders for parts have been placed.

Converter Testing

The first cylindrical converter is presently being installed in the completed test station. The converter is a 200 w(e) diode obtained from the Marine Engineering Laboratory. Parametric tests will be performed initially, to verify the converter performance. The converter will then be utilized to perform tasks on the previously reported thermal runaway phenomenon. Under this condition, a small increase in thermal input power can result in an unacceptably large increase in emitter temperature as a result of a significant decrease in electron cooling due to cesium desorption. An analysis of similar tests performed with planar converters indicates that the probability of this phenomenon occurring increases with increased efficiency of the thermionic converter.

After completion of the cesium desorption tests, the converter will be operated under open circuit conditions at extremely high emitter temperatures. An investigation of this mode of operation will provide data on the mechanical behavior of the converter. The resulting information can then be utilized in the design of the redundancy schemes for thermionic power systems.

PUBLICATIONS

None

SMALL CYLINDRICAL DIODE DEVELOPMENT

NASA Work Unit 120-27-06-11

JPL 320-71101-2-3420

P. Rouklove

OBJECTIVE

The objective of this program is the development of a thermionic diode which, when used in series-parallel arrays, can provide adequate reliability for spacecraft power systems on the order of a few hundred watts total capability. The small (approximately 15-watt) diode concept obtains the required reliability by means of the redundancy provided by an array of diodes.

PROGRESS

Diode Development Contract

As described in the previous report, an 18-month contractual effort has been negotiated with Electro-Optical Systems, Inc. (JPL Contract 952255) for the development of small, cylindrical thermionic converters. The goal of this effort is to demonstrate the feasibility of producing converters of cylindrical configuration capable of operating with a heat pipe as the heat-transmitting medium.

The first converter designated SC-1 has been assembled and tested. At emitter temperatures above 1400° the converter indicated an intermittent emitter-collector short circuit. The tentative reason for this deficiency is presumed to be an "oil canning" of the thin emitter supporting membranes. Presently, the converter is undergoing metallographic and metallurgical examinations to determine the mode of failure. The construction of a second converter SC-2, which incorporates features intended to prevent the excessive distortion of the emitter support structure, is presently underway. The converter, after a preliminary evaluation at the manufacturer's facilities, will be tested at JPL.

System Studies for Isotope Thermionic Generators

Studies to determine optimum diode size and configuration for isotope thermionic systems are continuing. These include the performance evaluation of the individual converter at various emitter temperatures, evaluation of the methods of interconnecting converters, and the determination of the optimum emitter size as a function of the optimum heat pipe diameter.

PUBLICATIONS

Contractor Reports

Jacobson, D., "Development of Thermionic Converters," EOS-401-Q-1, Electro-Optical Systems, May, 1969, JPL Contract 952255.

NUCLEAR SYSTEM STUDIES

NASA Work Unit 120-27-06-14

JPL 320-71401-0-3830

J. P. Davis, J. F. Mondt, G. Kikin,
B. Kelley, N. Simon

OBJECTIVE

The objectives of this work unit are to develop analytic techniques, supply technical information and conduct key experiments needed to design and evaluate nuclear electric propulsion spacecraft.

PROGRESS

Spacecraft Designs

The component arrangement drawing for a 300 kW electric propulsion spacecraft including the thruster system was completed. This information was transmitted to the contractor (General Electric) for use in the Thermionic Powerplant Study. The preliminary structural design for the 300 kW spacecraft is being accomplished by GE. The 50 to 100 kW electric propulsion spacecraft design will be investigated in more detail during the next six months.

Design Investigations

Heating 2 - A generalized three-dimensional heat transfer program for solving steady-state and transient problems was adapted for the UNIVAC 1108 at JPL. Operation of Heating 2 on the UNIVAC 1108 has increased the maximum number of usable nodes from 400 to 1500. This upgrading permits temperature and heat flux maps to be generated for very complicated geometries.

Heating 2 was used to calculate temperature distributions of the TECO diodes being tested in the dynamics loop. Good correlation was obtained between temperatures predicted by Heating 2 and temperatures measured on TECO diodes during open-circuit operations.

The complex geometry of the upper structure of the externally fueled diode being designed for JPL by Fairchild-Hiller was analyzed and thermal mapping revealed several areas which required design change. This is the first case where this program has been used to provide direct inputs to the design prior to fabrication.

Heating 2 was used to determine the error in computing the heat loss through an emitter lead when radiation loss and ohmic heating are not included. The error in the heat loss was found to be 10%.

Space Radiator - The space radiator code, M091, was used to compare radiator weights with different coolants and with different armor and fin materials. Results were reported in an SPS report.

Thermionic Converter Code - A one-dimensional converter heat transfer code combined with tabulated SIMCON data was used to calculate several cases for the externally-fueled, 8-inch-long converter. The code calculates detailed temperature distributions, thermal heat fluxes, power density and converter efficiencies for any given input axial power profile.

Vibration Testing

A General-Electric (flashlight) emitter-collector assembly was tested in a simulated launch vibration environment. The test set up is shown in Figure 1. The vibration amplitude and frequency was estimated from a 300 kWe electric-propulsion spacecraft conceptual design on the Titan III launch vehicle. The specified vibration input was sinusoidal with an acceleration of 5-g peak and a frequency of 5 to 3000 Hz. The results showed an emitter-collector natural frequency at about 600 Hz with an amplification factor of about 20 at the 600 Hz frequency. So with a 1-g peak input to the assembly the emitter end cap had a 20-g peak response.

The low-frequency environment (5 to 100 Hz) resulted in severe feedback response at the emitter and collector of 50 to 100-g peaks with only 2-g peak input. The 5-g peak inputs were not run at the low frequencies because of this severe response at the emitter and collector.

Post test visual examination shows the assembly in good condition. The intercell structure was intact, and the insulators were not cracked. There is a crack in the emitter end cap weld and very fine UO_2 powder in very small amounts was in the cold gap between fuel and emitter. The fuel pellets

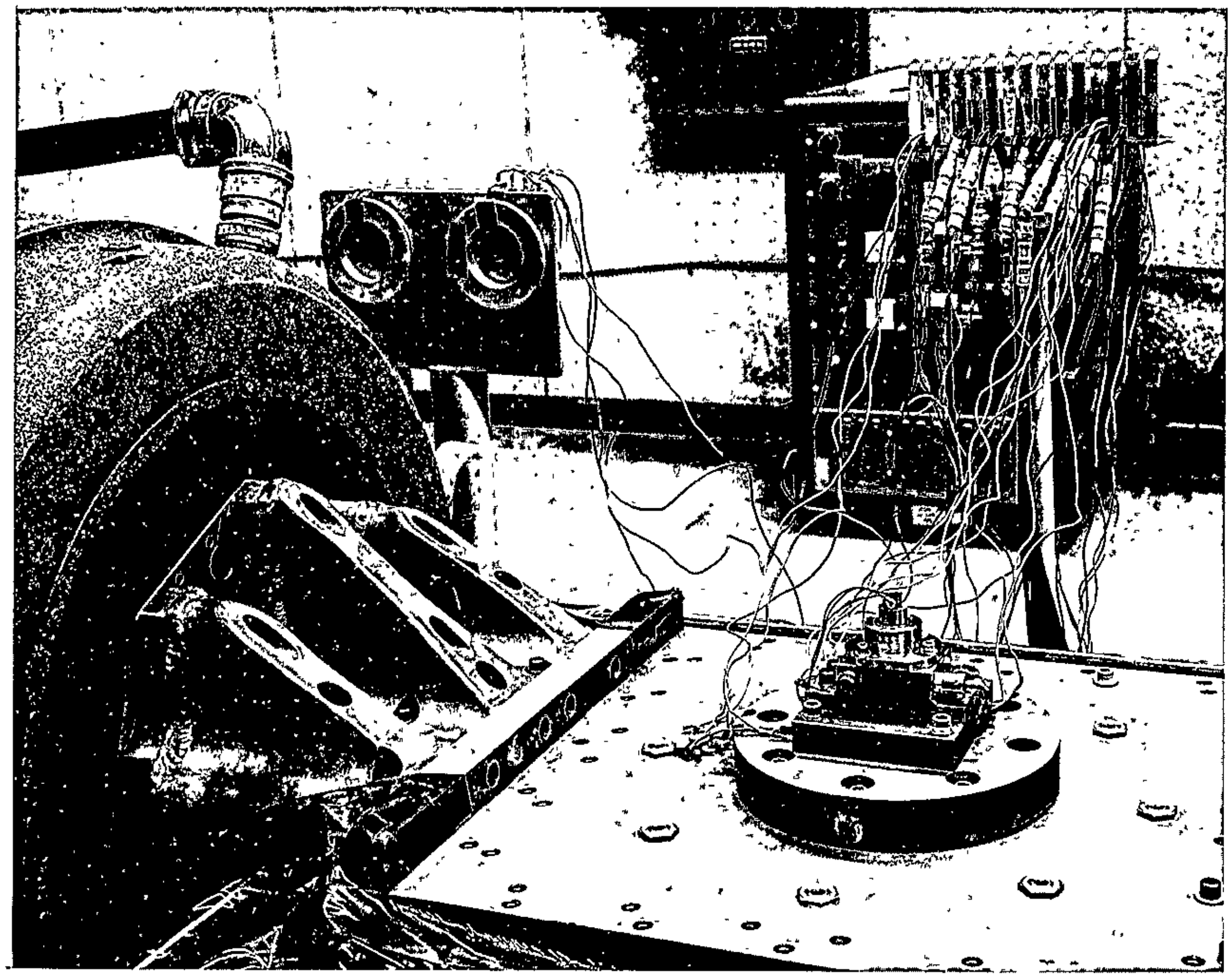

Figure 1. Emitter-Collector Vibration Test Setup

did not chip. However the fuel pellets will require restraint in the axial and radial direction for the 5-g, 5 to 100 Hz vibration environment.

Heat-Pipe Radiator Test

A 50-kW heat-pipe radiator developed and built by RCA under Air Force contract was received at JPL for test and evaluation. A picture of the radiator is shown in Figure 2. It consists of 100 heat pipes, sodium filled, 3/4 inch diameter, 316 stainless steel tubing with 0.010 inch wall thickness and a single wrap stainless steel wire mesh wick. The radiator is approximately 2 feet wide by 3-1/2 feet long, 2 inches thick and weighs 12 pounds.

Design detail drawings for the Heat Pipe Radiator (NaK) Test Loop are about 75% complete. The loop consists, basically, of an I^2R Heater, Hot Trap, Vacuum Chamber with Heat Pipe Radiator, NaK dump tanks, EM Pump, EM Flowmeter and Venturi Flowmeter. Calculations are complete for piping pressure drop, heat loss, hot trap dump tank and vacuum tank. All piping and components in contact with NaK are 316 stainless steel. Instrumentation will consist of NaK flowrate pressure and temperature measurements. Thermocouples on the surface of the heat pipe will be used to calibrate the I. R. photographic thermal maps taken during operation.

PUBLICATIONS

JPL Publications

1. Simon, N. K., "Radiator Design for a 300 kWe Thermionic Space Powerplant, SPS 37-56, Vol. III, April 30, 1969.
2. Kikin, G. M., "Effects of Thermal Radiation and Ohmic Heating on Heat Loss From Optimized Thermionic Diode Lead," SPS 37-56, Vol. III, April 30, 1969.

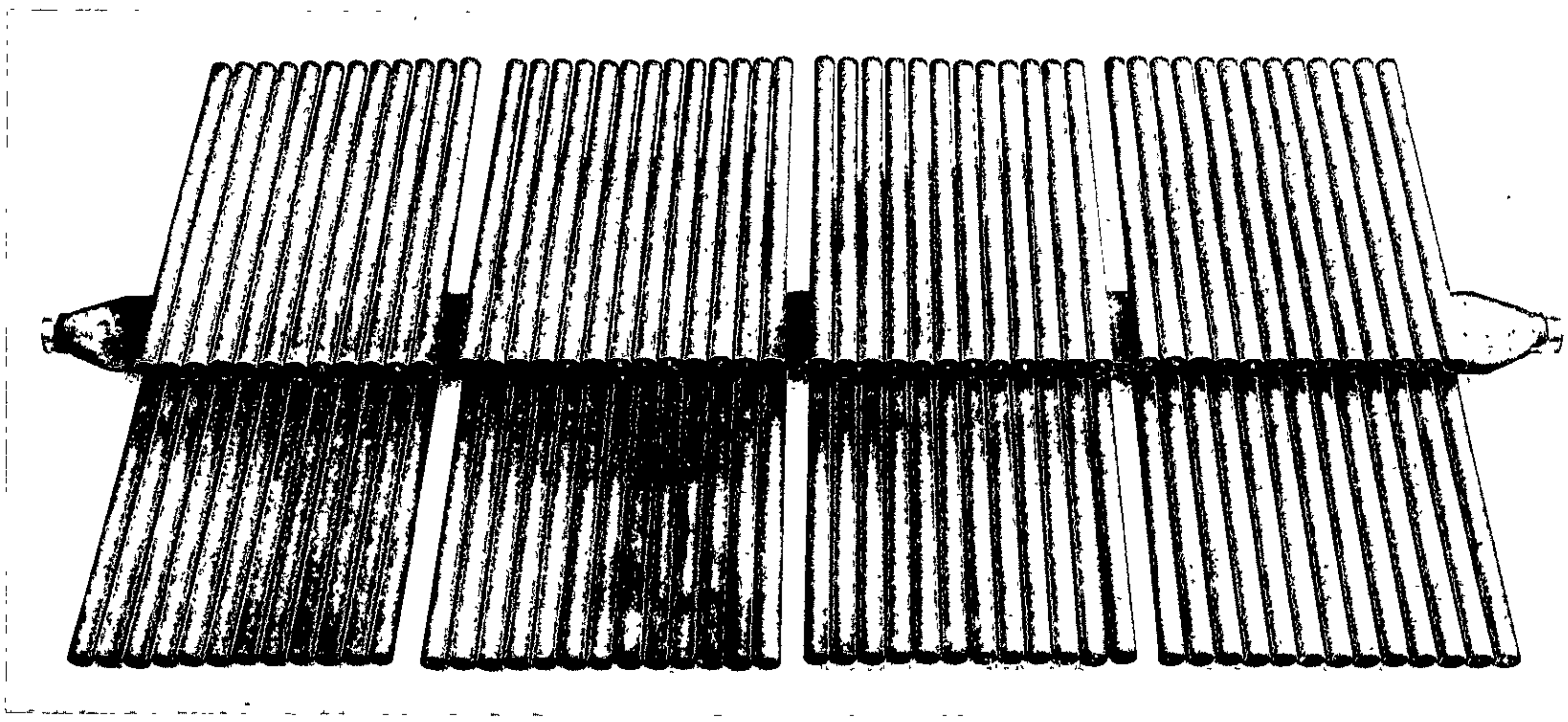

Figure 2. 50 kW Heat Pipe Radiator

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INSULATOR BREAKDOWN TEST

NASA Work Unit 120-27-06-20

JPL 320-72001-0-3830

J. P. Davis
G. M. Kikin

OBJECTIVE

The objective of this work unit is to consider the phenomena of sheath insulator arcing results from the series connections of nuclear thermionic converters. In the flashlight concept of in-core converter assemblies, the arcing problem is due to a voltage across a thin, cylindrical, ceramic insulator which separates the collector from the liquid-metal-cooled outer metallic sheath. This insulator is exposed to cesium vapor, and any small cracks in the ceramic may have electrical breakdown potentials which are less than the maximum potential developed from the series-connected (flashlight) thermionic converters.

Arcing across the crack may cause substantial degradation and puncture of the tri-layer structure allowing liquid-metal coolant to leak into the cesium vapor space. Failure of the punctured diode, plus loss of liquid-metal coolant, may cause further diode failures resulting in partial or complete failure of the nuclear-thermionic powerplant.

Under this one-year contract, which started in this period, the contractor (General Electric Nuclear Thermionic Power Operations at Vallecitos, California) will analytically and experimentally investigate arcing in the liquid-metal cooled tri-layer and the possible subsequent effects on the nuclear thermionic powerplant.

The analytic portion consists of two parts:

(1) an effort associated with defining the type and geometry of cracks in sheath insulators and,

(2) an effort associated with arc characteristics in cracked sheath insulators.

The experimental portion of the contract includes the design and fabrication of an apparatus to test representative cylindrical tri-layer structures having cesium in contact with the insulator and cooled with liquid metal (NaK). A total of eight tri-layer specimens will be fabricated (four of niobium-alumina and four of Kovar-alumina), and four will receive the full experimental test where the tri-layer is liquid metal cooled at 750°C and is exposed to cesium vapor at pressures from $\sim 10^{-2}$ to 5 torr.

Post test examination and analysis of the specimens will be performed with the intent of macroscopically describing the resulting effects and estimating whether these results would be representative of other tri-layer configurations.

PROGRESS

The analysis portion of this study is under way; the long-lead items required for the experimental work, niobium and alumina tubing, have been ordered and a test capsule design has been completed. Various techniques for cracking the cylindrical insulators are presently being used to determine the best method for producing sheath insulator cracks for the test program.

Although most phases of work will be performed at the contractor (General Electric) facility at Vallecitos Nuclear Center, the actual tri-layer-fabrication and electrical breakdown tests will be performed at a General Electric facility in Cincinnati, Ohio.

The starting date for the contract (JPL Contract 952405, in the amount of $97, 553) was March 17, 1969.

PUBLICATIONS

None

EXTERNALLY FUELED DIODE TEST
NASA Work Unit 120-27-06-21
JPL 320-72101-0-3830

J. P. Davis
J. F. Mondt

OBJECTIVE

The objective is to design, fabricate and test a prototype diode of the JPL-conceived externally fueled concept. This concept has no tri-layer in the core, and has liquid metal flow-through cooling, revolver-type fuel elements, and core-length diodes 8 inches long. The work is being performed under contract to Fairchild-Hiller.

PROGRESS

The detailed design of the converter is complete. The materials and components for the converter are on order or are being fabricated. The component quantities are sufficient to make four converters.

The nuclear analyses and mockup experiments were completed by Battelle Memorial Institute, Columbus, Ohio, who did the work under subcontract within estimated cost and on schedule. Therefore, the fuel enrichment is determined, and enriched UO_2 fuel is on order.

Should an in-pile test be warranted from out-of-pile test results, the present design includes 6 emitter thermocouples, snorkel fission gas vents, fission gas monitoring during operation, integral electrical loads, graded Al_2O_3 - niobium seals and complete testing of the fueled diode before in-pile testing.

PUBLICATIONS

None

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THERMIONIC SPACE POWERPLANT SYSTEM STUDY

NASA Work Unit 120-27-06-23

JPL 320-72301-0-3830

J. P. Davis
N. K. Simon

OBJECTIVE

The objective of this study is to design a 300 kwe nuclear electric spacecraft for unmanned missions in sufficient detail to predict a reliastic weight, configuration, and performance of such a vehicle. A secondary objective is to extrapolate the data to obtain estimates of spacecraft performance over the range of 70 kWe to 500 kWe. This work is being performed under contract to General Electric Company, Valley Forge.

PROGRESS

The contract (JPL Contract 952381, in the amount of $120,457) for this study has now been in effect four months. The first Quarterly Report has been published. The analyses of the nuclear radiation dose to the payload and shielding requirements, as a result of activated coolant in a one-loop system, was completed. The gamma dose from activated coolant in the primary loop was sufficiently high to justify the additional liquid metal loop with pump and heat exchanger. Configuration studies to determine spacecraft structural requirements are now in progress.

A reference mission was specified by JPL in the contract to aid in designing mission-related spacecraft functions. A similar reference mission, an orbiter of Jupiter, was recently described in the referenced SPS.

PUBLICATIONS

JPL Publications

1. Simon, N. K., "Reference Mission Specification for 300 kWe Thermionic Spacecraft Design Study," SPS 37-57, Vol. III, June 30, 1969, pp.

Contractor Reports

1. "A Design Study for a Thermionic Reactor Power System for a Nuclear Electric Propelled Unmanned Spacecraft," GESP-7011, General Electric Missile and Space Division, Philadelphia, Pennsylvania, May 1969, JPL Contract No. 952381.

NUCLEAR POWER SYSTEM DESIGN FOR PLANETARY MISSIONS

NASA Work Unit 120-27-06-24

JPL 320-72601-2-3420

R. G. Ivanoff

OBJECTIVE

This program provides the over-all power subsystem configuration and integration analysis required to assure the development and compatibility of a power subsystem to the spacecraft design for the Thermoelectric Outer-Planet Spacecraft (TOPS) project. Specifically, the effort involved is directed toward solutions of problems associated with the definition of the interfaces between the elements of the power subsystem and between the power subsystem and the other spacecraft subsystems. In addition, this task includes the development of high-efficiency, ultra-reliable power conditioning electronics (PCE) to convert the voltage from the power source to voltages and regulation levels compatible with spacecraft electrical subsystems. This equipment will be designed to meet a 12-year life requirement for the power subsystem using the most advanced techniques to assure minimum weight.

PROGRESS

Accomplishments during this report period include the support of spacecraft design activity, continued activity to obtain support from the Atomic Energy Commission for development of RTGs for the TOPS project, negotiations with NASA/Electronic Research Center for their support on the power subsystem, and the negotiation of a contract for the design and development of power conditioning electronics. Design team support has continued to supply tradeoff analysis on the power subsystem and its effect on and interaction with the TOPS spacecraft design and the various subsystem interfaces. A preliminary functional requirements document has been written outlining a description of the power subsystem.

Negotiations with the AEC have continued for the development of RTGs for long-life operation. In response to these requests, the AEC has issued and received responses to a request for proposals (RFP) for a "Multi-Hundred

Watt Long Lived RTG System Development Program." The objective of this program is to develop an RTG design concept which embodies high efficiency, light weight, long life, and high power output capabilities. The single design will have the capability of supporting a number of future mission requirements with minor modifications. The responses to the RFP have been evaluated by the AEC. A contract negotiation is expected in the early part of FY70.

The negotiations for a two-phase program for the design, development, and fabrication of power conditioning electronics have been completed during this report period. A basic letter contract (JPL Contract 952536) has been let to the General Electric Company, Valley Forge, Pennsylvania, in the amount of $200,000, and the design effort has started. A detailed analysis to determine the method of power distribution, with either ac or dc voltage as the primary distribution voltage, is nearing completion. Once this selection is made the more detailed design of the PCE can be started. The PCE design has been blocked out for both methods of power distribution.

The design and fabrication of a dc-dc converter for a 100-watt communications TWT transmitter has been completed during this reporting period. The breadboard unit is now undergoing testing. Initial test results are satisfactory but indicate some modifications of parts of the design are required to correct for some circuit instability.

During the reporting period, the NASA/ERC has been requested and has agreed to provide support for the development of advanced technologies in the area of PCE design for the TOPS project. The Power Systems Laboratory of ERC has agreed to provide support by reviewing the PCE contractor efforts in design and development of PCE hardware, to review and comment on technology advances in the PCE area, and to develop certain functional elements of a PCE design which ERC feels it is uniquely qualified to design. The aid given by ERC provides a broader coverage of technical skills and will insure that a more complete analysis of the PCE design can be achieved. ERC personnel have met with the PCE contractor and have agreed to develop a design of a dc-dc converter for a TWT transmitter operating at X band and having a power requirement of 70 watts.

Planned activity in the next reporting period includes continued negotiation with the AEC on their Multi-Hundred Watt contract, completion of the phase one detail electrical design of the PCE, and system design and integration analysis. Design team support will continue with emphasis on interface problems. The dc-dc converter testing and evaluation will be completed during this next period.

PUBLICATIONS

SPS Contributions

1. SPS 37-55, Vol. III, "Nuclear Power Subsystem Design for Planetary Missions," R. G. Ivanoff, February 28, 1969, pp. 93-96.
2. SPS 37-57, Vol. III, "TWT Power Conditioning for Planetary Missions," D. J. Hopper.

JPL Specifications

1. TOPS-4-2004, "Functional Requirement, Thermoelectric Outer Planet Spacecraft, Advanced System Technology, Power Subsystem," June 10, 1969.

RADIOISOTOPE THERMOELECTRIC GENERATOR DESIGN FOR PLANETARY MISSIONS

NASA Work Unit 120-27-06-25

JPL 320-72701-2-3420

O. S. Merrill

OBJECTIVE

The objectives of this effort are: (1) to develop an RTG to be used on the Thermoelectric Outer Planet Spacecraft (TOPS) Project, and (2) to investigate and attempt to solve the problems associated with integrating an RTG Power Source into the TOPS.

APPROACH

The tasks which have been undertaken during this reporting period can be categorized into two areas -- JPL/Internal and JPL/AEC. Those falling in the first category are tasks which have been defined and are being investigated as part of the TOPS Project. Those falling in the second category are those which will be performed by the Atomic Energy Commission, but in very close cooperating with JPL and with full cognizance of the TOPS Project requirements and subsequent outer-planet mission requirements.

JPL/Internal

The principal effort has been one of defining and solving interface problems between the RTG power source and other subsystems of the TOPS. This has been primarily a design study with various iterations and with trade-off considerations for each major iteration.

JPL/AEC

The principal effort in this category has been one of establishing liaison with the AEC and their technical arm, Sandia Laboratories at Albuquerque, N. M. The AEC, with technical direction by Sandia, will develop a multi-hundred watt RTG for TOPS and other user applications.

PROGRESS

JPL/Internal

A number of problems have been identified and investigated. Principal among these are 1) the methods of locating and mounting multiple RTGs on the spacecraft so as to give minimum radiation to the science instruments, 2) minimizing thermal interfaces between the RTG and thermally-sensitive subsystems, and between the mid-course rocket plume and the RTGs, 3) determination of neutron and gamma spectra, dose rates, and total integrated dosages as a function of time and position on the spacecraft, 4) determination of shield weights and location for most effective and efficient shielding of sensitive science instruments from gamma rays.

Also, the most pertinent performance parameters have been defined: power level, mission life, output voltage, specific performance, size, weight, excess heat rejection mode, allowable magnetic field, instrumentation, radioisotope fuel, environment, and preliminary safety considerations.

JPL/AEC

The AEC has issued an RFP and received proposals from five prospective contractors for the Phase I Study of the Multi-Hundred Watt Long-Lived Radioisotope Thermoelectric Generator Development Program. Placement of a contract is anticipated in FY69. Liaison and an acceptable working relationship has been established between the AEC, Sandia, and JPL; the working relationship between JPL and the contractor(s) is yet to be fully defined.

PUBLICATIONS

None

LIQUID-METAL MHD SYSTEM UTILIZATION STUDY

NASA Work Unit 120-27-06-26

JPL 320-72801-0-3830

D. G. Elliott

OBJECTIVE

The objective is to provide size, weight and mission performance estimates for liquid-metal MHD power systems employing a cesium-lithium impinging nozzle cycle for a range of power levels, temperatures, numbers of loops, component efficiencies, containment material strengths, and launch conditions.

PROGRESS

The contract (JPL Contract 952415) was awarded to the General Electric Company, Valley Forge, Pennsylvania, in the amount of $94, 032.

A conference was held with the contractor to review the technological basis for the MHD system to be studied, as well as to review the emphasis to be placed on the various aspects of the study. Initial studies will determine the design constraints for a chosen reference system. The reference design will then be parametrically studied to determine an optimum design.

PUBLICATIONS

None

SOLAR POWER GENERATION SYSTEM (120-33)

20 WATT/LB SOLAR ARRAY DEVELOPMENT

NASA Work Unit 120-33-01-02

JPL 320-30801-2-3420

W. Hasbach

OBJECTIVE

The objective of this effort is to develop the technology for the design and fabrication of a high-power, 1,250-ft^2 solar panel exhibiting a power density of 20 W/lb minimum.

PROGRESS

In FY 66, feasibility studies were completed in the application of large area, high-power photovoltaic arrays to electric propulsion type missions. The results of the studies were encouraging and lead to the expansion of the investigation to include detail design, fabrication, and testing of a prototype section of a 1,250-ft^2, 50-kW solar array. As described in the previous report, the Phase I and Phase II efforts, which included assembly and test of the mechanisms, installation and test of a simulated zero-g deployment fixture for ground testing and manufacture and test of a 100-ft^2 beryllium sub-panel assembly, have been completed under JPL Contracts 951653 and 951934 with the Boeing Company.

A follow-on program to evaluate further systems aspects of test and analysis of a full-size array was contemplated. It was determined that information generated by this follow-on activity would be very mission-dependent and that any such effort should be delayed until a more specific mission requirement needing this technology was defined. It should be anticipated that making the technology ready for any specific mission could require substantial deviation from this baseline design and adequate time should be planned for this occurrence. To date, no missions have been formally defined to employ this technology.

PLANS

Analysis of the design data and test results will be continued for application to future solar panel structural and power requirements.

PUBLICATIONS

Internal JPL Document

1. "The Hinge Controlled In-Plane Motion of a Two-Segmented Spacecraft Body," Herman P. Valentijn, JPL Document 900-245, February 7, 1969.

SOLAR CELL STANDARDIZATION

NASA Work Unit 120-33-01-03

JPL 320-31201-2-3420

R. F. Greenwood

OBJECTIVE

The principal objective of the solar cell standardization program is to provide applicable standards for (1) procurement and evaluation of solar cells, and (2) predicting the space performance of solar arrays. Standard solar cells are also provided for use in calibrating solar simulators.

PROGRESS

JPL Technical Report 32-1426 presenting detailed results of the 1968 balloon flight solar cell calibration program has been completed and is currently in the publication stage.

During the fourth quarter of FY 69, Contract 952496 with Litton Applied Science Division was executed. The contract provides for three 120,000-foot-altitude balloon flights to be conducted during the first quarter of FY 70. The CPFF contract, including fee, was negotiated for a total of $45,148 which includes all material costs, manpower, and other services. The contract further provides that the balloon flights shall be conducted in the vicinity of Minneapolis, Minnesota.

Agencies participating in the solar cell standardization cooperative effort and exchange of information program on the scheduled flights include the Johns Hopkins University Applied Physics Laboratory, the Air Force Aero Propulsion Laboratory, the NASA Goddard Space Flight Center, the NASA Langley Research Center, the NASA Ames Research Center, the Massachusetts Institute of Technology Lincoln Laboratory, and the Jet Propulsion Laboratory.

PLANNED ACTIVITIES

The first of the three high-altitude balloon flights is scheduled to take place during the week of July 28, 1969. Subsequent flights will follow in one to two week intervals depending upon weather conditions and flight preparations. Due to unpredictable weather conditions which caused a significant undesirable altitude loss on one flight last year, a ballast drop system will be incorporated into each balloon system this year. By using this system four independent ballast drops can be initiated by radio ground command. On a trial basis on one flight last year, the ballast system provided effective altitude control.

Several types of solar cells from the participating agencies have been received at JPL. These cells represent state-of-the-art production cells as well as recent developmental cells. Plans provide for a pre-flight and a post-flight calibration check of each standard cell using the JPL X-25L solar simulator.

Plans to fly an improved and simplified version of the JPL Active Cavity Radiometer have been formulated. It is anticipated that the improved radiometer, coupled with a higher measuring altitude, the experimental uncertainty will be reduced from the previous measurements made last year at the 80, 000 foot level.

Data will be reduced by computer at the completion of the flights and are expected to be distributed along with the standard solar cells to the participating agencies within two weeks. A technical report discussing the results of the solar cell standardization program is planned for publication during the third quarter of FY 70.

PUBLICATIONS

None

PHOTOVOLTAIC SUPPORTING DEVELOPMENT

NASA Work Unit 120-33-01-06

JPL 320-31601-2-3420

R. K. Yasui

OBJECTIVE

The objective of this program is to develop the technology necessary to aid the solar panel engineer in the design of solar arrays for deep space missions. Efforts will be made to investigate available photovoltaic cells under simulated space environments that exist from 0.3 to 5.0 AU to determine if further cell development is required to satisfy these objectives. This effort is accomplished by testing and analyzing individual cells or cell matrices under conditions which simulate the actual temperatures, solar intensities and space environment to which the panel will be exposed. Experience over the past years has shown this technique to be a valid method for predicting the performance of a solar panel within Sun-probe distances equivalent to Mars/ Venus missions. This effort also includes the electrical-mechanical evaluation of solar cells of advanced designs presently under development.

PROGRESS

Present solar cell assemblies used on spacecraft demonstrate a specific power output capability of approximately 10 W/ft^2 at one AU and have been used on spacecraft missions to Venus and Mars. Anticipated future spacecraft missions to Mercury and Jupiter will require solar panels to operate over wider ranges of solar intensities and operating temperatures. To prepare to meet these future mission objectives, parametric test and analysis of solar cell performance is required. Electrical parametric cell test programs have been continued during the reporting period to investigate the performance characteristics of silicon cells having base resistivities from 2 to 10 Ω-cm. The thin-film cadmium-sulphide cells have also been studied. Test reports are being prepared on cells which have been measured, describing their performance characteristics as a function of temperature and solar intensity.

Work has continued in the design and construction of a Martian environmental test chamber shown conceptually in Figure 1, as well as in the incorporation of a Dymec computerized solar cell test data acquisition system. It is anticipated that the above systems will markedly improve our testing capability, and increase the over-all output efficiency of the laboratory. The Martian test chamber is required to study the effects of atmospheric contamination on the performance of solar arrays on a Mars-like planet surface. Present schedule indicates that these investigations will commence during the second quarter of FY 70.

The JPL solar cell computer program to predict cell performance as a function of intensity and temperature is being modified to include treatment of cell temperature coefficients, varying parameters such as temperature coefficients, series resistance, cell efficiency, and standard deviation. Very good correlation to empirical solar cell performance characteristics has been achieved over a cell temperature range of -40°C to +60°C, and a solar intensity range of 5 mW/cm^2 to 250 mW/cm^2. Work has also progressed in the measurement of solar cell characteristics of much wider temperatures (-140°C to +140°C) and intensity ranges utilizing the X25L solar simulator and multi-cell thermal-vacuum test facility. Further refinement of the test facilities will be made with particular emphasis on control of operational test parameters, as well as in testing procedures. To achieve equivalent solar intensities greater than 250 mW/cm^2 (0.7 AU) a second generation solar simulator with interchangeable optical accessories is being purchased from Spectrolab. The solar simulator is expected to be in operation during the first quarter of FY 70 and will increase the testing capability to 1,000 mW/cm^2.

During the fourth quarter of FY 69 a contract for $55, 942 was awarded to Electro-Optical Systems Inc., under JPL Contract No. 952485 for the development of a one-step process of electroforming aluminum contacts and interconnections to form silicon solar cell matrices. The development of this process would represent a substantial advance in solar cell manufacturing technology. The achievements of such a process will provide a reduction of solar panel weight, permit exposure of cells to higher temperatures, since no soldering would be employed, and reduce solar panel costs.

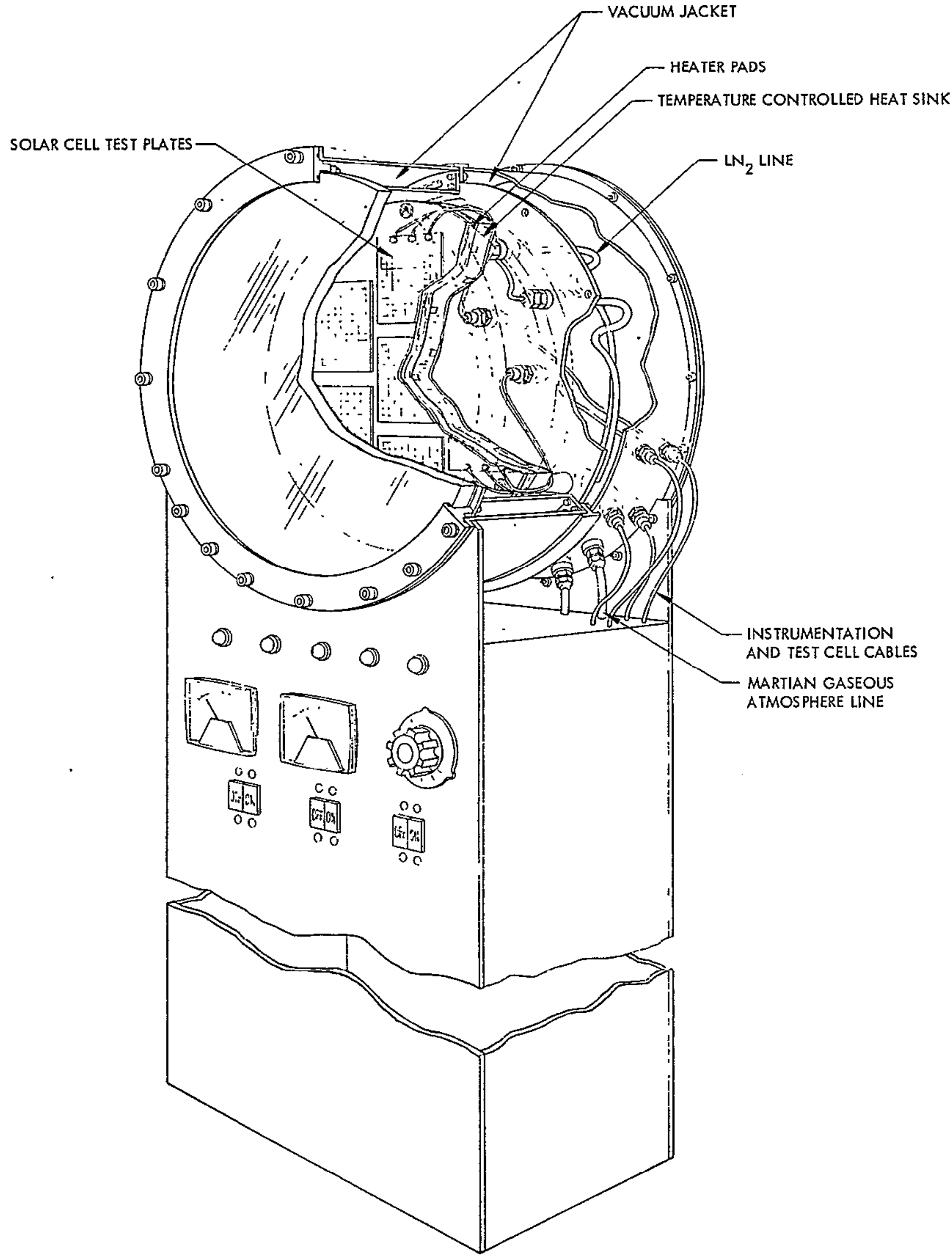

Figure 1. Martian Environmental Test Chamber

PLANS

Future plans are to continue improving the measurement of cell parameters in simulated space environments. Further, it is anticipated that some previously tested solar cells will be measured in larger quantities so that increased confidence in prediction of cell characteristics can be obtained.

PUBLICATIONS

None

ADVANCED ROLL-UP SOLAR ARRAY CONCEPTS
NASA Work Unit 120-33-01-07
JPL 320-31701-2-3420
W. A. Hasbach

OBJECTIVE

The objective of this program is to extend roll-up solar array technology into a multikilowatt system. Phase I established the feasibility of developing a 10-kW solar array system which would have a specific power capability of 30-W/lb and could be deployed after launch through a roll-out technique similar to that used in a window shade.

The objective of the present effort is to design, fabricate, and environmentally test the array.

PROGRESS

General Electric Co., Contract 952314, $811,400.00

This contract will deal with the design analysis, fabrication and test of a large-area flexible array having a deployed area of 250 ft^2. The array will be fabricated comparable to flight-type hardware and subjected to an environmental test program which is designed to determine the ability of the array to survive the most rigorous launch environment which is expected. Upon completion of the test program the results will be analyzed and compared with the predicted values.

This is a new contract which has been in effect for three months. During this period of time a detailed design and analysis has been in progress. Manufacture planning has begun and fabrication is about to begin.

PLANS

During the next reporting period array fabrication will be completed, and ground support equipment will be designed and built in preparation for the test program.

PUBLICATIONS

None

PLANETARY SOLAR ARRAY DEVELOPMENT

NASA Work Unit 120-33-01-08

JPL 320-32101-2-3420

L. W. Schmidt

OBJECTIVE

The objectives of this program are: (1) to perform a detailed analysis of the effects of the Martian environment on a solar panel (a computer program will be designed to compile data on the effects of the environment on panel output), (2) to produce a preliminary structural design of a solar panel for hard-impact landing on the Martian surface, and (3) to institute and conduct a test program to obtain survival information under conditions that would be encountered during a hard landing.

PROGRESS

Contract 952035 with Electro-Optical Systems, Inc., for $158,600.00 has been completed. The accomplishments are given in the following three sections.

Environmental Analysis and Computer Program

The computer program which has been developed is generally adaptable to finding power output for a wide variety of solar-panel configurations, during any period of time in which the daily temperature cycle used is valid. The user is allowed to position a flat panel at any latitude on the surface of Mars, and tilt it at any angle. He is further able to specify a number of atmospheric and radiation-attenuation functions, and the computer will integrate all effects and produce a large quantity of data with respect to the panel operation, including instantaneous and accumulated power.

The geometric values, such as the azimuth and elevation of the Sun with respect to the panel and local geographic frame, are printed. Additionally, the user may, by appropriately identifying a variable of interest, cause that variable to be output. This, of course, involves a slight program change to the WRITE statement. An example might be to cause the short-circuit current and open-circuit voltage of the reference I-V curve to be printed in place of cloud and dust attenuation values. The present computer program has provision for attenuation models for cloud and dust cover, but these models have not been developed completely, and therefore the computer program considers zero attenuation for these factors.

Design of Martian Hard-Lander Solar Array

The design study has indicated that a 24-square-foot solar array is feasible under a 5,000-g shock. The concept of keeping the unsupported substrate area small to reduce the deflection and stress has been demonstrated. This is a deviation from conventional panels with large uninterrupted surface areas.

With emphasis on designing the substrate and solar cells to survive under the impact, the mechanical and structural complexity is increased. As a result, the weight of the solar array exceeds the design requirement of 60 pounds. A detailed design or prototype study will be necessary to reduce the complexity and weight.

As a result of the tradeoff study of a flat panel vs. a foldout array, it was recommended that the design be based on the latter concept. The choice was made because the stress levels encountered were about 1/4 that of the flat panel system. There is also a desirable redundancy in the foldout concept inasmuch as a failure of one section affects only 1/8 of the panels, whereas if the top flat panel failed it would prevent deployment of all the others.

The selected array consists of 8 panel modules with each module having 21 subpanels (Drawing 7254-2000 in publication listed below). The total surface area for the placing of solar cells is 24.6 ft^2 and the array can be mounted in a 3.5-inch-deep cylinder. This gives an over-all volume of 2,540 $in.^3$.

Solar-Panel-Submodule Impact Testing

A brief, high-impact test program was carried out on solar-panel submodules using the JPL "slingshot" high-impact test facility. The tests conducted have furnished some insight into the failure mechanisms to be expected.

The failure mode under static loading using 770 SALA and RTV 41 bond material is cell/substrate adhesive peel, occurring at an approximate radius of 7 inches on the cell side of the bond. During curvature in the negative direction (i.e., when the cells are being forced closer together), bond failure also occurs, but it is located in the center of a cell. When the negative curvature becomes less than 7 inches in the static tests, cover-glass contact between adjacent cells causes cracking of the cover glass, and eventually of the cells themselves.

The dynamic-failure mode observed (under a loading sufficient to cause the radius of curvature to approach the static case) is cell fracture. Since the cell fractures were observed when the beam had almost certainly passed its structural yield points, predictions of radius are not totally accurate, but are on the order of 10 to 6 inches. It is suspected that the failure mode was caused by cell contact on the negative curvature portion of the beam vibration, and that higher loads and lower curvatures would be possible if the cells were spaced farther apart. Further, the dynamic tests have shown that the particular submodules tested here can withstand an input shock level of at least 4,750 g average, for a period of approximately 0.8 μsec, without damage.

PLANS

Contract 952606 with Electro-Optical Systems Inc. ($30,558.00) has been negotiated. The purpose of this contract is to modify the aforementioned computer program by adding the capability of printing various specified cell characteristics and the capability to accept voltage-current points as input at the discretion of the program user.

The contractor will also perform theoretical analyses, and verify the analyses with experimentation, to determine the effects on panel output when layers of Martian dust of varying thicknesses cover the solar panel. This information will then be used to compile a subroutine to be added to the main computer program.

Finally, the contractor will calculate atmospheric and dust-scattering effect on Mars and integrate these results into the dust-layering subroutine above.

PUBLICATIONS

Contractor Reports

1. Electro-Optical Systems, Inc., Final Report 7254-Final, 28 February 1969.

EFFECTS OF IONIZED PARTICLE RADIATION ON SOLAR CELLS

NASA Work Unit 120-33-01-09

JPL 320-32301-2-3420

B. E. Anspaugh

OBJECTIVE

The objective of this program is to obtain experimental data on the effects of proton irradiation on the electrical characteristics of various types of silicon solar cells. These data will eventually be used in conjunction with theoretical considerations to predict the effect of solar proton flares on the electrical characteristics of the cell types being considered for flight use. Cells to be investigated will be representative of Mariner and Surveyor hardware, as well as advanced technology silicon solar cells of 0.008 and 0.004-inch thickness.

PROGRESS

The JPL Dynamitron has reached a fully operational status for producing up to 3 MeV. Work is in progress to complete a beam transport system, including a bending magnet and beam scanner for acceleration of protons and other positive ions.

An extension of the low-energy proton irradiation of partially exposed solar cells previously reported was undertaken as a piggy-back activity on the ground test radiation portion of an ATS-E Solar Cell Flight Experiment development. Partially exposed cells and rear surfaces of cells were exposed to several radiation levels using a flux-energy spectrum characteristic of that found in synchronous orbit. The results of this activity will be forthcoming in the next reporting period.

The 30 MeV proton accelerator at Michigan State University has been contracted (Ref. JPL P.O. EC-446298, $5,000) for beam time to perform a series of proton irradiations in the near future.

PUBLICATIONS

None

SOLAR CELL CONTACT STUDIES

NASA Work Unit 120-33-01-11
JPL 320-33001-2-3420
R. K. Yasui

OBJECTIVE

The factor which is of prime importance in determining the reliability of environmental limit of a silicon solar cell is the quality of its ohmic contacts. It is the objective of this work unit to study the mechanical and electrical characteristics of contacts made to solar cells. The types of contacts presently under investigation include deposited silver-titanium, plated electroless nickel and sputtered aluminum.

PROGRESS

The conventional contact of present-day silicon solar cells is silver titanium. Several years ago, it was noted that these contacts weakened significantly after exposure to a high-temperature and high-humidity environment. This problem has been solved by the addition of a protective coating of solder on top of the silver-titanium, increasing cell weight and cost.

During the reporting period, another possible solution to the high-temperature, high-humidity weakening of silver-titanium solderless solar cells was investigated. It was proposed by representatives of Telefunken, at last years' Photovoltaic Specialist Conference, that the addition of a palladium barrier film between the silver and titanium would significantly reduce the degradation. JPL procured 100 samples of this configuration cell from each of the two major solar cell manufacturers in the United States. These cells were introduced into the on-going environmental test program which includes high humidity, high temperature (95%, 80°C); high-temperature soak (150°C, air); low-temperature soak (-196°C, liquid nitrogen); and mechanical pull strength test at temperature (-170 to +200°C). The results of the tests to date indicate that the addition of palladium does reduce high-humidity, high-temperature weakening of the solar cell for up to 20 days exposure. The test also shows essentially no degradation of the silver-titanium solar cells after 1000 hours of high-temperature soak, but significant degradation of the plated electroless nickel cells. The low-temperature soak of solar cells in liquid nitrogen did not reveal any degradation of solderless solar cells whereas cells with solder-coated contacts showed 2% power degradation after 700 hours. It is not known, however, if this loss is due only to the low-temperature soak, but also to stress induced into the contacts during removal of the cell from the liquid nitrogen bath every one hundred hours for electrical measurement.

Future plans are to continue the environmental test program and promote the introduction of palladium barrier cells if further tests continue to prove them superior to conventional silver-titanium cells.

PUBLICATIONS

JPL Publications

1. Moss, R., and Berman, P. "Effects of Environmental Exposures on Silicon Solar Cells," JPL Technical Report 32-1362, Jan. 15, 1969.

IMPROVED SOLAR CELL CONTACT DEVELOPMENT

NASA Work Unit 120-33-01-12

JPL 320-33101-2-3420

R. K. Yasui

OBJECTIVE

Solar panels for space applications are environmentally limited in many cases as a result of solar cell contact restrictions, and it can be expected that significant improvements in solar panel reliability will result from improvements in solar cell contacts and interconnection techniques. The objective of this program is the development of silicon cell electrical contacts and interconnection techniques which are less susceptible to mechanical and electrical degradation resulting from exposure to extremes of earth and space-type environments.

A major objective is the development of cell electrical contacts and interconnection techniques that do not require the use of solder. Contact strength and electrical characteristics are to be optimized with regard to minimization of degradation after exposure to thermal shock, humidity-temperature, vacuum-temperature, high-temperature, and low-temperature environments. The solar cell contact and interconnection techniques are also to be optimized with respect to the following: (1) effects on solar cell current-voltage characteristics, (2) series and/or contact resistance, (3) stresses due to fabrication procedure, (4) compatibility with requirements for fabrication into submodules, (5) reliability, (6) handling and manufacturing characteristics and restraints, (7) repair or rework capability, (8) reproducibility, (9) production cost, (10) case of production, (11) weight, (12) compatibility with large-area cells, (13) requirements for special equipment and tooling, and (14) compatibility with inorganic, integral protective coatings.

PROGRESS

Contracts awarded during FY 69 to Ion Physics Corporation under JPL Contract No. 952144 and to General Precision Systems, Incorporated, Librascope Group (JPL Contract No. 952145) have been completed.

The Contract awarded to General Precisions Systems Inc., Librascope Group, was cancelled for convenience to the Laboratory.

Ion Physics Corporation has completed their contract with JPL and a final report has been received.

Ultrasonic bonding was used successfully to bond aluminum ribbons to the aluminum contacts. It can be concluded from the electrical test and contact strength test and tape peel test that ultrasonic bonding could be a satisfactory method of solderless contacting to aluminum contact solar cells. Maintaining a good cell cleaning process prior to contacting was a severe problem with the sputtered contacted cells. Glow discharge cleaning prior to sputtering would be expected to eliminate and/or minimize this problem. Upon completion of the above contract no further progress has been made in regard to this particular work unit. However, related work involving electroformed aluminum contacts and interconnections are being investigated under NASA Work Unit 120-33-01-06.

PUBLICATIONS

Contractor Reports

1. Ion Physics Corp., Final Report, "Improved Solar Cell Contacting," JPL Contract No. 952144, Feb. 1969.

LARGE AREA SOLAR ARRAY INTEGRATION

NASA Work Unit 120-33-01-13

JPL 320-32901-2-3420

R. E. Oliver

OBJECTIVE

The objective of this work unit is to conduct a parametric study to establish relationships between performance and geometric characteristics of a large-area General Electric single-boom roll-up solar array. The study is divided into two areas: first the analysis of the retractible boom and array blanket and second, the analysis and sizing of the base structure supporting the boom and array blankets.

PROGRESS

The FORTRAN IV computer program for analysis of the boom and blanket is now operational and can calculate the optimum boom size and blanket tension to obtain a desired minimum frequency. The program calculates these parameters by using a root-finding subroutine to determine the tension that produces the highest first mode natural frequency given the stiffness of the boom. Then using another root-finding subroutine, it determines the boom stiffness necessary to obtain a first mode frequency above the required minimum.

PLANS

Further development will be done in the areas of establishing governing equations for the base support structure for the General Electric single boom roll-up array. The program will then be expanded to analyze other design configurations of the roll-up array.

PUBLICATIONS

JPL Publications

1. Oliver, R. E., Garba, J. A., and Hix, J. H., A Parametric Study of Variations in Weight and Performance Characteristics of Large-Area Solar Arrays, JPL Technical Report 32-1337, March 1, 1969.

SUB-PANEL TECHNOLOGY USING ADVANCED SOLAR CELLS

NASA Work Unit 120-33-01-16

JPL 320-33501-2-3420

W. Hasbach

OBJECTIVE

This program will evaluate: new light-weight array technology, advanced concept cell technology, and the fabrication associated with the combining of the two. An evaluation of the electrical-mechanical performance of the above will be compared with the characteristics associated with conventional panels fabricated with standard solar cells used on Mariner-type missions.

PROGRESS

Advanced-concept solar cells include 2 x 6 cm cells and thin 2 x 2 cm cells proposed for light-weight structures similar to the Large Area Solar Array (LASA) technology developed under NASA Work Unit 120-33-01-02, and the Roll-up Solar Array under NASA Work Unit 120-33-01-07. These cells will be integrated into a solar panel fabricated of fiberglass tapes supported in a beryllium frame. The details of fabrication, cost of fabrication and reproduction of the panels will be evaluated. After fabrication, the panels will be electrically and mechanically tested, the relative reliability, ruggedness, handling requirements and electrical performance will be studied.

This program has been designed to incorporate the LASA technology developed at the Boeing Company under NASA Work Unit 120-33-01-02, JPL Contracts 951653 and 951934.

Six sample panels will be fabricated, each having approximately one square foot of solar-cell area. Two of the solar panels will be assembled with a 2 x 6 cm cells 0.014-in. thick, two will be assembled with a 2 x 2 cm cells 0.008-in. thick, and two will be assembled with 2 x 2 cm cells 0.004-In. thick.

The solar panels will be tested under the following environments: thermal shock (up), thermal shock (down), low-temperature tests, high-temperature tests, thermal cycling, ultraviolet exposure, and humidity.

STATUS

The Boeing Company has been selected to perform the above fabrication and test program. Completion is expected ten months following contract execution.

PLANS

During the next reporting period the following tasks will be completed: tooling, fabrication, and assembly. Test procedures will be written, test fixtures and instrumentation prepared. The test program will begin approximately December, 1969.

PUBLICATIONS

None

ANALYSIS OF SOLAR CELL RADIATION DAMAGE

NASA Work Unit 120-33-01-07

JPL 320-33901-2-3420

P. A. Berman

OBJECTIVE

One of the primary considerations in the design of particle irradiation systems for spacecraft is the effect of exposure to ionized particle irradiation on the silicon solar cells used to convert solar energy to electrical energy. The objective of this work unit is to construct a mathematical model, suitable for machine programming, which will accurately predict the amount of degradation as a function of proton energy and enable optimization of the coverglass thickness for a given radiation environment.

PROGRESS

A mathematical model has been developed to describe the effects of a combined radiation environment consisting of protons and electrons on solar cells. A flow chart has been developed for the mathematical model with the primary inputs being the illumination energy spectrum as a function of wavelength, proton fluence as a function of energy, and electron fluence as a function of energy. The flow chart shows each of the sequential calculations which must be made and the input variables needed for each of these calculations. The basic solar cell equation can describe even highly-damaged cells.

An equation has been developed to describe the minority carrier concentration as a function of input illumination, distance from the junction, and minority carrier diffusion length. Thus, the current across the junction can be calculated as a function of diffusion length and illumination spectrum. The reverse saturation current becomes inversely proportional to the base region minority carrier diffusion length near the junction and also appears to vary as a logarithum of the light intensity. The characteristic voltage (V_o) appears to be independent of temperature, radiation exposure, and possibly illumination. The model is appropriate to omnidirectional fluences and takes into account the fact that initially monoenergetic particles after traversing X distance into the solar cell will have a spectrum of energies due to effects of slant penetration. Damage by protons of less than 5 MeV results in highly non-uniform damage and consequently non-uniform minority carrier diffusion length across the cell. Proton and electron damage coefficients as a function of energy have been developed for 10 Ω-cm P type material.

A statement of work has been developed and a procurement action initiated for continuation of this work.

PUBLICATIONS

Contractor Reports

1. Barrett, M. J., and Stroud, R. H., "Exotech Final Report, A Model for Silicon Solar Cell Performance in Space," 28 February 1969, JPL Contract 952246.

STUDIES OF RADIATION DAMAGE-UNIVERSITY CONTRACTS

NASA Work Unit 120-33-01-18

JPL 320-34401-2-3420

J. V. Goldsmith

OBJECTIVE

JPL has been recently assigned the prime responsiblity for administration of the NASA solar cell university development programs. The objective of this program is to stimulate university participation in the photovoltaic power source development effort. It is the intent of this program to contract work with universities which will contribute to both the educational and research activities of the university.

APPROACH

Contracts will be initiated with approximately seven universities during FY 69. Several of these programs will be essentially continuation of work initiated in past years when the responsibility for the program was with another NASA Center.

Programs will be primarily concerned with study of radiation degradation of solar cell power source assemblies, and improvement in the power conversion efficiency of solar cells.

PROGRESS

This is a new JPL program. All university contracts are administered under this work unit. Programs awarded in FY 69 are listed below:

Nasa Work Unit	Title	University	Principal Investigator	Contract Amount
120-33-01-32	Luminescent and Tunneling Phenomena in Irradiated Silicon	U of Illinois	D. Compton	$55K
120-33-01-33	Radiation Kinetics in Electronic Material	U of Utah	A. Sosin	18K

Nasa Work Unit	Title	University	Principal Investigator	Contract Amount
120-33-01-35-55	Investigation of the Optical Properties of Irradiated Silicon	Penn State U	K. Vedom	$19K
120-33-01-37-55	Investigation of the Structure of Radiation Damage in Lithium Diffused Silicon Solar Cells	RPI	J. Corelli	29K
120-33-01-40-55	Effect of Space Particle Bombardment on Solar Cell Materials	U of Denver	W. Hagel	35K
120-33-01-43-55	Structural Damage in Li Cells by Neutrons	U of Kentucky	G. Sargent	15K

PUBLICATIONS

None

RADIATION EFFECTS ON SOLAR CELLS WITH LITHIUM DOPING

NASA Work Unit 120-33-01-20

JPL 320-32001-2-3420

P. A. Berman

OBJECTIVE

One of the major concerns in the use of silicon solar cells for space is the fact that significant decreases in power can occur when the cells are subjected to irradiation by electrons and protons that exist in the Van Allen belts surrounding the earth and by proton flares that occur in deep space as the result of solar activity. The objective of this program is to study the properties of lithium-doped silicon and to investigate the applicability of lithium and other dopants in the radiation hardening of silicon solar cells.

PROGRESS

RCA (See Note)

RCA has irradiated a total of 32 crucible-grown cells with 1 MeV electrons to 1×10^{14} electrons/cm^2. The cells have exhibited no redegradation 69 days after irradiation. All cells except those from Lot C-2 exhibit significant recovery, in some cases yielding efficiences higher than 10 Ω-cm N/P control cells irradiated to the same level. The cells from Lot C-2 are quite interesting in that they have been doped with antimony rather than phosphorus (as is the case in all other cells investigated).

Measurements made by RCA on an experimental lot of float-zone cells with various lithium diffusion and redistribution schedules, Lot C-4, indicate that a decrease in lithium density and an increase in minority carrier diffusion lengths and photovoltaic response occur with increasing redistribution time. In some cases an inexplicable shunt leakage increase has been found after irradiation. Even the best sub-group of C-4 cells, that is, the group having the longest-minority carrier diffusion length, had a relatively short diffusion length of approximately 40 microns. Cells from each sub-group (i. e., having a given lithium diffusion schedule) were similar in behavior. The cells with the best initial performance suffered the greatest fractional degradation during irradiation; however, all groups recovered to within 4% of the original power, after irradiation to 10^{14} electrons/cm^2.

A type of redegradation of float-zone cells has been observed by RCA in which open-circuit voltage and curve shape degrade while the short-circuit current and diffusion length remain constant. Thus, this type of redegradation appears to be totally unrelated to minority carrier lifetime redegradation. Spurious increases in series resistance after irradiation which continued for some time after the irradiation had ceased was observed occasionally on some float-zone cells. In the case of the experimental C-4 Lot fabricated from float-zone material having different lithium distribution schedules, after 3×10^{15} electrons/cm^2 the relative open-circuit voltage degradation after 11 days recovery at room temperature was greater than the remaining damage to short-circuit current. There is a strong indication that poor junction properties and contacts might be more common causes for problems in lithium cells rather than changes (degradation) in minority carrier lifetime.

TRW Systems (See Note)

TRW has exposed groups of lithium-doped float-zone silicon solar cells to fluences of 3×10^{14} and 3×10^{15} 1 MeV electrons/cm^2 and subsequently stored them at room temperature. Half recovery times of 0.5 and 2 to 3 hours were observed for the respective fluences. Maximum annealed values were higher for the lower fluences. Experiments on lithium-doped crucible cells indicated that although the annealing times were considerably longer, both the initial outputs and the maximum annealed outputs were higher than the float-zone cells investigated here. Storage of lithium-doped cells fabricated from cruicible-grown silicon at temperatures between 60 and 100°C produces annealing times comparable to that of moderately lithium-doped float-zone cells stored at 28°C. Investigations have been carried out by TRW on silicon diffused with lithium through utilization of a lithium aluminum hydride source. It was found that lithium-diffused silicon with concentrations between 10^{15} and 10^{18} lithium atoms/cc exhibited Hall coefficients similar to those obtained for arsenic-doped silicon and silicon doped with lithium in the melt. Carrier removal studies of the lithium-diffused silicon also indicates an exponential dependence of the carrier removal rate on the carrier concentration as was observed previously in lithium melt-doped silicon. It has been found that P/N solar cells exhibit a 0.17 eV activation energy after irradiation identified as the A-center or oxygen vacancy pair. Float-zone and crucible-grown lithium-doped solar cells were found by TRW to exhibit a pre- and post-irradiation activation energy of approximately 0.06 eV. The absence of the 0.17 eV A-center activation energy immediately after irradiation and prior to annealing indicates that the simple model of A-center annihilation through lithium diffusion might be inadequate to explain the kinetics of radiation annealing in lithium-doped silicon. It is postulated by TRW that lithium might be involved in the initial defect site in some manner such as lithium-oxygen-vacancy or a lithium-vacancy complex.

Northrop Corporate Laboratories (See Note)

Northrop has been studying the effects of various dopants in silicon on the resultant radiation characteristics, primarily with respect to minority carrier lifetime. The first series of irradiations were performed in a Febetron 705 electron-beam machine with an average electron energy of 1.7 MeV. Damage coefficient determination by means of minority carrier lifetime measurements on irradiation samples indicated that aluminum-doped float-zone silicon fabricated by General Electric was a factor of four more radiation resistant than boron-doped crucible-grown silicon normally used in solar cell fabrication. The results were somewhat suspect, however, because the damage coefficient of phosphorus-doped cruicible-grown silicon appeared to be almost identical to that of the boron-doped silicon, in contradiction to results obtained by other workers. Further investigation of the experiment indicated that the Febetron has an extremely high component of low-energy electrons and that the lifetime measurements were strongly influenced by surface damage effects on the samples, despite efforts to avoid this through design of sample configuration. Subsequent exposure of additional samples to Co^{60} gamma irradiation which yields relatively uniform damage throughout the samples, indicated little, if any, damage coefficient superiority of the aluminum-doped samples over the boron-doped samples for this type of radiation (i.e., radiation which yields point defects uniformly throughout the sample).

NOTE

The three contracts to RCA, TRW Systems, Northrop Corporate Laboratories reported herein were initiated last year under Work Units 120-33-01-28, 120-33-01-29 and 120-33-01-30, respectively.

Conclusions

Some of the major conclusions drawn from this review are as follows:

(1) Lithium-doped cell efficiencies have been increased over the past year, especially for cells fabricated from crucible-grown material, to the point where they can be as high as good state-of-the-art N/P cells (11-11.5% under space sunlight conditions at 28°C).

(2) An interesting syllogism stimulated by the foregoing observation, might be:

(a) Non-lithium-doped P/N cell efficiency distributions are normally one efficiency percent lower than non-lithium-doped N/P cells.

(b) Lithium-doped P/N cells can be made with efficiencies equal to non-lithium-doped N/P cells.

(c) If manufacturing techniques for fabricating non-lithium-doped P/N cells are improved to the levels of non-lithium-doped N/P cells, so that non-lithium P/N and N/P cell efficiencies are equivalent, then lithium-doped P/N cells might be an efficiency percent higher than non-lithium-doped N/P cells.

(3) The diffusion of boron into N-type silicon by the BCl_3 process appears to cause significant embrittlement of the silicon, probably the result of strains introduced by this process. This would be expected to reduce the ultimate efficiency in the resultant cell. This also appears to be an area where major improvements can be made, even for non-lithium-doped P/N cells.

(4) Crucible-grown cells in general have higher efficiency, due mainly to higher V_{oc}, than float-zone cells having similar lithium diffusion schedules.

(5) The recombination centers created by the introduction of lithium into silicon are no more effective than those introduced by more conventional dopants such as antimony or arsenic and, in fact, may be less effective.

(6) Changes in lithium diffusion schedule appear to affect primarily the long-wavelength cell response.

(7) Lithium-doped cells fabricated from crucible-grown silicon stored at elevated temperatures (60 to 100°C) behave almost identically to lithium-doped cells fabricated from float-zone material stored at 28°C. Thus, fast recovery of crucible-grown lithium cells can be expected for cells operated at 1 AU conditions where they would attain a temperature of about 60°C.

(8) Different defect centers appear to be formed in lithium-doped crucible-grown and float-zone silicon. In crucible-grown silicon the primary defect center is probably a lithium-oxygen-vacancy combination while in float-zone silicon the defect is most likely a lithium-vacancy combination.

(9) The lithium-oxygen-vacancy center is far more stable than the lithium-vacancy center.

(10) It is interesting that despite the indications that different defect centers are formed in lithium-doped crucible-grown and float-zone silicon, at temperatures of 28°C or above, the gross cell characteristics behave as though the main difference is a diffusion-associated phenomenon. (Reference Item (7) above.)

(11) The term "redegradation" might be a misnomer since there are indications that the phenomenon is really a non-irradiation (or shelf-life) associated degradation. Perhaps the phenomenon would be more accurately termed "radiation-independent degradation" or "RID".

(12) Two types of "redegradation" have been observed:

(a) "Redegradation" of the cell short-circuit current. This is most apparent in highly lithium-doped (greater than 5×10^{15} li/cc near the P-N junction) cells fabricated from float-zone material.

(b) "Redegradation" of the cell curve-shape, especially open-circuit voltage with little or no change in the short-circuit current.

PUBLICATIONS

JPL Publications

1. Berman, P. A., "Study of Radiation Effects in Li-Doped Solar Cells," JPL Space Power Summary SPS 37-55 Vol. III, February 28, 1969.

2. Berman, P. A., "Studies of Dopants for Radiation Resistant Silicon," JPL Space Power Summary SPS 37-55 Vol. III, February 28, 1969.

Contractor Reports

1. Brucker, G. J., Faith, T. J., Holmes-Siedle, A. G., "RCA Third Quarterly Report: Action of Lithium in Radiation Hardened Silicon Solar Cells," 15 February 1969, JPL Contract 952249.

2. Downing, R. G., Carter, J. R., Van Atta, W. K., "TRW Third Quarterly Report: Study of Radiation Effects in Li-Doped Silicon Solar Cells," 14 February 1969, JPL Contract 952251.

3. "Northrop Corporate Laboratories Third Quarterly Report: Effects of Impurities on Carrier Lifetime in Bulk Solar-Cell Material," February 1969, JPL Contract 952256.

RESEARCH AND DEVELOPMENT OF LITHIUM SOLAR CELLS - CONTRACT D

NASA Work Unit 120-33-01-21

JPL 320-34601-2-3420

P. A. Berman

OBJECTIVE

One of the major concerns in the use of silicon solar cells for space is the fact that significant decreases in power can occur when the cells are subjected to irradiation by electrons and protons that exist in the Van Allen belts surrounding the Earth and proton flares that occur in deep space as the result of solar activity. Within the past few years, work on cells with lithium doping has indicated that cells can be fabricated which exhibit considerable annealing out of radiation damage at temperatures of 28° C or greater. This phenomenon could be of great significance if the effect can be reproducibly controlled, stabilized, and accurately predicted. The objective of this program is to develop and fabricate radiation-resistant, high-efficiency, lithium-doped silicon solar cells for space use.

PROGRESS

As described in the previous report, three contracts were awarded, one to each of the three major suppliers of solar cells, Texas Instruments Inc., Heliotek Division of Textron, and Centralab Division of Globe Union Inc., to perform this program. The use of three contractors provides greater flexibility, opportunies for analysis of the effects of process and equipment variables, and assurance that successful cell designs can be duplicated by all three major solar cell manufacturers.

T.I. has delivered to JPL 600 lithium-doped solar cells having various designs. Lots of 60 cells were fabricated using the same type of starting material and the same lithium diffusion schedule. The slices of one lot were sawed and polished to final dimensions prior to fabrication into solar cells. The cells from a second lot were processed as whole slices through all high-temperature steps and finally sawed into individual cells only after contact sintering. Two cells were obtained from each slice. The processing sequence. utilized in the fabrication of the whole-slice lots was designed to eliminate non-uniform lithium concentrations at the cell edges. The whole-slice lots exhibited higher average open-circuit voltage and a tighter open-circuit voltage distribution. The short-circuit current density per unit active area, however, was somewhat lower for the whole-slice lots resulting in power at a voltage of 0.43 volts almost identical for the two lot types. The lower short-circuit current of the whole-slice lots might well be the results of other process variables and may not be germane to this particular experiment; however, the increase in voltage might be significant.

Centralab has submitted to JPL five hundred and forty lithium-doped silicon solar cells having various designs. In general, both short-circuit current and open-circuit voltage are higher for cells made from crucible-grown material than for cells made from oxygen-lean silicon (such as float zone or Lopex silicon) for equivalent lithium diffusion schedules. A closely controlled experiment was performed to verify this general observation. Slices from a crucible-grown and a float-zone refined ingot were co-processed through all fabrication steps. Under these controlled conditions the same superiority of the cells fabricated from the crucible-grown ingot was again found. Etch pit studies gave no conclusive connection or correlation to the observed differences between crucible and float-zone material.

Investigations were performed by Centralab on the use of methods of lithium introduction other than the presently utilized mineral-oil paste technique; however, a greater spread in cell characteristics was always obtained with the other methods. Investigations were also carried out to replace the boron trichloride diffusion operation, which gives rise to significant silicon embrittlement, by a less detrimental process. Similarly, no method was found which gave the cell reproducibility and high efficiency which can be obtained with the boron trichloride process.

Centralab has obtained lithium concentration profiles for various lithium diffusion treatments and cycles. Under some conditions a redistribution cycle can produce a more uniform lithium distribution through the cell; however, the lithium concentration is usually lower near the junction and near the back face of the cell. In general, redistribution results in a lower total lithium concentration in the body of the cell. Redistributing (reheating) silcon previously diffused with lithium at a temperature of 450°C to temperatures greater than 1000°C led to almost complete loss of the lithium. Differences in lithium diffusion schedules primarily affect the long wavelength cell response.

Heliotek has submitted to JPL 600 lithium-doped P/N solar cells having various cell designs. Lithium-doped cells fabricated from crucible-grown material could be fabricated with air mass 0, 28°C efficiencies as high as state-of-the-art N/P cells. The variation of cell efficiencies within a given lot of cells has been significantly decreased, and Lots 2 and 10, which were fabricated 8 months apart, but which were identical in design, were essentially identical in average efficiency and efficiency distribution. Crucible-grown cells were found to have higher efficiencies for similar lithium diffusion schedules than cells fabricated from either Lopex or float-zone material. Attempts to improve on the lithium-oil suspension paint-on method of introduction have thus far been unrewarding. Attempts to improve the boron diffusion technique were also unsuccessful. Work will continue in these areas. Experiments involving contact heat treatment (sintering) indicate that such heat treatment may increase cell starting efficiency.

PUBLICATIONS

JPL Publications

1. Berman, P. A., "Research and Development of Lithium Solar Cells," JPL Space Program Summary SPS 37-55, Vol. III, February 1969.

Contractor Reports

1. Payne, P., "Heliotek Third Quarterly Report: Development of Lithium Diffused Radiation Resistant Solar Cells," 15 January 1969, JPL Contract 952247.

2. Payne, P., "Heliotek Final Report: "Development of Lithium Diffused Radiation Resistant Solar Cells," 20 March 1969, JPL Contract 952247.

3. Iles, P. A., "Centralab Semiconductor Second Quarterly Report: Study of Lithium Doped Solar Cells," 15 November 1968, JPL Contract 952250.

4. Iles, P. A., "Centralab Semiconductor Third Quarterly Report: Study of Lithium Doped Solar Cells," 15 January 1969, JPL Contract 952250.

5. Kendall, D. L., Vineyard, R. A., "Texas Instruments Quarterly Report No. 2: Lithium-Diffused Solar Cells," 30 September 1968, JPL Contract 952248.

6. Vineyard, R. A., Kendall, D. L., "Texas Instruments Quarterly Report No. 3: Lithium-Diffused Solar Cells," January 1969, JPL Contract 952248.

RADIATION DAMAGE IN LITHIUM-DOPED SOLAR CELLS - CONTRACT C

NASA Work Unit 120-33-01-22

JPL 320-34101-2-3420

P. A. Berman

OBJECTIVE

One of the major concerns in the utilization of silicon solar cells for space use is the fact that significant decreases in power can occur when the cells are subjected to irradiation by electrons and protons which exist in the Van Allen Belts surrounding the earth and proton flares which occur in deep space as the result of solar activity. For the past ten years considerable effort has been expended to develop solar cells with improved resistance to radiation exposure. Within the past few years work on cells with lithium doping has indicated that cells can be fabricated which exhibit considerable annealing out of radiation damage at temperatures of 28°C or greater. This could have a great impact on the total space program if this effect can be reproducibly controlled, stabilized and accurately predicted. The objective of this program is to study the characteristics of lithium-doped silicon as a function of exposure to electron irradiation, the formation of defects in lithium-doped silicon, and the interaction between the lithium impurity and the radiation induced defects.

PROGRESS

A contract (JPL Contract 952387) to perform the investigations discussed above was awarded to Gulf General Atomic, Incorporated, in the amount of $92, 925. The contract was initiated on 24 December 1968.

The contractor has prepared lithium-diffused silicon samples grown by the vacuum float zone process having lithium concentrations between 5×10^{14} and 5×10^{16} lithium atoms/cc (10^3 and 0.25 ohm-cm resistivity respectively). The samples with resistivity greater than 11 ohm-cm were found to have non-uniform lithium concentration profiles (high in the center and lower at the faces). Samples with resistivity lower than 11 ohm-cm had uniform lithium profiles. Minority carrier lifetime measurements were performed on the 11 ohm-cm material at a temperature of 300°K with the 600-Kev flash x-ray technique, and the lifetime was found to be 50 ±10 μsec. After irradiation by 30-Mev electrons at room temperature, the damage coefficient associated with this material was found to approximate that of non-lithium-diffused silicon and was significantly lower (by a factor of 2) than more highly lithium-doped material (10^{16} - 10^{17} lithium atoms/cc). After a second irradiation, only partial annealing was observed for temperatures as high as 420°K, indicating that the mobile lithium had been depleted.

PUBLICATIONS

Contractor Reports

1. Naber, J. A., Passenheim, B. C., "Radiation Effects in Silicon Solar Cells: Gulf General Atomics Quarterly Report," 10 April 1969.

LOW FLUX RATE RADIATION DAMAGE IN LITHIUM SOLAR CELLS - CONTRACT A

NASA Work Unit 120-33-01-23

JPL 320-34501-2-3420

J. V. Goldsmith

OBJECTIVE

Lithium-diffused solar cells offer a potential technique to improve the radiation resistance of photovoltaic power sources. Early and preliminary investigations have indicated that the degree of radiation resistance is a function of cell construction, type of damaging particle, and radiation rate sensitivity. It is the objective of this program to investigate the rate sensitivity of radiation degradation to lithium solar cells.

APPROACH

Lithium solar cells of various configurations will be exposed to low flux-rate exposure to energetic particles. The performance of the solar cells will then be evaluated as functions of temperature of the cell under irradiation and cell physical characteristics. It is proposed that intial experiments be conducted using a radioactive isotope as a source of Beta particles, with a flux rate representative of that experienced by spacecraft in near-earth orbit. A parallel program is also to be initiated with a different contractor to observe the effects of different experimental techniques, test facilities and procedures (Ref. NASA Work Unit 120-33-01-41-55, JPL 320-36401-2-3420).

PROGRESS

JPL Contract 952585 for $61,450 was awarded to Philco-Ford Corp., Palo Alto, California, in June, 1969. The program's principal investigator at Philco Ford is Mr. D. Reynard. Formal quarterly and semiannual reports are required on this effort. The first report is due for publication in September, 1969. No significant progress has been made at this time.

PUBLICATIONS

None

FILTERS FOR NEAR-SUN MISSIONS

NASA Work Unit 120-33-01-24
JPL 320-31501-2-3420
W. A. Hasbach

OBJECTIVE

The objective of this program is the development of partially-reflecting filters to be used on solar cell panels for spacecraft destined for near-sun missions. The purpose of the filters is to limit the effective incoming intensity so that the resulting maximum equilibrium panel temperature at Mercury encounter of 0.44 AU will be less than 120 °C. Since this approach to panel thermal control is passive, the reliability of such missions is judged to be much greater over approaches using mechanical concepts such as window shades, louvers, etc.

APPROACH

A method for controlling the operating temperature of a photovoltaic array at a Sun-probe distance of 0.44 AU is the use of selective control coatings. At present, the thermal properties of the solar array have been optimized for only back-side emittance. Filters in use at present provide a measure of temperature optimization at moderate solar distances and protection against UV radiation for the filter-mounting adhesive. This effort is being directed to the development of narrow-band-pass filters to optimize the electrical performance and provide thermal control for near-Sun solar arrays.

The narrow-band-pass filter is effective because it provides for the transmission of solar energy in the spectral region near the peak of cell response while rejecting energy which is less effective in producing electrical power. It does not appear feasible to achieve satisfactory photovoltaic thermal performance by use of band-pass filters alone. However, a significant increase in power per unit array area can be achieved by use of filters in conjunction with other methods such as highly-reflecting surfaces and/or inclination to incident solar radiation. Alternate methods and combinations including the results of this work unit are being evaluated under another task (NASA Work Unit 120-33-01-39-55, JPL No. 320-36101-2-3420).

PROGRESS

Analysis of results of tests on narrow-band-pass filters and review of filter technology have shown that near-optimum rejection and transmission is not practical and indicate that somewhat broader band selective filters combined with highly-reflective, nonselective coatings will produce maximum power. Sample quantities of medium-band pass filters, with and without second surface mirror reflectors applied, have been ordered to evaluate absorption, reflection, and cell-response characteristics. From the tests conducted earlier in the fiscal year and evaluation of filters now on order, filter system design can be optimized to maximum power at a specified upper temperature limit.

PLANS

The medium-band filters now on order will be evaluated early in the next period. The results plus those from earlier tests will permit filter design optimization for maximum power at specified temperature limits and solar intensities for inner planet missions.

Results will be coordinated with a parallel study of alternate methods for array temperature control.

PUBLICATIONS

None

SOLAR CELL FLIGHT EXPERIMENT

NASA Work Unit 120-33-01-31

JPL 320-35301-2-3420

B. E. Anspaugh

OBJECTIVE

The objective of the Solar Cell Flight Experiment, scheduled for launch on the ATS-E spacecraft, is to determine the effect of the synchronous orbit radiation environment on selected solar cell/coverslide configurations. The experiment is designed to provide high-accuracy data on the entire I-V curve of each solar cell. A supplemental extensive ground test program is concurrently in progress which is designed to predict the behavior of the cells on the experimental package and to furnish information which will allow an optimization of the experimental design.

PROGRESS

As described in the previous report, the Hughes Aircraft Company (HAC) has been contracted (JPL Contract 952351) to build the experimental apparatus, and to assume a large portion of the effort in implementing the ground test program. HAC is the prime contractor for building the ATS-E satellite, and interfacing the experiment with the spacecraft was accomplished with minimal perturbation. JPL assumed the responsibility for assembling the rigid solar panel using HAC-supplied cells and substrate. JPL has also assumed the responsibility for all post flight data analysis.

The experiment consists of the following components (a total of 80 solar cells (2 x 2 cm) will be flown; twelve I-V pairs will be obtained from each cell upon activation of the experiment by ground command):

(1) A rigid solar panel, tangentially mounted to the spacecraft, containing five each of 13 types of solar cells (total of 65 cells), and 13 thermistors.

(2) A flexible solar panel mounted radially to the spacecraft. Panel substrate will be a kapton-fiberglass sandwich 2 mils thick. Five

each of three types of solar cells (total of 15 cells), and three thermistors will be mounted. This panel is designed to investigate the effect of radiation on the back cell surface and to discover the potential problems which will be encountered in the design of large-area flexible arrays.

(3) Two signal processor units which sequentially select the solar cells and load resistors, and process the signal into the format for telemetry via the ATS-E encoders. Each processor handles half the cells.

(4) A spacecraft payload regulator.

The following project milestones have been passed:

(1) Completion of ground test program consisting of ultraviolet, electron and proton irradiation of a wide cross section of solar cell/coverslide combinations.

(2) Construction of signal processors and solar panels.

(3) Successful qualification and flight acceptance testing of signal processors and solar panels.

(4) Delivery of signal processors and solar panels to the ATS-E spacecraft.

(5) Successful completion of compatibility testing with the spacecraft subsystems upon initial installation and following vibration.

(6) Preparation of a computer program to decommutate and analyze the data received by telemetry.

HAC is currently preparing a draft of the final report covering the ground test program and all aspects of constructing the experimental package.

The ATS-E spacecraft is presently scheduled to be launched on or before August 19, 1969.

PUBLICATIONS

None

LUMINESCENT AND TUNNELING PHENOMENA IN IRRADIATED SILICON

NASA Work Unit 120-33-01-32

JPL 320-35401-2-3420

J. V. Goldsmith

OBJECTIVE

The objectives of this program are: (1) a study of the type and nature of electron transitions in the energy band structure of single crystalline, lightly-doped silicon, and (2) a study of the behavior of electrons in the impurity bands in heavily-doped silicon. Both of these studies will be performed as a function of irradiation, and as a function of types of impurities. It is anticipated that, by a more thorough understanding of electron behavior in irradiated silicon, a better understanding of the interactions of radiation-induced defects with the silicon lattice and existing impurities will be obtained. The approach was outlined in the previous report.

PROGRESS

Work was initiated on this Contract with the University of Illinois in October, 1968. Dr. D. Compton, the programs principal investigator has reported that substantial progress has been made; however, measurements are still in progress and final conclusions are not possible at this time. The areas of research to-date have been:

(1) The study of the influence of uniaxial stress and temperature upon the high-resolution luminescence spectra of electron-irradiated silicon.

(2) The study of the effects of lithium dopant upon the spectra of the recombination luminescence of irradiated silicon.

(3) The thermal stability of the defects that are responsible for the recombination luminescence in irradiated silicon.

(4) The influence of irradiation upon the electron-tunneling characteristics of highly-doped silicon.

ANTICIPATED PUBLICATIONS

A rough draft of the first semiannual report of this program was approved for release by JPL.

PUBLICATIONS

None

RADIATION KINETICS IN ELECTRONIC MATERIALS

NASA Work Unit 120-33-01-33

JPL 320-35501-2-3420

J. V. Goldsmith

OBJECTIVE

The objective of this work unit is to achieve theoretical understanding in mathematical terms of the nature, and the rate of production and annealing, of radiation damage in doped and undoped silicon. The approach was outlined in the previous report.

PROGRESS

JPL Contract 952384 for $16, 000 was awarded to the University of Utah in February 1969. The program is to last twelve months and is under the directorship of Dr. Sosin. Formal reports every six months are required, the first of which is scheduled for July, 1969. There has been no significant progress reported at this time.

PUBLICATIONS

None

EFFECTS OF SUB-THRESHOLD HIGH ENERGY ELECTRONS ON SILICON CELLS

NASA Work Unit 120-33-01-34

JPL 320-35601-2-3420

J. V. Goldsmith

OBJECTIVE

The objective of this task is to study the effects of high energy (>50 KeV) electrons on the properties of silicon. The appraoch was described fully in the previous report.

PROGRESS

JPL Contract 952386 for $13,673 was awarded to Brown University for this program. This effort will be directed by Dr. J. Loferski. The present contract is for nine months and was initiated in April, 1969. Formal quarterly reports are required, the first of which to be issued in July, 1969. No significant progress has been reported at this time.

PUBLICATIONS

None

INVESTIGATION OF THE OPTICAL PROPERTIES OF IRRADIATED SILICON

NASA Work Unit 120-33-01-35

JPL 320-35701-2-3420

J. V. Goldsmith

OBJECTIVE

The objective is to characterize the imaginary and real components of the complex index of refraction of the doped and undoped silicon substrate as well as the thickness and refractive index of the oxidation film on the silicon substrate. The approach was outlined in the previous report.

PROGRESS

JPL Contract 952385 for $16,500 for this program was awarded to the University of Pennsylvania in February 1969. The investigations will be under the direction of Dr. Vedam. The present contract is for nine months. Formal reports are required after four and one-half and nine months. The first report is scheduled for issuance in July, 1969. There has been no significant progress reported at this time.

PUBLICATIONS

None

SOLAR CELL RESEARCH

NASA Work Unit 120-33-01-36

JPL 320-35801-2-3420

P. A. Berman

OBJECTIVE

One of the major concerns in the utilization of silicon solar cells for space is the fact that significant decreases in power can occur when the cells are subjected to irradiation by electrons and protons which exist in the Van Allen Belts surrounding the earth, and proton flares which occur in deep space as the result of solar activity. Another major concern is the prediction of solar cell performance in various space environments (e.g., various combinations of temperature and solar intensity). This involves more complete characterization of solar cell parameters. The objective of this program is to determine the effects of space type environments such as radiation, temperature, and solar intensity on the operating characteristics of state-of-the-art and developmental-type solar cells.

PROGRESS

The work described below is being carried out by the Naval Research Laboratory under Contract to JPL (WO 8056). The use of Hall-effect measurements of irradiated, lithium-doped (10^{14} li/cc), float-zone silicon over a temperature range of 4 to 300°K has allowed a separate determination of the acceptor and donor concentrations. Measurements by other investigators thus far have been limited to temperatures greater than 77°K and therefore indicated only the donor concentration minus the acceptor concentration. It is postulated from the results that two donors are lost for each acceptor center neutralized. As annealing proceeded, the Fermi level moved from the vicinity of the lithium donor level to the level of the lithium-oxygen donor. The free lithium concentration was first depleted and subsequently the lithium-oxygen concentration was similarly depleted (but at a much slower rate). After annealing for 61 hours at 300°K there was no structure observed which would correspond to the A-center normally found in non-lithium-doped silicon at an energy level of 0.18 eV below the conduction band. However, structure interpreted as a deep-lying donor level was observed at an energy level approximately 0.15 eV below the conduction band, and this donor level appeared to be unaffected by annealing at 300°K.

Gamma irradiations are being conducted on Li-doped solar cells by means of a CO^{60} source. This is a preliminary experiment to determine the limitations of the equipment and techniques and to seek areas of improvement. Thus far, it is felt that improvements can be made by: (1) improvement of experimental statistics through larger sample sizes (2) improvement of cell temperature control and (3) careful choice of material to be used within the radiation chamber (i. e., wire insulation) to prevent undesirable reaction with gamma rays. Work is being done on preparing and refining equipment for ion implantation. This equipment will be used in an effort to improve solar cell contacts. A focused, controlled boron beam has been obtained.

Investigations of the electrical characteristics of nine silicon solar cells of three different types were made over light intensities between 1 and 140 mW/cm^2 and temperatures between 85 to 300°K. Some of the cells exhibited a non-ohmic behavior at temperatures below 200°K. All cells exhibited some efficiency increase (over 140 mW/cm^2 300°K conditions) at 85°K, the increase becoming more pronounced for high intensities.

A computer program adapted from a general least-squares program, is being developed to fit experimental solar cell current voltage data to the solar cell equation.

A critique has been made of Chapters II and III of "The Handbook of Space Environmental Effects on Solar Cell Power System." Some suggestions for improvement are: (1) introduction of solar cell parameters and their functional dependencies should be treated as a separate chapter at the front of the book, (2) greater consideration should be given to dependence of cell properties as a function of temperature and light intensity, (3) directions for planning a sample matrix to assure statistical validity for a typical radiation experiment would be very helpful to the reader.

PUBLICATIONS

Contractor Reports

1. Statler, R. L., Radiation Effects in Silicon Solar Cells, International Conference on Physics and Technology of Nonmetallic Crystals, New Delhi, India, 13-17 January 1969.

2. Faraday, B. J., Analysis of Radiation Damage in Silicon by Thermal Annealing of Solar Cells, International Conference on the Physics and Technology of Nonmetallic Crystals, New Delhi, India, 13-17 January 1969.

3. Stannard, J. E., Electron Irradiation of Lithium-Doped Silicon at Low Temperatures, Bull. Am. Phys. Soc., 14 326 (1969).

4. Faraday, B. J., Analysis of Radiation Damage in Silicon by Thermal Annealing of Solar Cells, NRL Report of Progress, February 1969.

5. Stannard, J. E., 300°K Annealing of Electron Damage in Lithium-Doped Silicon, presented at Review of Progress in Lithium-Diffusion Solar Cells, JPL, Pasadena, California, 8 April 1969.

6. Statler, R. L., Status of Semiconductor and Solar Cell Research at NRL, presented at Solar Working Group, IAPG, Washington, D. C., 18 March 1969.

7. "Semiannual Report for Solar Cell Research," Naval Research Laboratory, 16 April 1969, JPL Contract No. WO-8056.

INVESTIGATION OF THE STRUCTURE OF RADIATION DAMAGE IN LITHIUM DIFFUSED SILICON

NASA Work Unit 120-33-01-37

JPL 320-35901-2-3420

J. V. Goldsmith

OBJECTIVE

The objective of this work unit is to study the radiation-produced defect structures in lithium-doped solar cells. The approach was described in the last report.

PROGRESS

JPL Contract 952456 for $26,195 was awarded to Rensselaer Polytechnic Institute for nine months. The program's principal investigator is Dr. John Corelli. The program was initiated in February 1969 and requires the submission of formal reports in July and November. No significant progress has been reported at this time.

PUBLICATIONS

None

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PHOTOVOLTAIC ARRAY STRUCTURE TECHNOLOGY

NASA Work Unit 120-33-01-38
JPL 320-36201-2-3420
W. Hasbach

OBJECTIVE

The objective of this work unit is to provide solar panel advancements utilizing the technology developed under NASA Work Unit 120-33-01-02-55. The design will be developed to provide important light-weight solar array integration and array interaction technology for use in planetary spacecraft.

APPROACH

A detail design, fabrication and test program will be initiated predicated upon the Viking '73 spacecraft. Efforts will be coordinated between project requirements and development to the extent that mission restraints will be placed on the design and fabrication of the solar array.

PROGRESS

This is a new task which will be performed by the Boeing Company under JPL Contract No. 952571, beginning in July, 1969. The cost for the program has been negotiated to be $560, 000, it is scheduled to last one year.

PUBLICATIONS

None

MERCURY-VENUS FLYBY SOLAR ARRAY

NASA Work Unit 120-33-01-39

JPL 320-36101-2-3420

W. A. Hasbach

OBJECTIVE

The objective of this program is to determine the performance characteristics of photovoltaic solar arrays for use in near-sun missions (sun probe distances 0.6-0.3 AU) and to develop, where necessary, technology required to survive the high-intensity, high-temperature environment of a Mercury-Venus flyby.

APPROACH

Solar cell arrays using present fabrication techniques, have a maximum operating temperature of approximately 150°C. Using constraints of a typical Mercury-Venus flyby mission, techniques of thermal control of the array system are being studied to establish feasibility of performing missions of this type with conventional solar panels. Various approaches will be considered and trade-offs made to determine the most desirable means by which thermal control can be achieved and to establish design considerations which will enhance the reliability of solar cell arrays for near-sun missions.

PROGRESS

Major efforts have been in three areas of investigation:

(1) Solar cell performance.

(2) Thermal control by means of special band-pass filters, mirror surfaces, tilting of the solar panel or combinations.

(3) Materials evaluation.

The performance of solar cells in the environment induced by a near-sun mission is extremely limited as was shown during a literature search. Available data are not consistent from one experimenter to another. Based upon this literature search, it is obvious that an in-depth test program must be performed to obtain electrical data up to a sun probe distance of 0.3 AU and at elevated temperatures.

A test program has been initiated to evaluate the effects of long-term exposure to elevated temperature. Thus, far more than 1,000 hours of exposure to 125°C temperature storage have been recorded and indicate no major electrical degradation. This test will continue to simulate a nine-month mission.

Several iterations of solar panel design utilizing a mosaic pattern of solar cells and mirrors have been evaluated for effective temperature control. By placement of 2/3 mirror coverage on the solar panel an operating temperature not to exceed 140°C can be expected. Two mosaic patterns have been considered, the macro mosaic which places the mirrors adjacent to each row of solar cells, and the micro mosaic which makes the mirror part of the solar cell filterglass. Either technique appears to be an effective approach of thermal control.

Another method for control of the solar panel temperature is achieved through tilting the panel away from the normal plane of the sun. This technique, although effective, introduces other problems such as shifting the spacecraft center of gravity, introduction of mechanisms, and possible interference with other spacecraft functions. To minimize the effects on the spacecraft by tilting the panels, it may be desirable to use a combination of both the mosaic pattern and limited tilting of the panels.

A material study was made to determine applicability of present systems used on the Mariner series to a Mercury-Venus flyby. In general, no major changes are considered necessary at this time, although more in-depth investigations are desirable upon acceptance of a final design.

PLANS

During the next reporting period sample solar panels will be purchased for the purpose of evaluating fabrication techniques proposed by manufacturers for near-sun missions. Manufacturers are proposing modest extensions in the state-of-the-art for fabrication by use of thermal diffusion bonding and high-temperature solders. The solar panels will be subjected to thermal shock to simulate Sun occultation, temperature cycling, and electrical measurements at various angles of illumination.

Special band-pass filters will be purchased for evaluation and test. Mirrors will be purchased, both as integral parts of filter glass and as separate units.

Up to this time much of the activity has been in studies; during the following reporting period the efforts will be test and hardware oriented.

Performance characteristics of solar cells will be measured as applicable to near-sun missions.

PUBLICATIONS

None

EFFECTS OF SPACE PARTICLE BOMBARDMENT ON SOLAR CELL MATERIALS

NASA Work Unit 120-33-01-40

JPL 320-36301-2-3420

J. V. Goldsmith

OBJECTIVE

The objective of this task is to determine the nature of the surafce and bulk defects in irradiated, doped and undoped, float-zone and pulled silicon. The approach is described in detail in the previous report.

PROGRESS

JPL Contract 952533 for $31,405 was awarded to the University of Denver for this program in April, 1969 and work has been in progress only two months at this writing. The contract has been written for one year and requires the submission of formal reports every six months. There has been no significant progress reported to this time.

PUBLICATIONS

None

LOW FLUX RATE RADIATION DAMAGE IN LITHIUM SOLAR CELLS - CONTRACT B

NASA Work Unit 120-33-01-41

JPL 320-36401-2-3420

J. V. Goldsmith

OBJECTIVE

Lithium-diffused solar cells offer a potential technique to improve the radiation resistance of photovoltaic power sources. Early and preliminary investigations have indicated that the degree of radiation resistance is a function of cell construction, type of damaging particle, and radiation rate sensitivity. It is the objective of this program to investigate the rate sensitivity of radiation degradation to lithium solar cells in parallel with Work Unit 120-33-01-23-55.

APPROACH

Lithium solar cells of various configurations will be exposed to low-flux-rate energetic particles. The initial experiments are to be conducted using a radioactive isotope as a source of Beta particles, with a flux rate representative of that experienced by spacecraft in near-Earth orbit. The performance of the solar cells will then be evaluated as functions of temperature of the cell under irradiation and cell physical characteristics. This program is to be carried out by a different contractor to observe low flux effects using different experimental techniques, test facilities, and procedures.

PROGRESS

This is a new program, and a contract has not been formally negotiated.

PUBLICATIONS

None

PLANETARY SOLAR ARRAY DEVELOPMENT, CONTRACT B

NASA Work Unit 120-33-01-42

JPL 320-36501-2-3420

L. W. Schmidt

OBJECTIVE

The objective of this program is to determine the effects of the Martian dust environment on solar-cell performance and on the solar-irradiation transmission characteristics of the filter covers. The filter covers evaluated will include microsheet, quartz, sapphire, and integral glass. The analyses and tests shall include exposures to simulate the environmental conditions expected to exist on Mars. As a minimum, these conditions will be atmospheric pressure, temperature, and composition, solar insulation, and wind and dust storms.

PROGRESS

A lot of 384 three-cell modules has been purchased against NASA Work Unit 120-33-01-08-55 with delivery scheduled for early June. The cells on the modules will have the various filter covers as noted. These modules are to be exposed to the simulated Martian atmospheric conditions outlined above. The task is to be accomplished under Contract 952582 ($72, 224.00) with Texas Technological College of Lubbock, Texas.

The contract has been submitted to the contractor for final review and approval and is expected to be formally initiated in June, 1969.

PUBLICATIONS

None

STRUCTURAL DAMAGE IN SILICON CELLS PRODUCED BY NEUTRONS

NASA Work Unit 120-33-01-43

JPL 320-36701-2-3420

J. V. Goldsmith

OBJECTIVE

The objective of this program is to study the structural damage produced in silicon semiconductors by neutron irradiation. Characteristics to be studied include the nature of surface and bulk lattice defects and the effects of thermal treatment on the annealing of induced defects.

APPROACH

The planned approach for this program is summarized in Table 1 Design of Experiments. Six repeat samples shall be in each matrix cell and will be subject to a complete statistical analysis. Irradiated samples will be subjected to various heat treatments, also indicated in Table 1 to determine the thermally-induced recovery of defects. The examination techniques to be used will chiefly be through the use of an electron microscope.

PROGRESS

A nine-month, $12, 761 contract (JPL Contract No. 952561) was awarded to the University of Kentucky for this program in May, 1969. The effort will be under the direction of Dr. G. Sargent. Work has recently been initiated with no significant progress reported to this date. Formal reports are expected on this program in September, 1969 and January, 1970.

PUBLICATIONS

None

Table 1. Design of Experiments — Experimental Matrix

Experimental Techniques by Electron Microscopy 1) Replication of Surface 2) Transmission 3) Selected Area Diffraction Analysis		EXPERIMENTAL OBSERVATIONS 1) MOROPHOLOGY OF DISORDERED REGIONS	2) SIZE OF DISORDERED REGIONS	3) DISTRIBUTION OF DISORDERED REGIONS	4) RECOVERY OF DISORDERED REGIONS
	10^{12}				
Neutron	10^{13}				
Dose	10^{14}				
(Neutron/cm^2)	10^{15}				
Lithium	0				
Dopant	10^{15}				
Concentration	10^{16}				
Atoms/cm^3	10^{17}				
Crystal	110				
	111				
Direction	100				
Thermal	293				
Annealing	500				
	700				
(°K)	900				

RADIATION DAMAGE IN LITHIUM-DOPED SOLAR CELLS
CONTRACT D

NASA Work Unit 120-33-01-44

JPL 320-36801-2-3420

P. A. Berman

OBJECTIVE

One of the major concerns in the use of silicon solar cells for space is the fact that significant decreases in power can occur when the cells are subjected to irradiation by electrons and protons that exist in the Van Allen belts surrounding the earth and by proton flares that occur in deep space as the result of solar activity. Within the past few years, work on cells with lithium doping has indicated that cells can be fabricated that exhibit considerable annealing out of radiation damage at temperatures of 28°C or greater. Some major problems, however, exist with the lithium-doped cells, mainly in the area of long-term stability. The lithium ion is highly mobile in silicon, even at room temperature, and thus storage at room temperature and above can result in a redistribution of the lithium, especially near the P-N junction and at the back surface. Cells stored for periods of time have shown changes in electrical characteristics, and in the case of irradiated cells, which have exhibited annealing out of damage, redegradation has occurred in some instances. The objective of this program is to study the properties of lithium-doped silicon and to investigate the applicability of lithium and other dopants in the radiation hardening of silicon solar cells. This program was previously reported under NASA Work Unit 120-33-01-20-55. This program is essentially a parallel effort to that described under NASA Work Unit 120-33-01-47-55.

PROGRESS

A statement of work was developed and a contract awarded to RCA (Contract 952555) in the amount of $153, 000 to perform the studies outlined above. The tentative start date is June 1969.

PUBLICATIONS

None

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DOPANTS FOR RADIATION RESISTANT SILICON

NASA Work Unit 120-33-01-45

JPL 320-36901-2-3420

P. A. Berman

OBJECTIVE

One of the major concerns in the use of silicon solar cells for space is the fact that significant decreases in power can occur when the cells are subjected to irradiation by electrons and protons that exist in the Van Allen belts surrounding the earth and by proton flares that occur in deep space as the result of solar activity. For the past ten years, considerable effort has been expended to develop solar cells with improved resistance to radiation exposure. Within the past few years, work on cells with lithium doping has indicated that cells can be fabricated that exhibit considerable annealing out of radiation damage at temperatures of 28°C or greater. Some major problems, however, exist with the lithium-doped cells, mainly in the area of long-term stability. The lithium ion is highly mobile in silicon, even at room temperature, and thus storage at room temperature and above can result in a redistribution of the lithium, especially near the P-N junction and at the back surface. Cells stored for periods of time have shown changes in electrical characteristics, and in the case of irradiated cells which have exhibited annealing out of damage, redegradation has occurred in some instances. The objective of this program is to investigate the applicability of dopants other than lithium for possible application in the radiation hardening of silicon solar cells, and to study the properties of lithium-doped silicon.

This program was previously reported under NASA Work Unit 120-33-01-20-55.

PROGRESS

A statement of work was developed, and a contract was awarded to Northrop Corporate Laboratories (JPL Contract 952523) in the amount of

$74, 765 to perform the work described above. The program is scheduled to be initiated in June 1969.

PUBLICATIONS

None

DYNAMIC STRUCTURAL INTERACTIONS OF SOLAR ARRAYS WITH ATTITUDE CONTROL SYSTEMS

NASA Work Unit 120-33-01-46

JPL 320-36001-0-3530
JPL 320-36002-0-3440

H. K. Bouvier
R. E. Oliver

OBJECTIVE

The objectives of this work unit are to study the compatibility of the lightweight solar arrays developed for planetary missions with the control requirements of space stations.

APPROACH

The approach taken was to first investigate the currently-proposed space station configurations and their methods of control and then to define structural configurations and control systems to be used in this study. To accomplish this, the work being done on manned space stations at the Langley Research Center and the Marshall Space Flight Center was reviewed.

PROGRESS

There is, at the present, no definite or preferred space station configuration. It is not expected that one will be defined in less than one year. It is clear, however, judging from the amount of activity in this area that control moment gyroscopes are the preferred, if not only, control method to be used on space stations. Even though these devices are non-linear, a linear approximation suitable for digital computer simulation is feasible.

PLANS

Based on these findings, it has been decided to investigate the stability of several hypothetical space station configurations. The Boeing LASA concept is to be used on the RCA Power System Module Space Station configuration. This configuration consists of the Apollo command and service module connected to a modular multipurpose space station. The solar arrays are arranged in an "H" configuration.

Also, it is planned to adapt a roll-up array to the RCA configuration. Further investigations will include a cluster of Apollo modules elastically interconnected.

PUBLICATIONS

None

RADIATION DAMAGE IN LITHIUM-DOPED SOLAR CELLS
CONTRACT E

NASA Work Unit 120-33-01-47

JPL 320-37001-2-3420

P. A. Berman

OBJECTIVE

One of the major concerns in the use of silicon solar cells for space is the fact that significant decreases in power can occur when the cells are subjected to irradiation by electrons and protons that exist in the Van Allen belts surrounding the earth and by proton flares that occur in deep space as the result of solar activity. Within the past few years, work on cells with lithium doping has indicated that cells can be fabricated that exhibit considerable annealing out of radiation damage at temperatures of 28°C or greater. Some major problems, however, exist with the lithium-doped cells, mainly in the area of long-term stability. The lithium ion is highly mobile in silicon, even at room temperature, and thus storage at room temperature and above can result in a redistribution of the lithium, especially near the P-N junction and at the back surface. Cells stored for periods of time have shown changes in electrical characteristics, and in the case of irradiated cells, which have exhibited annealing out of damage, redegradation has occurred in some instances. The objective of this program is to study the properties of lithium-doped silicon and to investigate the applicability of lithium and other dopants in the radiation hardening of silicon solar cells. This program was previously reported under NASA Work Unit 120-33-01-20-55. This program is essentially a parallel effort to that described under NASA Work Unit 120-33-01-44-55.

PROGRESS

A statement of work was developed and a contract awarded to TRW Inc., (Contract 952554) in the amount of $96,697 to perform the studies outlined above. The tentative start date is June, 1969.

PUBLICATIONS

None

RESEARCH AND DEVELOPMENT OF LITHIUM SOLAR CELLS CONTRACT E

NASA Work Unit 120-33-01-48

JPL 320-37101-2-3420

P. A. Berman

OBJECTIVE

One of the major concerns in the use of silicon solar cells for space is the fact that significant decreases in power can occur when the cells are subjected to irradiation by electrons and by protons that exist in the Van Allen belts surrounding the earth, and proton flares that occur in deep space as the result of solar activity. Within the past few years, work on cells with lithium doping has indicated that cells can be fabricated that exhibit considerable annealing out of radiation damage at temperatures of 28°C or greater. This phenomenon could be of great significance if the effect can be reproducibly controlled, stabilized, and accurately predicted. The objective of this program is to develop and fabricate radiation-resistant, high-efficiency, lithium-doped silicon solar cells for space use. The work was previously reported under NASA Work Unit 120-33-01-21-55.

PROGRESS

A statement of work was developed and a contract awarded to Heliotek Division of Textron (Contract No. 952547) in the amount of $62,136. The tentative start date is June 1969.

PUBLICATIONS

None

PHOTOVOLTAIC SUPPORTING DEVELOPMENT - CONTRACT B

NASA Work Unit 120-33-01-49

JPL 320-37201-2-3420

R. K. Yasui

OBJECTIVE

The interconnecting operation adds complexity and cost to solar cell module and panel fabrication, often exceeding original cell costs. This limits the usefulness of solar cells for terrestrial applications and is a major cost item in large size, high power spacecraft systems. It is desirable to improve interconnecting techniques in order to reduce costs, minimize environmental effects, and improve cell performance. Some approaches have included automated interconnecting, use of less expensive materials, simultaneous interconnecting and cell laydown on the substrate, or improved contracting materials and procedures which reduce cell costs, or simply interconnecting. The major objective of this work unit is to investigate and study various interconnect techniques. In conjunction with this, methods of application will be studied, together with more conventional contacts and processes. This information will then be used to develop improved economical solar cell matrices and/or solar arrays.

APPROACH

The development of an economical advanced integrated lightweight silicon solar cell array will make a significant contribution to the state-of-the-art. In fact, the solar cell has progressed faster than the complete system or array development. Consequently, the units of merit such as watts per pound and dollars per watt for individual silicon solar cells have been able to be significantly improved over the past years. Unfortunately, these improvements in cell performance characteristics, although significant when applied to the individual cell weights and costs, do not have the same impact on the complete solar array. State-of-the-art array fabrication designs and techniques result in an array weight about ten times the weight of the essential active device, and costs that are increased by more than a factor of two. Therefore, if progress is to be made in the reduction of weight and cost of silicon cell arrays, it must include studies of all components in the array and not be restricted toward the solar cell device alone. As a result of this study JPL Contract 952256, for approximately $85, 000, is presently being negotiated with Heliotek to study new materials and techniques to determine the proper approach for making a significant improvement in array designs. The complete program is expected to be separated into three related phases to facilitate adequate performance control and continuity. Phases I and II would be concerned primarily with materials and process development, refinement, and testing.

Each of these two phases would include the fabrication of a small solar cell array to demonstrate fabrication feasibility and a projection of tasks to be accomplished during the subsequent phase. Phase III would be devoted to hardware fabrication and testing to qualify the advanced concepts developed in the other two phases.

PUBLICATIONS

None

SOLAR THERMIONIC DEVELOPMENT

NASA Work Unit 120-33-02-01

JPL 320-30201-2-3420

O. S. Merrill
P. Rouklove
G. Stapfer
F. de Winter

OBJECTIVE

The objective of this program includes the development and evaluation of improved thermionic converters, the design, procurement, and evaluation of multiconverter generators, the parametric evaluation of converters and generators; the evaluation of new convertor accessories such as heat pipes and gas additives, and the life testing of converters and generators.

PROGRESS

Diode With Heat Pipe Collector

The effort, under JPL Contract 951263 with Thermo-Electron Corporation which was redirected to develop converters using a heat pipe as a collector radiator assembly and heat rejection medium, was successfully completed. A final report on the effort (TE4055-65-69) was released and distributed.

Six-Converter Geneator JG-4

After completion of the laboratory tests, the generator was installed in the vacuum system at the Table Mountain solar facility. The initial solar tests revealed that one of the converters was shorted to the mounting block. This was due to the faulty placement of thermal shields around the emitter support sleeve. The converter was subsequently replaced with a spare converter. Solar testing was further delayed due to the spring storms which caused heavy damage to the testing site and equipment. Testing of the JG-4 generator should be completed by September 15, 1969.

Converter Life-Tests

Six life-test stations continued to operate during this period. Converter SN-101 is continuing to operate after more than 20,000 hours of operation. The converter is operating at an emitter temperature of 2000°K and produces an average of 25 watts/cm^2 at 0.7 volt output voltage. The converter performance exhibits no discernable signs of degradation.

Analytical and Experimental Description of Parabolic Solar Concentrators

Work has continued on the analytical and experimental description of parabolic mirror performance. All the important Hartmann test data, calorimeter data, and flux intensity data are now reduced. The results seem to be of good quality. All comparisons between analytical and experimental results seem to be quite close. Reports on both the experimental and analytical efforts will be published shortly.

In the analytical work, representation of parabolic solar concentrators is made through the use of Monte Carlo ray tracing. Energy distributions can be calculated for any surface. Recently the Monte Carlo programs were used for extensive calculations on "concentrator photovoltaics", in which a parabolic concentrator was to be used to produce acceptable solar fluxes for the use of photovoltaics as far away from the sun as Jupiter. A report on this program will be released shortly.

Applied Thermionic Research

The final report on JPL Contract No. 952184 with Thermo-Electron Corp., Waltham, Mass., has been issued (Ref. 2). This report presents the work performed during the one-year period ending December 1, 1968. The primary objective of the program was the improvement of converter performance by a continuous interplay between theoretical analyses and experimental results. This work was a continuation of a NASA/JPL sponsored applied research program which has been in progress for several years. With the issuance of this final report, the program under NASA/JPL sponsorship comes to an end. The principal results were summarized in the previous semi-annual report. No further semi-annual reports on this program will be presented.

Advanced Thermionic Development

This effort is being performed by Electro-Optical Systems, Inc., a Xerox Company, Pasadena, California, under JPL Contract No. 952217. The principal objectives of this program are the identification and characterization of potentially high bare work function (and consequently low cesiated work function) electrode materials and the fabrication and testing of variable-spacing test vehicles and planar and cylindrical converters using such materials. A secondary objective has been the obtaining of a one-to-one correlation in performance between the test vehicle and the planar and cylindrical converters.

The principal accomplishments achieved during this reporting period follow:

(1) The effective bare work functions of several candidate tungsten alloy electrodes have been determined over a temperature range of 1800 to 2150°K. A comparison of the results at 2000°K is shown in Table I. The relatively high values for the iridium and osmium alloys, as well as the 5% tantalum alloy, would indicate the desirability of further investigation and characterization of these materials.

(2) The effective bare work functions of six samples of tungsten/22 to 26% rhenium (W/22-26 Re) have been measured. The average value at 2000°K, for comparison with the values in Table I, was 4.81 ±0.04ev. Extensive data have been taken on the test vehicle, particularly at the 10-mil spacing and 2000°K emitter temperature, the design point for the planar and cylindrical fixed-spacing converters. The planar and cylindrical converters have been built and preliminary testing of them was initiated toward the end of this reporting period.

(3) The second of two cylindrical converters (SN 109CB) has been fabricated and tested. Table II shows the comparison of the performance of planar converter SN 109 to both cylindrical converters SN 109CA and SN 109CB at 1800°K. All units have a 2.0 cm^2 emitter area, a 1.88 cm^2 collecting area at 6^{+1}_{-0} mil interelectrode space and have chemically vapor-deposited rhenium emitters and collectors.

Table I. Effective Work Function of Various Tungsten Alloy Electrodes at 2000°K

Sample	$\phi_{eff} \pm 0.04ev$
W-5%Re	4.91
W-15%Re	4.89
W-5%Ta	5.09
W-10%Ta	4.84
W-26%Ta	4.92
W-1%Ir	5.10
W-2%Ir	5.10
W-2.5%OS	4.99
2-5%Os	4.99

Table II. Comparison of Planar and Cylindrical Converters

	Planar SN109	Cylindrical SN109CA	Cylindrical SN109CB
Emitter Temperature (°K) (True Hohlraum)	1800	1800	1800
Voltage Output (volts)	0.40	0.40	0.40
Current Output (amps)	49	49	48
Power Density (watts/cm^2)	10.4	10.4	10.1

PUBLICATIONS

Contractor Reports

1. Gyftopoulos, E. P., et al, "Applied Thermionic Research", Thermo-Electron Corp., Waltham, Mass. Final Report No. TE 4092/3-108-69, JPL Contract No. 952184, covering the period of 1 December 1968.

2. Jacobson, D. L. and Hamerdinger, R. W., "Thermionic Research and Development Program", Electro-Optical Systems, Inc., A Xerox Company, Pasadena, California, Third Quarterly Progress Report, EOS Report No. 4006-Q-3, 3 February 1969.

3. Lieb, D., et al, "Applied Thermionic Research", Thermo-Electron Corp., Waltham, Mass., Third Quarterly Progress Report No. TE 4092/3-53-69, JPL Contract No. 952184, covering the period of 4 June 1968 to 4 November 1968.

4. "Design and Fabrication and Advanced Thermionic Converters", Thermo-Electron Corp., Waltham, Mass., Report No. TE 4055-65-69, Contract 951263, 3 November 1968.

SPS Contributions

1. Stapfer, G., "Electrical Testing of a Six-Converter Thermionic Generator", SPS 37-55, Vol. III, February 1969.

SOLAR POWER SYSTEM DEFINITION STUDIES

NASA Work Unit 120-33-05-01

JPL 320-30901-2-3420

H. Wick

OBJECTIVE

The over-all objective of this effort is to investigate the problems associated with developing spacecraft electrical power systems for unmanned planetary missions. The effort stresses the development of the technology required to solve system design problems associated with meeting JPL mission requirements. One task that is presently being undertaken is the investigation and development of computer programs for power system design and analysis.

PROGRESS

Recent activities have been directed toward the conversion of the Shephard's equation-double discharge curve computer program for use on the UNIVAC 1108 Executive 8-System of the JPL Scientific Computing Facility. A power profile computer program has been developed to aid in the analysis of power requirements for the Thermoelectric Outer Planet Spacecraft (TOPS). This computer program is similar in structure to the Mariner Mars 1971 power profile computer program which has been reported on in SPS 37-57, Vol. III.

Documentation is presently being prepared for several JPL computer programs. Current plans are to submit these codes to the Computer Software Management and Information Center (COSMIC), University of Georgia, for distribution.

PLANS

Current plans call for termination of this work unit at the conclusion of FY 69.

PUBLICATIONS

SPS Contributions

1. Wick, H., "Solar Power System Definition Studies," SPS 37-57, Vol. III, June 1969.

MARS SPACECRAFT POWER SYSTEM DEVELOPMENT

NASA Work Unit 120-33-05-04

JPL 320-32701-2-3420

H. Wick

OBJECTIVE

This program is directed toward the development of an optimum Mariner-class spacecraft power system to provide improved utilization of solar array power, greater reliability, and higher performance than the present Mariner Mars power system.

PROGRESS

As stated in the previous report, the Phase I study effort, performed by General Electric and TRW Systems, has been completed, and the contractor final reports have been distributed. Results of the Phase I effort have been reviewed by JPL. Although the contractors have improved the performance characteristics of Mariner-class power systems, these improvements are not significant enough to justify a Phase II hardware development effort. The results of Phase I are presently being examined for possible inclusion in the Viking '73 power system.

PUBLICATIONS

JPL Publications

1. Wick, H., "Mars Spacecraft Power System Development," SPS 37-55, Vol. III, February 1969.

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POWER CONVERSION CIRCUIT DEVELOPMENT

NASA Work Unit 120-33-08-04

JPL 320-34201-2-3420

D. J. Hopper

OBJECTIVE

The objective of this task is to increase reliability and efficiency and to reduce the weight of spacecraft power conditioning hardware. There are a number of circuit and functional element technology areas which, if improved, could greatly affect over-all power system performance. In particular, voltage regulator and converter performance is a key factor in determining power system weight, efficiency, and reliability. Much of the effort in this task will be directed toward improving regulator and converter performance characteristics.

PROGRESS

There are several items being investigated. The first item is a high-frequency converter. This converter is being designed to operate at a frequency between 50 and 100 kHz with an expected efficiency of approximately 90%. The input voltage is 28 Vdc with an output voltage of 50 Vdc. The output is 100 W. The reason for going to high frequency is to minimize weight and size. The switching losses in the transistors are being kept low by using the new high-power, high-speed devices currently available. Another item being investigated is a high frequency buck type regulator. The running frequency of the regulator is also between 50 and 100 kHz. The efficiency design goal is 90%. An input voltage of 40 to 80 Vdc will be bucked down to 28 Vdc with a power capability of 100 W.

A study is being made of saturation of inverter transformers. If the saturation voltages of the switching transistors are different, a net direct current will flow in the transformer, which may cause it to saturate. Selection of matched transistors would solve the problem, but there is no guarantee that the saturation voltage will remain the same after exposure to severe environments (radiation, temperature, etc.). The study is also attempting to determine the best transformer design to solve the problem.

Two types of buck-boost regulators, Figures 1 and 2, are being investigated. The configuration which appears to have the best characteristics will be breadboarded and tested. Both of these circuits operate by the same mechansim. Energy is stored in the inductor when the transistor is "on" and is transferred to the load when the transistor turns "off". The input voltage range is 23 to 80 Vdc and the output voltage is 56 Vdc. The output power is 400 W. This work on the buck-boost regulators is being done under Contract 952500 for $19, 079 with Wilorco, Inc.

Also part of this Wilorco contract is the development of an input current limiter for regulators and converters. The limiters will protect the power system from the excessive currents that would result from a shorted regulator or a converter. Once the current is limited, the power system can be repaired by inserting a redundant regulator or converter.

PLANS

In the future, spacecraft will undoubtedly get larger, requiring more power. Eventually the source voltage will have to be increased to keep the current levels tolerable. High voltages in the order of hundreds of volts would probably require the use of SCR's as power switches since transistors presently have limited voltage capabilities. As a result, regulators using SCR's will be investigated.

Transformer core losses are higher for a square wave than for a sine wave. One of the tasks to be performed will be to compare the different waveform losses over a range of frequencies for different types of core material.

From time to time, new devices are available in industry. It is also the intent of this task to search out and investigate any new piece part that might be used in power conditioning equipment.

PUBLICATIONS

SPS Contributions

1. Hopper, Donald J., "Power Conversion Circuit Development," SPS 37-57, Vol. III, June 1969.

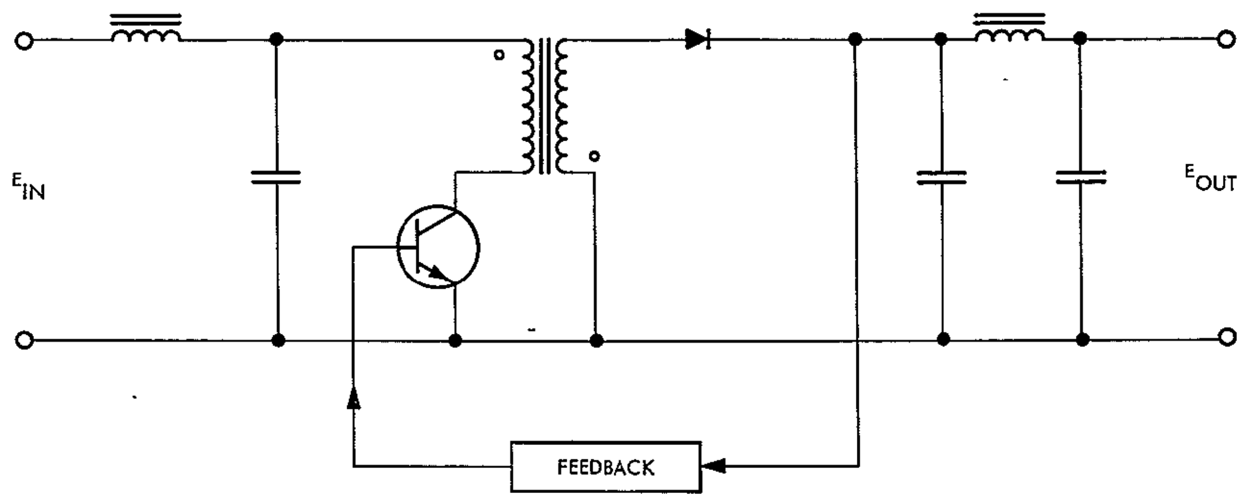

Figure 1. Type I Buck-Boost Regulator

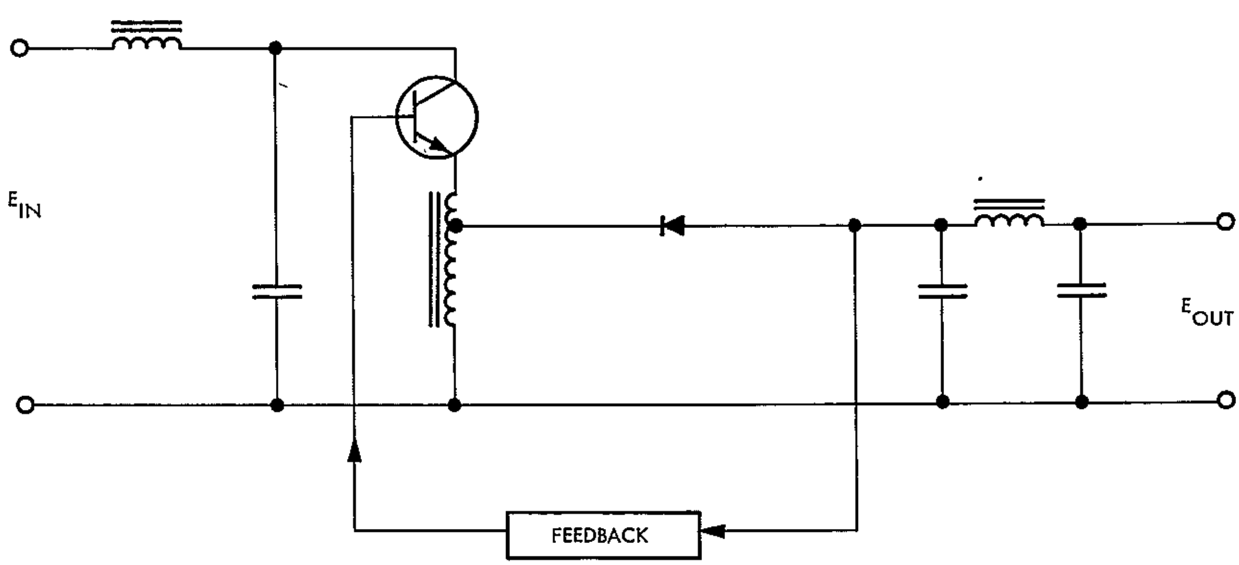

Figure 2. Type II Buck-Boost Regulator

VERIFICATION OF LOW SATURATION DROP TRANSISTOR

NASA Work Unit 120-33-08-05
JPL 320-32201-2-3420
A. Schloss

OBJECTIVE

The objective of this task is to develop high-current, low-saturation-drop silicon transistors which can be used to convert efficiently the low voltages from several types of power sources to higher voltage levels.

APPROACH

There are several sources of electrical energy that have output voltage in the range of 2 to 5 volts. To distribute power in an efficient manner, the voltage must be converted to higher levels, and to accomplish this, transistors are used as switches in dc to dc converters. To operate efficiently, these switches must have as low a saturation voltage drop as possible, at rated current. Germanium transistors do have very low saturation drops. However, permissible operating ambient temperatures must be quite low because of the maximum allowable junction temperature of germanium transistors. Such a constraint places severe design limitations on a spacecraft, which generally operates at the higher ambients permitted by silicon transistors. Silicon transistors do not in general exhibit low saturation drops. However, theory indicates that there is no inherent physical reason for their higher drops; therefore, it was decided to develop a silicon transistor with low saturation drop.

PROGRESS

During the past year the contractor pursued the double epitaxial base approach which was to yield higher absolute gains and thus reduce the saturation voltage. After some investigations, however, it was found that higher absolute gain did not produce any dramatic improvement in saturation drop. It turned out that the major problem in the thin wafer double epitaxial approach was not breakage, as initially predicted, but alloying through of the bonding solder. An improvement in the method of attaching the chip to the heat sink might have made useful the thin wafer approach which did show promise before the final bonding step.

A proposal to supplement the existing contract was received. The contractor proposed using several matched chips in one package as a simple way to achieve low-current density and hence low drop. After receiving JPL approval, the contractor pursued this method by mounting a single defused process chip in his special "Pow-R-disc." This package has advantages with respect to heat and current resistivity. Two of these packages are mounted in a special fixture (the "Pow-R-disc," requires external pressure to assure good contact). The units are matched to assure current sharing. No internal balancing resistors are used, since even in the absence of a good match either transistor alone is capable of the full rated current. The initial results show that the transistors are well within the requirement of 0.1V at 75 amperes except at 100°C junction temperature. It appears from the data that the unit would be completely in specification at temperatures as high as 75°C. A room temperature value of saturation voltage at 50 amperes is typically 70 millivolts. Total switching time is 7 μsec, or less at 75 amperes. The present contract calls for delivery of 37 transistors of this type by February, 1970.

These dual chip transistors have met the major objectives of this development.

PUBLICATIONS

Contractor Reports

1. Final Report, Contract No. JPL 952309, "Design and Development of a High Power, Low Saturation Voltage, Multi-Chip Silicon Switching Transistor," May 1969, Westinghouse Electric Co., Semiconductor Division, Youngwood, Pennsylvania 15697.

POWER PROCESSING ELECTRONICS LIFE AND PERFORMANCE EVALUATION

NASA Work Unit 120-33-08-11

JPL 320-36601-2-3420

A. Krug

OBJECTIVE

The objective of this new task is to determine the lifetime and performance degradation of carefully manufactured flight-quality hardware. The information obtained will be applied to the design of power-conditioning electronics (PCE) for the outer-planet missions requiring lifetimes of up to 12 years. Residual Mariner-Venus 1967 flight hardware will be life tested initially for 17 months, (≈500 days) to simulate a nominal trajectory to Jupiter. The life test will be performed in a vacuum, with decreasing temperature over the first 12 months. The temperature deviation (80 to 30°F) was chosen to simulate the worst case expected on an essentially sun-independent spacecraft bus.

Failures which occur in the PCE will be carefully evaluated to determine the mechanism of the failure, and to ascertain whether the failure was circuit induced, or if the part lifetime was exceeded.

Spare operational support equipment (OSE) maintained in the Mariner-Venus 1967 configuration will be used to provide inputs to, and monitor the outputs of, the power subsystem.

PROGRESS

The Boeing Company has been selected from seven proposers to prepare the necessary test procedure, provide facilities for and perform the life test, and to perform failure analysis if required. Negotiations have been completed, and a contract is expected prior to the end of August 1969. It is anticipated that preparatory work will be completed and the life testing started by October 15, 1969.

ANTICIPATED PUBLICATIONS

JPL Publications

1. Krug, A., "Long-Term Life Test of the Spare MV '67 Power Subsystem Hardware," SPS 37-57, Vol. III, June 1969.

PUBLICATIONS

None

CHEMICAL POWER GENERATION SYSTEMS (120-34)

REACTION GEOMETRY OF ALKALINE ELECTRODES

NASA Work Unit 120-34-01-01
JPL 320-40101-2-3420
G. L. Juvinall
A. A. Uchiyama

OBJECTIVE

The long-range objective of this task is to obtain a more fundamental understanding of the electrode processes involved in batteries using silver, zinc, and cadmium electrodes. The immediate objectives include studies of the mechanism of the oxidation and reduction of the alkaline silver electrode, variation of the effective electrolytic surface area as a function of physical stress, the nonuniformity of reaction of the alkaline electrode, and conditions for the formation and stabilization of silver III. These studies are directed toward the solution of problems which are pertinent to the design of more versatile and reliable batteries for spacecraft.

PROGRESS

The contract (942268) with Brigham Young University has been extended for a period of fifteen months at a cost of $27,879.00. The level of effort will be substantially the same as in the first period of this contract.

During this report period, further work has been done on the cyclic current-step method of determining the exchange current density, transfer coefficient and rate constant for the silver-silver oxide system. Measurements made during the Ag-Ag_2O oxidation gave results very similar to those obtained from other systems (Ag-$Ag(NH_3)_2^+$, and Fe^{+2} -Fe^{+3}) where the over-voltage is dependent upon diffusion of an electroactive species to the surface of an electrode. These results confirm the applicability of the method.

The ohmic resistance of the silver-oxide films formed in potassium hydroxide solutions at selected concentrations from 0.0543 to 10.9 molar have been measured. The maximum area-resistance of the oxide ranged from

0.31 to 0.16 Ω- cm^2. As this work is expanded, the results will be related to existing flight battery data.

The acceptance of charge by silver foil and wire electrodes as a function of applied potential under potentiostatic conditions has been measured. Three maxima were observed before oxygen evolution. At 0.66V., an elevenfold increase over the charge acceptance at 0.56V was observed.

The studies of the efforts of physical stress on the charge acceptance of silver electrodes have been discontinued. Preliminary results showed insufficient promise to warrant further work in this area.

PLANS

Future work will include further studies of the kinetic parameters of the silver-silver oxide system, a more extensive investigation of the variations of the silver oxide film resistance as related to battery cell behavior, and studies of techniques for the formation and stabilization of silver III. It is anticipated that the surface area studies will be completed during the next report period.

PUBLICATIONS

JPL Publications

1. Juvinall, G. L. "The Measurement of the Oxide Film Resistance of Silver Battery Electrodes" SPS 37-56, Vol. III, Feb. 1, 1969 to Mar. 31, 1969.

Contractor Reports

1. Butler, E. A., and Blackham, A. U. "Studies of Reaction Geometry in Oxidation and Reduction of the Alkaline Silver Electrode," Brigham Young University, Third Quarterly Report, Feb. 15, 1969 JPL Contract 952268.
2. Butler, E. A., and Blackham, A. U., "Studies of Reaction Geometry in Oxidation and Reduction of the Alkaline Silver Electrode,"

Brigham Young University, Fourth Quarterly Report, May 15, 1969. JPL Contract 952268.

HEAT STERILIZABLE BATTERY DEVELOPMENT

NASA Work Unit 120-34-01-03

JPL 320-40301-2-3420

R. Lutwack

OBJECTIVE

This program is directed toward the development of heat-sterilizable Ag-Zn batteries. The general objectives are: (1) to obtain information regarding the effects of heat sterilization on battery components, (2) to develop the technology for the design and fabrication of heat sterilizable and high-impact-resistant batteries, and (3) to produce batteries meeting flight program requirements. The program is comprised of two phases. Phase I includes studies of electrochemistry, case development, sealing techniques, cell design, cell fabrication, and cell testing. Phase II includes the design, fabrication, testing, and delivery of cells for heat-sterilizable and high-impact-resistant batteries.

PROGRESS

The major effort is being done under Contract 951296 with ESB Inc; this is supplemented by a JPL in-house effort. The program is divided into two main sections, one of which has the high-impact-resistance requirement in addition to that for heat sterilizability.

The following cells are being developed: (1) an 80 A-h primary; (2) a 25 A-h secondary (90 cycles at 50% depth-of-discharge (DOD); (3) a 48 A-h secondary (400 cycles at 50% DOD); (4) a 5 A-h high-impact-resistant primary; (5) and a 25 A-h high-impact-resistant secondary (90 cycles at 50% DOD). The progress which has been made in these developments is illustrated by the following results: (1) The capacity loss, which occurs at a high discharge rate, is minimized by the use of the stoichiometric ratio for the epoxy/catalyst formulation. (2) Framed grids are being used in the 80 A-h cell, which had previously performed with energy densities of 45 to 50 W h/lb but had failed vibration tests. (3) First model 48 A-h cells failed between 60 and 70 cycles due to separator deterioration at the plate edges and shorting through the separator. In addition, the Zn plate was 40 to 70% eroded. (4) If a heat cycle is used immediately after the electrochemical conversion of the Zn plate additive, the first cycle capacities after sterilization were only 5 to 7% below the values before sterilization. (5) A new sintered Zn plate containing Teflon has been fabricated. The new structure eliminates the need for a retainer, inhibits erosion, and is easy to handle. (6) Five 5 A-h cells, in which the packs had been sterilized, yielded in excess of 0.3 A-h/gm Ag after two years on float.

Efforts are continuing to improve all of the cells. Large numbers of 25 A-h and 80 A-h cells will soon be placed on extensive testing regimes.

PUBLICATIONS

<u>JPL Publications</u>

1. Lutwack, R., "Development of the Heat Sterilizable Battery," SPS 37-56 Vol. III, April, 1968.

STUDY OF SEPARATOR MEASUREMENTS

NASA Work Unit 120-34-01-05

JPL 320-40501-2-3420

W. von Hartmann

OBJECTIVE

The objective of this program is an in-house study of the properties of heat-sterilizable battery separators for the Ag-Zn battery. The study is required to establish meaningful criteria for the evaluation of candidate separator materials. The results will be used to describe the separator and its properties in detail and to establish criteria for quality control.

PROGRESS

Measurements of resistivity, tensile strength, dimensional stability, silver oxide diffusion, and wettability are continuing. In addition, some materials are being evaluated via spectroscopic measurements and by in-cell testing. Among the materials being studied are products from JPL contracts 951524 and 951966 with Monsanto Research Corp., and 951525 with Westinghouse Electric Corp. The greatest effort, however, is being concentrated on the polyethylene-based material stemming from JPL contract 951718 with the Southwest Research Institute.

The polyethylene-type separator can be made with good uniformity. Its resistance is low and its tensile strength is adequate. Its resistance to silver oxide diffusion, however, requires improvement. During the last year the equipment for reliable measurement of silver oxide diffusion via a radioisotope tracer technique has been assembled and tested. Initial experiments show that the rate of silver oxide diffusion through the polyethylene-type separator is about four times as high as through cellophane and that grafting with methacrylic acid instead of acrylic acid may reduce this diffusion. Measurements designed to relate, if possible, the crosslink density with the silver oxide diffusion rate are in progress. The results from these measurements will be used to guide research in progress at the Southwest Research Institute under JPL contract 951718.

A number of heat-sterilized cells containing a separator made by the Monsanto Research Corp., have been on charged open-circuit stand for the past six months without a failure. The separator is a copolymer of ethylene and ethyl acrylate.

PUBLICATIONS

None

HEAT STERILIZABLE REMOTELY ACTIVATED BATTERY

NASA Work Unit 120-34-01-06

JPL 320-40601-2-3420

W. von Hartmann

OBJECTIVE

The objective of this program is to develop a heat-sterilizable, remotely-activated battery capable of 200 W-h capacity. This battery should supply sufficient current at an output voltage range of 26 to 30 V dc for a 1200-W load for 10 min or a 500-W load for 24 min. The Ag-Zn system is considered as a first choice, but the study of other electrochemical systems is not precluded. In addition to the electrical properties, the battery will be designed to be sealed and capable of: (1) shelf storage for a minimum of one year at temperatures between -10 and +25°C, (2) being made ready for sterilization within 24 h, (3) a 9-mo storage period in the dry-charged state at temperatures between -10 and +60°C, (4) being brought from zero to operating voltage at full load within 2 min and standing at open circuit prior to the application of the load for up to 30 min, and (5) activation under conditions of 10^{-4} mm Hg between 20 and 45°C. The program comprises the design, development, fabrication, and testing of a heat-sterilizable, remotely-activated battery capable of meeting these requirements.

PROGRESS

Studies of the heat sterilizability of various cell components for the silver oxide-zinc cell have been completed. Silver oxide and zinc electrodes were sterilized, and it was found that the silver oxide electrode lost nearly 40% of its capacity through decomposition of the higher oxide at the sterilization temperature. The volume of oxygen thus produced cannot be safely accommodated in the cell and it was decided to pre-sterilize the electrodes. The zinc electrode shows no effects from sterilization. A sandwich of one layer of asbestos between two layers of hemp has been selected as the separator on the basis of extensive testing. A commercial copper tubing electrolyte reservoir filled with 31% KOH solution survived sterilization without damage.

A 583 AF propellant was tested and found to be heat sterilizable. For the case material, Polysulfone was selected.

The contractor is presently building cells from the components mentioned above. The cells will eventually be incorporated into a remotely activated heat-sterilizable battery. The present tentative design calls for plates 2.5 in high and 2.3 in. wide. There will be 9 to 13 plates per cell and 19 to 20 cells per battery. The separation will consist of the above mentioned asbestos hemp sandwich. The weight is estimated to be 12 to 14 lb including all activation hardware and outer stainless steel battery case. After sterilization this battery will deliver about 12 A-h.

PUBLICATIONS

Contractor Reports

1. "Heat Sterilizable, Remotely Activated Battery Development Program," Eagle-Picher Industries, Inc., Second Quarterly Report, January 1969; Third Quarterly Report, April 1969.

GRAVITY EFFECTS ON BATTERIES

NASA Work Unit 120-34-01-07

JPL 320-40701-2-3420

G. L. Juvinall
A. A. Uchiyama

OBJECTIVE

The primary objective of this task is to investigate the effects of gravitational forces on the performance characteristics of batteries. Of special interest will be gravity conditions related to planetary encounter and landed operations on extraterrestrial bodies. It is anticipated that knowledge will be obtained by this program which will enable the design of batteries uniquely suited to mission requirements.

PROGRESS

The previous report described the capabilities of a breadboard unit which was designed and fabricated by the General Electric Research and Development Center to investigate the effects of low-gravity environments on batteries and battery electrodes. Preliminary testing of the breadboard unit at JPL has been completed for those components which implement the studies of smooth zinc electrodes and commercial silver-zinc cells. The performance of the equipment to-date has been excellent. Testing of the components which relate to the electrode bubble studies has been initiated.

Silver-zinc cells which have been subjected to charge-discharge cycling at selected sustained high-g levels have been returned to JPL from the U.S. Naval Ammunition Depot, Crane, Indiana, and dissected. Study of the negative electrodes showed that removal of the active material from the upper regions of the electrodes was greatly enhanced in high-g environments. A definite increase in the shape changes of the negative electrodes due to cycling in high-g environments was observed in the range of 1 to 20 g's. At higher-g values, in the range of 20 to 75 g's, further shape changes were not apparent, although measurements of the electrode thickness showed that more active material is lost from the electrodes at the higher-g levels.

Limiting current data were also obtained on silver zinc cells in sustained high-g environments. These data are now undergoing computer analysis.

Future work will include the design and fabrication of a prototype flight model of the reduced gravity battery test unit. In addition, the high-g tests will be extended to starved silver-zinc cells. The required cells have been procured and shipped to the U.S. Naval Ammunition Depot at Crane where the centrifuge work will be performed in the near future.

PUBLICATIONS

JPL Contributions

1. Juvinall, G. L., and A. A. Uchiyama, "The Effects of Sustained High-Gravity Environments on Silver Oxide-Zinc Cells," SPS 37-55, Vol. III, February, 1969.

Contractor Reports

1. Final Report, "Reduced Gravity Battery Test Program," General Electric Research and Development Center, Contract 952121, May, 1969.

BATTERY ENGINEERING STUDIES

NASA Work Unit 120-34-01-09

JPL 320-40901-2-3420

W. L. Long

OBJECTIVE

The objective of this task was to determine optimum battery designs based on anticipated mission requirements. This task was maintained as an active task for the purpose of obligating previously committed funds. The work resulting from the procurements is described under NASA Work Unit 120-34-01-15-55, Advanced Battery System Development.

PUBLICATIONS

None

HEAT STERILIZABLE NICKEL-CADMIUM CELLS

NASA Work Unit 120-34-01-10

JPL 320-41001-2-3420

R. Lutwack

OBJECTIVE

This program is directed toward the development of heat-sterilizable nickel-cadmium batteries. The general objectives are: (1) to obtain information regarding the effects of heat sterilization on battery components, (2) to develop the technology for the design and fabrication of heat-sterilizable and high-impact-resistant batteries, and (3) to produce batteries meeting flight program requirements. The program is comprised of two phases. Phase I includes studies of electrochemistry, terminals, and cell design, fabrication, and testing. Phase II includes the design, fabrication, testing, and delivery of cells for heat-sterilizable and high-impact-resistant batteries.

PROGRESS

This program is being performed under Contract 951972 with Texas Instruments Inc. The program is divided into two main sections, one of which has the high-impact-resistance requirement in addition to that for heat sterilizability. The only cell under development is a 25 A-h size.

The progress which has been made in these developments is illustrated by these results: (1) These conclusions were derived from a fractional factorial experiment in which the variables were the separator material, KOH concentration, percent pore fill with solution, sterilization and rate of discharge: (a) The dominant factor influencing performance is sterilization. (b) Sterilization causes increases of 20% in efficiency above that prior to sterilization, of about 60 mV in the end-of-charge voltage, and of the pressure during charge. (c) Only one available separator material, a polypropylene, provides satisfactory cell performance after sterilization. (2) Seventeen plate 4 A-h cells have been cycled 131 times with stable capacities, high end-of-charge voltages of about 1.47V, and efficiencies of about 80%. (3) The efficiencies of the prismatic and cylindrical 25 A-h cells are comparable to non-sterilizable cells. (4) The prismatic 25 A-h cell yields 13-16 Wh/lb after sterilization with concomitant high end-of-charge voltage and pressure. (5) The cylindrical 25 A-h cell yields 10-16 Wh/lb after sterilization without end-of-charge voltage or pressure abnormalities.

PLANS

Efforts continue to reduce the high end-of-charge voltage and pressure values on the prismatic cells and to improve performance and uniformity on the cylindrical cells. Both types will soon be placed on extensive testing regimes.

PUBLICATIONS

JPL Publications

1. Lutwack, R., "Development of the Heat Sterilizable Battery," SPS 37-56, Vol. III, April, 1969.

Contractor Reports

1. Elder, J. P., et al., "Heat Sterilizable Ni-Cd Battery Development," Texas Instruments Inc., Report for Fifth Quarter, September, 1968.

HEAT STERILIZABLE BATTERY CASE DEVELOPMENT

NASA Work Unit 120-34-01-11

JPL 320-41101-2-3420

R. Lutwack

OBJECTIVE

This program was for the development of a heat-sterilizable separator and a sealed case for the heat-sterilizable silver-zinc battery described by NASA Work Unit 120-34-01-03. The sealed case development was a backup effort to that of Contract 951296 with ESB Inc.

PROGRESS

As stated in the last report, this effort was performed under Contract 951091 with the Narmco Division, Whittaker Corp. Tensile samples of poly 2, 2' — octamethylene — 5, 5' — bibenzimidazole were delivered to JPL and were evaluated by JPL as a potential case material. Since the properties were not superior to those for polyphenylene oxide, which is currently being used as the case material, no further work is contemplated with these polymers.

PUBLICATIONS

None

BATTERY SEPARATORS INCORPORATING CHELATING GROUPS

NASA Work Unit 120-34-01-12

JPL 320-41201-2-3420

R. Lutwack

OBJECTIVE

The objective of this work unit is to develop a separator for the heat-sterilizable Ag-Zn battery, described by NASA Work Unit 120-34-01-03.

PROGRESS

An investigation of films fabricated from polymers containing chelating groups consisted of a research and development phase and a limited production phase. The work was accomplished under JPL Contract 951524 by the Monsanto Research Corporation. The films were evaluated at JPL, and found to be unusable for separator materials because of dimensional changes caused by sterilization. No further effort in this work unit is planned.

PUBLICATIONS

None

COMPOSITE MEMBRANE DEVELOPMENT FOR HEAT STERILIZABLE BATTERY SEPARATORS

NASA Work Unit 120-34-01-13

JPL 320-41301-2-3420

R. Lutwack

OBJECTIVE

The objective of this work unit is to develop a separator for the heat-sterilizable Ag-Zn battery, described by NASA Work Unit 120-34-01-03.

PROGRESS

The work consisting of a research and development and a limited production phase was done under JPL Contract No. 951525 by the Westinghouse Electric Corporation. The films have been evaluated at JPL, and it was found that flaking of the composite occurred, rendering the films unusable for separator materials. No further effort on this work unit is planned.

PUBLICATIONS

None

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RADIATION GRAFTED POLYETHYLENE SEPARATORS

NASA Work Unit 120-34-01-14

JPL 320-41401-2-3420

W. von Hartmann

OBJECTIVE

This is a program to develop a separator for the heat-sterilizable Ag-Zn battery, described by NASA Work Unit 120-34-01-03. It consists of a research and development phase and a production phase.

PROGRESS

The preparation of separator materials from polyethylene grafted with acrylic acid using radiation from a Co^{60} source is being studied under JPL Contract No. 951718 with the Southwest Research Institute. Investigations of some of the parameters involved in the grafting and crosslinking of the polyethylene have led to the following conclusions: (1) The dose rate and total dose for irradiation grafting with acrylic acid have been standardized at 0.012 Mrad/h and 0.815 Mrad, respectively; (2) the grafting can be done in aqueous solutions if a gel inhibitor is used; (3) the temperature during neutralization and washing has an effect on the properties of the separator; treatment at 97°C results in a better material than treatment at 80°C; (4) Dow 400 polyethylene film yields a more uniformly grafted separator than the previously used polyethylenes; (5) cotton cheese cloth is superior to paper toweling as an interlayer material during grafting and crosslinking; and (6) polyethylene film has been grafted successfully with methacrylic acid, acrylic acid/N-vinylpyrrolidone mixtures, acrylic acid vinylpyridine mixtures, and acrylic acid/sodium vinylsulfonate mixtures.

A machine which neutralizes and washes continuous lengths of separator material has been assembled and tested. It is now in operation, and is used for processing all of the material from the production phase of the contract; 12, 000 ft of the material, which is processed in 14 in. wide 100 ft long rolls, have been made to date. Work toward the improvement of the material is continuing with emphasis on reducing silver oxide diffusion through the separator.

PUBLICATIONS

SPS Contributions

1. Lutwack, R., "Heat Sterilizable Battery Development," JPL SPS 37-56, April 1969.

Contractor Reports

1. "Development of Battery Separator Material Process," Southwest Research Institute, Quarterly Report, April 10, 1969.
2. "Development of Battery Separator Material Process," Southwest Research Institute, Interim Report, May 29, 1969.

ADVANCED BATTERY SYSTEM DEVELOPMENT

NASA Work Unit 120-34-01-15

JPL 320-41501-2-3420

R. Patterson
A. Uchiyama

OBJECTIVE

This task has two major objectives. The first is to develop batteries capable of meeting the life requirements for complex and long-duration missions; the second is to develop the battery system technology which will permit greater control over batteries used on these missions. Future missions — especially those contemplated by the NASA/JPL to the outer planets — will impose much more severe requirements on the flight batteries due to the complexities of the spacecraft and to the longer periods of the missions. Current model flight batteries and battery systems will not meet these requirements. Consequently, the overall purpose of this task is to develop the technology which will permit the design and fabrication of batteries and battery systems suitable for future missions. This task will be specifically directed toward obtaining cell and battery data simultaneously. The total system will then be capable of automatically sensing and analyzing impending failures in time to prevent or correct cell and battery malfunctions during the mission.

PROGRESS

Tests of the Mariner-type monoblock are continuing. Efforts from the platelock development phase of Contract 951927 have led to the recommendation of Furane Plastics epoxy system Epocast 221/927 as a suitable platelock material for Mariner-type monoblocks. Ten monoblocks each of seven designs have recently been obtained to evaluate materials which have shown some promise of improving cycle life of silver-zinc cells. The material variations include type of separator, electrolyte additives, and negative electrode Teflon content. These monoblocks will be placed on tests simulating operational requirements of future missions.

The storage optimization and design studies are continuing at the U.S. Naval Ammunition Depot at Crane, Indiana. As this program is only about one quarter completed, it is too early to draw definite conclusions. Tests have been made on six of the eighteen remotely-activated silver-zinc batteries (Eagle Picher GAP 4184) sent to Crane. Five of the batteries were tested to determine stand life after activation. The tests showed that the batteries have activated stand capacity of at least four days. One battery was subjected to sterilization temperature of 257°F for 24 hours and then failed to activate because the squib failed to ignite. The remaining twelve batteries are on storage tests at temperatures of 68, 105 and 150°F.

A data reduction computer program has been written for use on data acquired on magnetic tape by the battery data acquisition system at JPL. Data are automatically sorted, converted, tabulated and plotted

Test results on the breadboard unit for monitoring individual battery cells during flight indicated a minor design change was necessary. The change has been made and the unit is now undergoing a life test simulating flight conditions.

ESB Inc., Raleigh, North Carolina was awarded Contract 952472 for the development of a long-life, high-cycle-life, sealed silver-zinc battery. The total amount allotted was $59,333. The major design goal is the development of a sealed silver-zinc battery capable of 100 or more charge/discharge cycles at 50% depth of discharge after seven months of activated stand operating in a temperature range of 50° to 100°F. Sixty cells equally divided into twelve different design groups are now being fabricated. Design considerations include type of separator system, electrolyte concentration, active material ratio, and negative electrode contour. Future work on this contract includes testing of the 60-cell design matrix and the fabrication and testing of 5 batteries, one each of the five most promising designs from the design matrix.

Developing batteries for long and complex missions requires long life tests. This poses severe restrictions on development since a complete evaluation of a design cannot be made until a life test has been performed. With the intention of reducing time required for testing, accelerated testing techniques will be studied. Silver-zinc battery development is at a point where positive indications have been given as to the feasibility of using such a system on orbiter-type missions. More work needs to be done, however, and additional support will be given to silver-zinc development. Future work also includes studies of other systems such as silver-cadmium, nickel-zinc, nickel-cadmium, zinc-air, mercury-cadmium, and lithium-copper fluoride.

PUBLICATIONS

SPS Contributions

1. Patterson, R. E., Bogner, R. S., "Charge-Discharge Controller and Data Acquisition System for Electrochemical Cells and Batteries," SPS 37-55, Vol. III, page 112, February, 1969.

Contractor Reports

1. Farris, C. D., "Development of Improved Platelock for Mariner Type Sealed Ag0-Zn Cells," ESB Report No. E-2-69, ESB Inc., Exide Missile and Electronics Division, January, 1969, JPL Contract No. 951927.

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STATE-OF-CHARGE INDICATOR FEASIBILITY STUDY

NASA Work Unit 120-34-01-16

JPL 320-41601-2-3420

S. Krause
A. A. Uchiyama

OBJECTIVE

For any space mission that uses batteries as one of its sources of power, it is highly desirable to know the exact amount of battery power available for use at any time, particularly during critical periods of spacecraft operation such as launch, maneuvers, encounter, landing, and data playback. The need for state-of-charge indicators cannot be overemphasized, since it is possible that the performance of these critical phases may depend upon a knowledge of available power from the battery. The prime objective of this task is to develop techniques whereby the available energy output of a battery may be determined at any time, and with particular emphasis on measuring devices which may be incorporated as a part of the battery. At the present time, emphasis is on development of state-of-charge indicators and measuring techniques for silver-zinc batteries.

PROGRESS

Silver electrodes were procured to evaluate further the observed correlation between charge-state and infrared absorption, as previously reported. No further laboratory work was accomplished in this report period since available Attenuated Total Reflectance (ATR) spectroscopy equipment was being fully utilized by the Biosatellite Program. At the present time, there are no plans to continue work under this task number. However, future plans have been formulated for additional work in the state-of-charge indicator area, including investigations of the infrared absorption properties of silver electrodes using ATR and "light pipe" combinations, rotating electrode studies of thin silver film absorption characteristics, and investigations into miniaturized infrared emitters and detectors.

ANTICIPATED PUBLICATIONS

1. Krause, S. J., "State-of-Charge Indicator Investigations," SPS 37-57, Vol. III, June, 1969.

PUBLICATIONS

None

REACTIONS OF ZINC, CADMIUM, AND SILVER ELECTRODES

NASA Work Unit 120-34-01-17

JPL 320-41701-2-3420

G. L. Juvinall
A. A. Uchiyama

OBJECTIVE

The primary objective of this task is to obtain a more fundamental understanding of the electrode processes involved in silver, zinc, and cadmium electrodes. The studies included in this task are directed toward the solution of problems to pave the way for design of more reliable and versatile batteries and development of new battery systems. Immediate plans include further overpotential studies with particular emphasis on gassing. A major objective of this effort is the extension and expansion of studies on liquid-amalgam electrodes. The discovery of the liquid mercury-potassium electrode by the principal investigator during the earlier phase of this effort has made this area of study possible. Such electrodes appear to be particularly useful in applications where very high peak currents are required.

PROGRESS

Electrode gassing studies continued during this report period. Recent data indicate that the extrapolated exchange current density i_o, for the hydrogen overpotential on zinc, is much greater in 10N KOH than in 1N KOH solutions. In 10N KOH, i_o is greater than 100 $\mu A/cm^2$. This fact suggests a greater problem with hydrogen evolution during overcharge conditions at electrolyte concentrations normally used in alkaline cells than would be found at lower concentrations.

The liquid amalgam electrode work has now been extended to open-circuit potential studies. Open-circuit potentials for Na(Hg) electrodes were measured for systems with electrolyte concentrations ranging from 5 normal to saturated solutions. In addition, the measurements included electrodes at various states of charge. The potentials changed in the direction predicted by the Nernst Equation. However, for a reversible electrode at high amalgam concentrations, the changes were greatly in excess of the predicted values. This is not unexpected because the amalgams are approaching or have reached saturation, and activity coefficients would be expected to change rapidly with concentration. At low concentrations, ideal behavior may be approached. At present, there is no information about the metal activities in the amalgams at room temperature.

Maximum open-circuit potentials of the sodium amalgam electrode ranged from -1.91 V vs Hg/HgO in 5N NaOH to -1.72 V in saturated NaOH. It was observed that the maximum potential was established by the time the electrode was charged to 27% of its full capacity in the more concentrated electrolyte systems. In the 5N NaOH systems the maximum was developed at 15% of full charge.

Future work will include additional stand life measurements for all amalgam systems, more precise correlations of electrode open-circuit potentials with amalgam and electrolyte concentrations, and measurement of metal activities in both amalgam and aqueous phases.

Discharge rates will be pushed to their limits by using smaller electrodes and by using power supplies with higher current capabilities. It is expected that limiting current densities will exceed 1200 mA/cm^2.

PUBLICATIONS

JPL Publications

1. Juvinall, G. L., "Liquid Amalgam Electrodes," SPS 37-55, Vol III, p. 105, December 1, 1968 to January 31, 1969.

Contractor Reports

1. Arcand, G. M., "Investigation of Electrode Materials for Alkaline Batteries," Idaho State University Third Quarterly Report, February 25, 1969, JPL Contract 952265.
2. Arcand, G. M., "Investigation of Electrode Materials for Alkaline Batteries," Idaho State University Fourth Quarterly Report, May 25, 1969, JPL Contract 952265.

CHEMICALLY GRAFTED POLYETHYLENE SEPARATORS

NASA Work Unit 120-34-01-18

JPL 320-41801-2-3420

R. Lutwack

OBJECTIVE

The objective of this program was to develop a separator for the heat-sterilizable silver-zinc battery described by NASA Work Unit 120-34-01-03. It was comprised of a research and development phase and a phase for limited production.

PROGRESS

The effort, which includes the synthesis of ethylene/methyl acrylate copolymers by high-pressure mass copolymerization, conversion of the copolymers to thin films, vulcanization of the film, and saponification, was performed under JPL Contract 951966 with the Monsanto Research Corp. Evaluation of the films continues with some promising results. A final determination of their usefulness will be made, probably by incorporation in electrochemical cells.

PUBLICATIONS

None

STUDY OF PERMEABILITY CHARACTERISTICS OF MEMBRANES

NASA Work Unit 120-34-01-20

JPL 320-42001-2-3420

R. Lutwack

OBJECTIVE

The objective of this work unit is the study of the permeability characteristics of membranes as a function of the application of different forces and includes a detailed theoretical application of thermodynamics of the steady state to transport across membranes and an experimental determination of the derived relationships.

PROGRESS

This study is being done under JPL Contract No. 952109 with the University of California at Berkeley.

The transport cell, which is equipped with feedback mechanisms to keep the concentrations in the compartments constant, has been shown to meet all design specifications. The conductance of the cell solutions is held between maximum deviations from the initial state of +0.02% and -0.01% for the donating side and of -0.03% and +0.01% for the receiving side. The temperature in either cell half is held to within ±0.01°C of the starting temperature, this uncertainty adding ±0.02% to the concentration uncertainty unless a temperature compensation of the conductance is applied. Data have been obtained for NaCl solutions and an AMF membrane. Experiments will be done with alkaline solutions containing Ag and Zn species and the polyethylene battery separator material.

PUBLICATIONS

SPS Contributions

1. Lutwack, R., "Development of the Heat Sterilizable Battery," SPS 37-56, Vol. III, April, 1969.

Contractor Reports

1. Spiegler, K. S., et al., "Study of Permeability Characteristics of Membranes," University of California at Berkeley, Quarterly Progress Report No. 5, February, 1969.

2. Ibid, Annual Report, November, 1968, Contract 952109.

BASIC ELECTROCHEMISTRY STUDIES

NASA Work Unit 120-34-01-22

JPL 320-42201-2-3420

R. Lutwack

OBJECTIVE

This program for basic electrochemistry studies of the Ag-Zn cell consists of tasks for: (1) studies of oxidation and reduction mechanisms, crystallographic and electrical properties, and rate of dissolution using Ag_2O crystals, (2) studies of dendritic growth and oxidation and reduction mechanisms of fresh zinc surfaces, (3) studies of the frequency response of the Ag-Zn battery, i.e., the transient overpotential and the over-all frequency vs impedance behavior of a rotating disc redox system; the impedance during the charging process as correlated with dendritic formation; and the frequency response as correlated with the battery condition, (4) studies of the diffusivity of the zincate ion in alkaline solutions as functions of temperature and concentration, and (5) studies of diffusivities in battery separators using a modified rotating disc method.

PROGRESS

A contract to perform these studies is being negotiated with the University of Pennsylvania.

PUBLICATIONS

None

124

SPACE VEHICLE SYSTEMS SRT (124)

SPACE VEHICLE AEROTHERMODYNAMICS (124-07)

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PLANETARY ENTRY GAS DYNAMICS

NASA Work Unit 124-07-01-01

JPL 324-71401-0-3530

J. M. Spiegel

OBJECTIVE

This task has had the general objective of reducing uncertainties in predicting heat transfer and aerodynamic behavior during planetary entry in areas where these factors are considered important to the science payload of an entry vehicle. The work unit was terminated July 1, 1969. During the present report period, primary areas of activity were in development of rapid techniques for (1) screening and optimizing descent stages for gross landed payload weight, and (2) accurate calculation of graphite ablation rates.

PROGRESS

Approximate Entry Screening and Optimization Program

Selection of stage-to-total mass ratios, staging velocities, and total entry weight have a very strong effect on landable payload. A simplified computer program which will maximize landed payload weight for a given class of planetary atmospheric entry missions is under development. The objective of the program described herein is to coordinate selection of the gross design features of the entry stages as they are performance-related through staging conditions. Three stages, namely: entry capsule, parachute, and impact attenuator, are considered during this development phase. Only a minimum set of mission constraints is imposed.

Input Information

(1) Initial mission conditions:
- (a) Entry velocity
- (b) Path angle
- (c) Atmosphere and planet

(2) Stage design parameters:

(a) Maximum deployment acceleration

(b) Maximum impact acceleration

(c) Maximum capsule diameter

(d) Maximum parachute diameter

(e) Capsule and parachute drag coefficients and shapes

(f) Maximum impact attenuator stroke

(g) Payload density and shape (sphere)

(h) Materials properties

Methods

(1) First the ballistic coefficient (BCE) required for a single entry capsule stage to impact at a trial parachute deployment velocity, V2, is determined.

(2) Adding a second stage (parachute) and its trajectory, that minimum deployment altitude and maximum corresponding capsule BCE is found which will allow a parachute of maximum allowable size to impact at a required trial impact velocity, VI.

(3) Adjustments in BCE to meet a required maximum deployment acceleration (DA) are made, if necessary.

(4) Maximum ballistic coefficients of total entry vehicle and parachute stage are now known. Entry weight and weights of capsule and parachute are next calculated.

(5) BCE is decreased incrementally from step 4 until an impacted weight (WI) consisting of impact attenuator and payload is achieved. Then a maximum WI is found by iteration of BCE.

(6) WI is further optimized by repeating steps 2 through 5 over a range of parachute deployment velocity, V2.

(7) Having the maximum possible WI (total weight of impact attenuator and payload), the fraction of WI which will be devoted to hemispherical crushable material protection, in order to keep payload acceleration below a specified peak level, is calculated assuming the originally specified impact velocity, VI. Then steps 2 through 7 are repeated to maximize payload versus VI.

All elements of the program have been written in FORTRAN II and independently operated on an SDS 940 computer such as to solve seperate test problems in each individual area. Integration of the subroutines has been carried through the middle of step 6 of part B above, giving plausible outputs.

PLANS

Weight calculation methods currently used are valid only for planet Mars at direct entry path angles. Work to broaden these capabilities, economize on run time, and test the effect of different computational strategies on performance prediction accuracy is contemplated under a different funding source.

Graphite Ablation Program

A computer program has been developed to quickly and accurately determine graphite ablation rates for planetary entry into atmospheres composed of arbitrary ratios of N_2 and O_2, or N_2 and CO_2. Ablation is assumed to be quasi-steady; that is, the heat conducted into the graphite is assumed equal to m_w x $(h_{c_s} - h_{c_i})$, where m_w is the ablation flux and h_{c_s} and h_{c_i} are the enthalpies of an infinitely thick carbon slab at the surface and at $-\infty$, respectively (alternatively, the heat conducted into the graphite may be specified). Equilibrium is assumed at the surface, and oxidation, nitration and sublimation (of species C through C_5) reactions are included.

The program has been designed to operate via teletype on a timesharing computer system. A number of input-output formats has been used, but typically, for stagnation point ablation, input information required are atmospheric composition (arbitrary N_2-O_2 or N_2-CO_2 mixtures), radiative heating rate, surface emissivity, ambient density, vehicle nose radius and vehicle velocity. The output then gives ablation rate, convective blocking factor, surface temperature and gas composition at the surface, among other information.

Calculations for typical Venus and Earth entry conditions have agreed quite well with a much more complex and detailed equilibrium boundary layer computer program (Aerotherm Corp. BLIMP program), and it is felt that the speed and conversational mode of subject program make it suitable for preliminary design calculations. It would be desirable in the future to adapt the program to a simplified treatment of charring ablators and to eliminate the need for the quasi-steady ablation assumption by incorporating a simplified transient conduction routine.

ANTICIPATED PUBLICATIONS

(1) Spiegel, J. M., Wolf, F., and Zeh, D. W., "Simulation of Venus Atmospheric Entry by Earth Re-Entry," Journal of Spacecraft and Rockets.

PUBLICATIONS

None

PLANETARY ENTRY AEROTHERMODYNAMIC RESEARCH

NASA Work Unit 124-07-01-04

JPL 324-70800-2-3730

F. R. Livingston

OBJECTIVE

Knowledge of radiative flow fields and heat transfer is necessary to determine the feasibility of any mission requiring vehicles to enter a planetary atmosphere. To obtain this needed basic aerothermodynamic information, a program involving both experimental and theoretical work is under way.

PROGRESS

Jupiter Atmospheric Entry

Experimental facilities were further developed for studying the radiative intensity of Jovian atmospheric gases at very high temperatures. The close-coupled annular magnetic arc driver (CAMAD) flow simulation model was completed and preliminary measurements were made to determine the mass-flow rates. The prototype model of the driver chamber was completely fabricated and is soon to be installed in a newly acquired 60- by 30-ft laboratory space. Shake down and calibration tests of the prototype model will be made during the next fiscal year.

Results of Jupiter experimental work were presented at the AIAA 7th Aerospace Sciences Meeting in January, 1969.

Heating Rate Measurements in Air and Venus Atmospheric Gas

Convective plus radiative shock tube model stagnation point heating rate measurements were completed. Platinum thick-film calorimeter gages, both uncoated and carboncoated, sensed the heat flux on the external surface of the hemispherical and truncated-cylinder models. This thorough experimental study of total heat flux provided quantitative data necessary to verify existing theoretical radiative flow-field methods. In contrast with past experiments, the radiative flux emanating from 2π steradian solid angle at all wavelengths is a significant fraction of the total heating measured by the calorimeter.

Experimental thermochemical and geometric conditions were systematically changed in order to interpret the results in terms of convective heating, radiative heating, and coupling effects. At tempertures between 12,000 and 15,000°K, the measurements agree with theoretical uncoupled convective heating summed with isothermal radiative flux reduced by a radiative cooling factor. At lower temperatures, the measured heating was considerably more than expected, especially in air.

Results were presented at the AIAA 4th Thermophysics Conference June 18, 1969. JPL is now preparing to measure the distributed radiative plus convective heating over the 5-in.-D. hemisphere models now in use as an extension of this work.

Air and Venus Atmospheric Gas Radiative Intensity

Radiative intensity calculations have been performed for the major atomic processed in plasmas containg mixtures of carbon, nitrogen, and oxygen. The actual spectral detail was computed from 240 to 30,000°A for the continuum and line contributions. The radiative contribution of each continuum process as well as the contribution of each line was calculated from 600 to 1,700°A, accounting for reabsorption.

A report on the Venus atmosphere radiative intensity calculations is being prepared for publication.

Non-Equilibrium and Equilibrium Thermochemistry

Three volumes of the report "Shock Tube Thermochemistry Tables for High Temperature Gases" were written. The first was for air and the second was for a Venus atmosphere mixture containing 90% CO_2 and 10% N_2. Tables for argon, neon, and helium were also generated. A report entitled "The Computation of Partition Functions and Thermochemistry Data for Atomic, Ionic, Diatomic, and Polyatomic Species" was written by Prof. T. E. Horton.

The study of diagnostic techniques for shock tube applications has continued. Four time-integrated spectrograms of shock-heated argon were obtained in the free piston shock tube. At 12,000°K several argon lines were identified in the visible spectrum. The atomic line at 4,159°A is very intense and well isolated from other strong lines. It will be used in an attempt to measure the plasma temperature behind the incident shock wave by the line-to-continuum method. The appropriate line-to-continuum equations for argon are being programmed.

The study of nonequilibrium phenomena in a strong shock wave has also continued. An analytical investigation on the effect of water vapor contamination in shock tube experiments was initiated. Preliminary results indicated that small concentrations of water vapor can decrease the electron density of air by a factor of 5 at some shock velocities.

Nitrogen, Oxygen, and Carbon Continuum Radiation Calculations and Measurements

Interpretation of our experimental measurement of the photoionization cross sections of N, O, and C atoms has been hampered by the unknown radiative cooling effect on our calibrating He line intensity. In order to understand and account for this phenomenon, a fairly sophisticated model for one-dimensional flow of a nonviscous, nonisothermal radiating shock layer was formulated, which is expected to give accurate results with a minimum amount of computer time.

The experimental results for N^- are essentially complete. The results at threshold for the transition $N^-(^3P) - N^-(^2D)$ agree within 13% with those predicted by an earlier theoretical analysis. The threshold for the transition $N^-(^2P) - N^-(^2D)$ was also observed, further confirming the existence of the $N^-(^3P)$ state. The report on our SCF calculations for N, O, C was completed during this period.

Viscous Shock Layer Analysis

The influence of nonequilibrium effects on hypersonic blunt-body flow of a radiating gas at low density has been studied. Estimates based on the governing equations for the viscous, radiating shock layer and the radiating shock transition zone show that, in the density regime of interest, relaxation times for dissociation and ionization are large enough to prevent particles from substantial dissociation and ionization during their flow on the stagnation streamline. Vibrational degrees of freedom may be either frozen like dissociation and ionization or in nonequilibrium depending on density and temperature. The shortest relaxation times are those for electronic excitation; they are an order of magnitude smaller than vibrational relaxation times, according to latest measurements. A program has been written to calculate the viscous flow field, including radiative energy losses.

Shock Wave Structure

The Navier-Stokes Equations in one dimension were used along with two relaxation equations to solve the shock wave structure for a gas having both rotational and vibrational modes of relaxation. The characteristic relaxation times, as well as Mach number, were varied in the numerical computations in order to note the corresponding nonequilibrium effects. Viscosity and heat conduction coefficients are allowed to vary as functions of temperature. Results of this study have now been submitted for publication as a JPL Technical Report. This problem has been programed for both the IBM 7094 and Univac 1108 computers.

Shock Tube/Tunnel Heat Transfer Instrumentation

Work has continued on analysis and calculation of the fractional heat loss to substrate and error due to temperature distribution for the two-layer heat conduction model of a thick-film heat transfer gage. The aim has been to check correctness of the expressions derived by recourse to alternative derivations, limiting cases, and numerical results, and also to seek more manageable expressions in some cases. When the calculations are completed, they will be compared with experimental measurements to give a check of the thermal analysis model.

A new calorimeter radiative heat flux gage has been constructed which is as sensitive as a thin-film gage. Since it gives an absolute measurement, it needs no calibration. Preliminary measurements with this new gage are 50-60% lower than previous measurements which used the thin-film gage. The reason for the discrepancy has not as yet been uncovered.

ANTICIPATED PUBLICATIONS

(1) Stickford, G. H., Jr., "Total Radiative Intensity Calculations for 100% CO_2 and 90% CO_2 - 10% N_2," submitted to Journal of Quantitative Spectroscopy and Radiative Transfer.

PUBLICATIONS

Meeting and Symposia Papers

(1) Menard, W. A., and Stickford, G. H., Jr., "Shock Tube Measurements of Radiation from Simulated Jupiter Atmosphere," AIAA 7th Aerospace Sciences Meeting, AIAA Paper No. 69-184, N. Y., N. Y., Jan. 20–22, 1969.

(2) Blair, M., "An Experimental Study of Shock Speeds and Test Times for a Shock Tube With a Turbulent Wall Boundary Layer," 31st Meeting of the Supersonic Tunnel Association, April 24–26, 1969.

(3) Livingston, F. R., and Williard, J., "Planetary Entry Body Heating Rate Measurements in Air and Venus Atmospheric Gas up to T=15,000°K," AIAA paper 69-635, AIAA 4th Thermophysics Conference, June 16–18, 1969.

(4) Williard, J. W., "Performance of a Ceramic-Lined 6-in.-Diam Arc Driver," Technical Note, AIAA Journal, Vol. 7, No. 2, February 1969.

JPL Publications

(1) Menard, W. A., and Horton, T. E., "Shock Tube Thermochemistry Tables for High Temperature Gases:
Vol I -Air", Technical Report 32-1408.
Vol II -90% CO_2 - 10% N_2", Technical Report 32-1408.
Vol III -He, Ne, Ar", Technical Report 32-1408.

(2) Horton, T., "The Computation of Partition Functions and Thermochemistry Data for Atomic, Ionic, Diatomic and Polyatomic Species," Technical Report 32-1425.

(3) Blair, M., "The Performance of the JPL 43-in. Hypersonic Shock Tunnel," Technical Report 32-1370.

(4) McRonald, A. D., "Measurement of Distributed Heat Transfer on 60-degree blunted Cones in Nitrogen at M=12.5 in a Shock Tunnel," JPL Document 900-244, March 17, 1969.

(5) Blair, M., "An Experimental Study of Shock Speeds and Test Times for a Shock Tube With a Turbulent Wall Boundary Layer," SPS 37-55, Vol. III, pp. 157–163.

FLOW FIELD COMPUTER PROGRAM FOR PLANETARY ENTRY

NASA Work Unit 124-07-01-06

JPL 324-70601-0-3530

Z. Popinski

OBJECTIVE

The development of an analytical formulation of the time-dependent solution for an inviscid flow field has been, in essence, completed for an axisymmetric and for a three-dimensional case. These developments encompass the following facets of the analytical formulations:

(1) Conservation equations for the inner region of the shock layer.

(2) Conservation equations for the shock and body region in shock-or body-oriented systems.

(3) Characteristic directions and compatibility equations for shock and body regions.

(4) Rankine-Hugoniot relations for a moving shock.

In order to bring the analytical formulation into a form suitable for programming a computer, some supplementary derivations will be required. It is envisioned that the numerical solution would proceed in the following steps:

(1) Initial assumptions are made for shock shape, location of shock, and smooth distribution of flow properties between the shock and body.

(2) Shock conditions and body conditions at the next time step are matched with the initial inner conditions by one-dimensional method of characteristics in time domain.

(3) Matching in time in the inner region is performed by Taylor expansion method.

(4) Matching of inner conditions with shock and body conditions is continued for subsequent time increments until satisfactory convergence is obtained.

This work unit has been terminated as of July 1, 1969. Because of insufficient time available on this program, no comparison between the axisymmetric and three-dimensional analyses could be made. For the same reason no coding on a computer was initiated.

PUBLICATIONS

None

SPACE VEHICLE STRUCTURES (124-08)

VEHICLE CONCEPTS FOR PLANETARY MOBILITY

NASA Work Unit 124-08-01-04

JPL 324-81201-0-3530

E. Heer

OBJECTIVE

The general objective of this work unit is to develop advanced structural technology of planetary mobility systems for planetary and lunar surface operations and exploration. A long-term plan is required involving extensive investigations into conceptual and detailed aspects of mobility systems and locomotion. Particular FY 69 objectives are to determine and identify the existing mobility concepts, to establish criteria for the evaluation of mobility concepts, to assess, in a morphological sense, the existing and newly created mobility concepts with respect to such criteria, to establish interface requirements with other disciplines, to define advanced research areas for future investigations of the structural and mechanical aspects of planetary vehicles.

PROGRESS

The work initiated during the first half of FY 69 has been continued during this reporting period at a low level effort. This effort consisted mainly of organizing the material and information and preparing an interim report which discusses existing and newly proposed mobility concepts, some evaluation criteria for mobility concepts and advanced research areas requiring further investigations. The report of this study is in preparation. No additional work is planned in FY 70.

ANTICIPATED PUBLICATIONS

1. Heer, E., "A Review and Evaluation of Vehicle Concepts for Planetary Mobility," Jet Propulsion Laboratory Report in preparation.

PLANETARY ENTRY HEAT SHIELDS

NASA Work Unit 124-08-03-02

JPL 324-80401-2-3510

T. F. Moran
R. G. Nagler

OBJECTIVE

The long range objective of this work unit has been to conduct exploratory research into extraterrestrial planetary entry heat shield problems developing from JPL/NASA mission studies. The primary emphasis in this effort has been experimental through the assembly and use of a small, inexpensive, highly adaptable entry simulation facility. This facility was to provide experience in the particular problems of extraterrestrial planetary entry and was to be useful in providing mission oriented guidance for larger research and development programs at the NASA research centers. With changing emphasis within JPL, this work unit is not being continued in FY 70.

PROGRESS

During this reporting period all of the remaining capital equipment purchased in this program was installed and operated to ensure conformance to specifications. The facility shown schematically in Fig. 1 is essentially intact except for the pulsing controls. Little in the way of diagnostic information is available and a few minor problems still remain. Probably the biggest problem is the need for a ballast resistance to stabilize starting transients so that the large 1.7 Mw silicon diode power supply can become operationally consistent. Complete description of the facility, its components, and its known or anticipated operational envelope is contained in the document listed below.

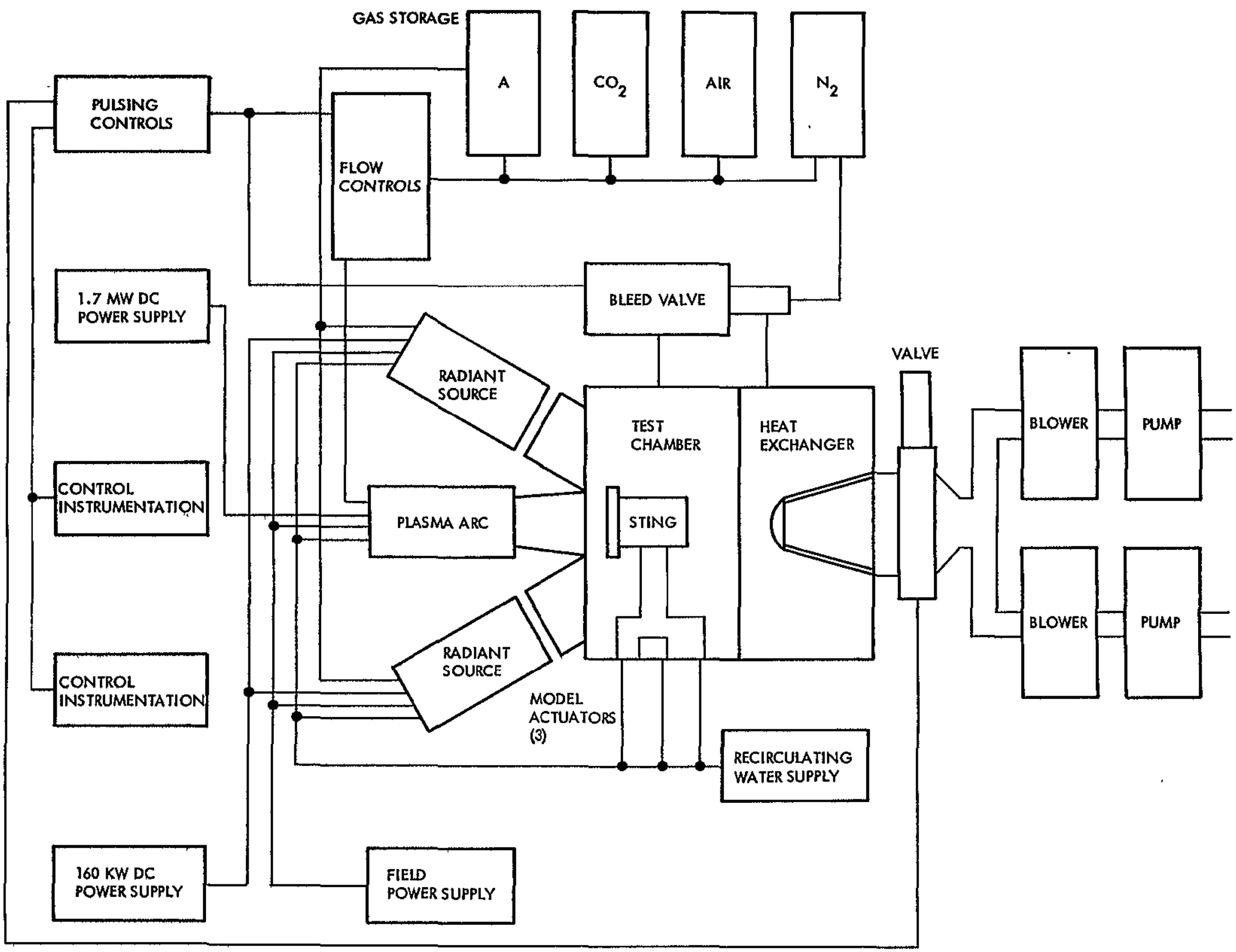

Figure 1. JPL's Planetary Entry Simulation Site

ANTICIPATED PUBLICATIONS

JPL Publications

1. Moran, F., "A Test Facility for Extraterrestrial Planetary Entry," JPL TR (Number not determined).

INTERCENTER ABLATION ANALYSIS AND SCREENING

NASA Work Unit 124-08-03-03

JPL 324-80601-2-3510

R. G. Nagler

OBJECTIVE

The long range objective of this work unit has been the coordination of those activities within NASA which have been oriented toward heat shield research and development for extraterrestrial atmosphere entry. Much of the work has been accomplished through the informally organized Intercenter Planetary Entry Heat Shield Coordination Group. The major objective for this year has been the formulation of a planning methodology to aid as a guide for future heat shield research and development. With the changing emphasis within JPL, this work unit is not being continued in FY 70.

PROGRESS

No further meetings of the Intercenter Planetary Entry Heat Shield Coordination Group have been held. The planning document has been completed. The general methodology is described in detail in the report listed below. A set of detailed recommendations for preproject research and development is included in the report as a sample of the utility of the planning methodology.

ANTICIPATED PUBLICATIONS

JPL Publications

1. Nagler, R. G., "A Systematic Review of Heat Shield Technology for Extraterrestrial Atmospheric Entry," JPL TR (Number not determined).

SPACECRAFT STRUCTURAL DYNAMICS

NASA Work Unit 124-08-05-02

JPL 324-80701-0-3530

E. Heer
M. Trubert
R. Simpson
J. Yang

OBJECTIVE

The objective is to initiate and conduct a research program to discriminately examine the diverse techniques in spacecraft structural dynamics in the light of meaningful experimental data and to synthesize a test and analysis approach which realistically simulates actual loading conditions. It is also the objective to define those areas requiring innovation and further study and to implement investigations in the most vital areas and to incorporate the results into an integrated test and analysis approach for space vehicle structures.

PROGRESS

Transfer Function Concept - RECEP Program

The computer program was written during the previous reporting periods. It is designed to compute the transfer functions of subsystems and combining these to compute the transfer functions of the entire coupled system and then to compute the response due to determinate or random inputs. The main effort has been directed to incorporate a fast Fourier transform routine in the program in order to compute the time responses of structures to multiple time variable loads.

Flight Data Analysis

An analysis has been developed using the frequency domain approach which extracts the loads induced on a vehicle from the flight acceleration measurements. The method permits the determination of a number of load components equal to the number of flight acceleration transducers placed on the vehicle. Six accelerometers were placed on the Centaur adapter for the flights of Mariner VI and VII and other spacecraft and the acceleration time history recorded during the entire boosted flight of the vehicle. The data will be used shortly to determine the loading conditions at significant events in the flight. The computer program used is an extension of the RECEP program which is being adapted to solve that particular problem. An analog simulation of a simple structure and its response to a known load is being used to check out the program.

Flexible Structure Attitude Control Interaction

The frequency transfer function type of solution proposed for flexible structure attitude control interaction has been investigated further. The transfer function of the control loop on the three axes of control has been included in the analysis and a preliminary computer program is being written on a timeshare computer to check out the method.

Environmental Vibration Test Level Investigation

An investigation of the adequacy of sine sweep test level is under investigation. To this end, the Mariner Mars 1969 spacecraft has been modeled on an analog computer and the six acceleration time histories representing the six degrees-of-freedom motion of the base of the spacecraft are being applied to the model to determine the response at critical locations. Sine sweep response is compared to transient flight type response. The work is in progress.

Fatigue Failure of Structures

When a structure is subjected to a nonstationary random excitation, the distribution of peaks of the response process is no longer the Rayleigh distribution even if the response process is a narrow-band gaussian. Since the peak distribution is essential in estimating the fatigue life, effort has been made to establish the distribution of peaks of a nonstationary narrow-band gaussian random process. The paper "Nonstationary Peak Distribution" has been prepared.

Optimum Design of Structures

A report entitled "Optimum Design of Structures Based on Reliability and Proof Load Test" has been prepared. An investigation is being conducted to establish design criteria for space structures based on fracture mechanics and reliability criteria. The results show a substantial improvement both of weight and reliability as compared to standard optimum design approaches.

Nonlinear Vibrations

An initial study of nonlinearly coupled dynamic systems was completed. A test of two simple beams coupled by a nonlinear spring has been conducted and the test results are being analyzed.

ANTICIPATED PUBLICATIONS

1. Shinozuka, M., Yang, J. N., and Heer, E., "Optimum Design Based on Reliability Analysis," to be presented at the 8th International Symposium on Space Technology and Science, Tokyo, Japan, August 1969 (to be published in the Proceedings of the Symposium).
2. Heer, E. and Yang, J. N., "Optimum Pressure Vessel Design Based on Fracture Mechanics and Reliability Criteria," accepted for presentation at the ASCE-EMD Specialty Conference on Probabilistic Concepts and Methods in Engineering, Purdue University, November 1969 (to be published in the Proceedings of the Conference).
3. Shinozuka, M., and Yang, J. N., "Nonstationary Peak Distribution," accepted for presentation at the ASCE-EMD Specialty Conference on Probabilistic Concepts and Methods in Engineering, Purdue University, November 1969 (to be published in the Proceedings of the Conference).

PUBLICATIONS

Journal Articles

1. Shinozuka, M., and Yang, J. N., "On the Bound of First Excursion Probability," Journal of Engineering Mechanics Division ASCE, Vol. 95, pp. 363-377, April 1, 1969,

JPL Publications

1. Heer, E., and Trubert, M. R., "Analysis of Space Vehicle Structures Using the Transfer-Function Concept," TR 32-1367, April 1, 1969.

2. Shinozuka, M., and Yang, J. N., "Optimum Structural Design Based on Reliability and Proof-Load Test," TR 32-1402, June 15, 1969. To be presented at the AIAA/ASE/ASME 8th Conference on Assurance Engineering and Science, Denver, Colorado, July 1969, and to be published in the Annals of Reliability and Maintainability, Vol. 8, July 1969.

PLANETARY ENTRY AEROSHELL STRUCTURES

NASA Work Unit 124-08-06-04

JPL 324-80201-0-3510

R. G. Nagler
R. A. Boundy

OBJECTIVE

The long range objectives of this work unit is the investigation of the technology necessary for the utilization of large, lightweight aeroshell structures for planetary entry missions. Resin-fiberglass honeycomb sandwich structures have been stressed but adhesive bonded aluminum honeycomb sandwich composites have been studied as economically competitive alternatives. Recent work has emphasized analysis of the contracted results and verification of the utility of the extensive flat sample data through tests on doubly curved models of the same basic construction.

PROGRESS

With the completion of the two and one-half year effort with Rohr Corporation investigating lightweight honeycomb sandwich structures, a time for review and re-evaluation was considered appropriate. The final report for the contract was analyzed and the results will be published in the JPL report referenced below. In the report a comparison is made between resin-fiberglass and adhesive-bonded aluminum honeycomb sandwich structures and specific design values are recommended for either mission study or project use.

The structural strength verification tests described in the last semiannual report were carried out on identically fabricated doubly-curved aeroshell models. The tests showed primary failure of the aeroshell by core shear, perpendicular to the ribbon direction, as expected from analysis. Strain gauges mounted on the face sheets verified the stress calculations taken from a thin shell approximation to the sandwich structure. Based on the closeness of the calculated and experimental strain data, it is felt that slight strengthening of the core would transfer the failure mode over into the face sheets but lack of time prevented final verification.

A facility was assembled from essentially available parts which would allow a ground simulation of the important portions of the total environmental history experienced by an entry capsule on a Mars mission. In this facility ETO surface decontamination, dry heat sterilization, launch pumpdown, transit vacuum and the entry heat and pressure pulses are simulated consecutively without interim exposure to ambient conditions. Through such a facility, the coupling effect of early environments on performance during later environments can be determined. The facility was designed and partly assembled before time constraints indicated the impossibility of carrying out a prototype test in this fiscal year.

ANTICIPATED PUBLICATIONS

1. Nagler, R. G. and Boundy, R. A., "Fabrication Development of Lightweight Honeycomb Sandwich Structures for Extraterrestrial Planetary Probe Missions," (TR number not determined).

PUBLICATIONS

Contractor Reports

1. Scholl, J. A., Kiss, M. L., and Dawson, J. E., "Fabrication and Test of Lightweight Honeycomb Sandwich Structures," Final Report 24-1512 on JPL Contract 951612, Rohr Corporation, Chula Vista, California, January 30, 1969.
2. Scholl, J. A., Koss, M. L., and Dawson, J. E., "Fabrication and Test of Lightweight Honeycomb Sandwich Structures," Addendum Number 1 to Final Report 24-1512 on JPL Contract 951612, Rohr Corporation, Chusa Vista, California, April 30, 1969.

SPACE ENVIRONMENTAL FACTORS (124-09)

EFFECT OF ENVIRONMENT ON SPACECRAFT THERMAL CONTROL MATERIALS

NASA Work Unit 124-09-18-01

JPL 324-90401-2-3510

W. F. Carroll

OBJECTIVE

The objective of this work unit is to plan and perform analytical and experimental tasks which will improve the utilization and assure high reliability of materials used for spacecraft temperature control. This will include the effects of various environments on the optical properties of thermal control materials as well as a study of the materials problems associated with active temperature control devices.

PROGRESS

Photolysis of Thermal Control Coating Materials

Work continued during the period at Stanford Research Institute (JPL Contract No. 951522) on photolysis of pigments and methods to prevent degradation. The aim of this program is to study the mechanisms of photolytic degradation and to provide active surface sites to prevent photo produced changes.

Spin resonance studies of zinc oxide additive systems have produced what may be a major step in photolysis work. The resonance at $g \approx 1.96$ has been resolved into the permanent damage signal at $g = 1.9600$ and an oxygen bleachable signal at $g = 1.9564$. While no correspondence has been established, these may be analogous to the permanent optical damage near the absorption edge and the oxygen bleachable damage in the near infrared for zinc oxide. In addition to the obvious possibility of this observation leading directly to better understanding of photolysis, the greatest benefit may be in future testing methods. If correspondence to observed optical degradation can be demonstrated, quantitatively discernable changes can be observed to study the generation, prevention and annihilation of optically absorbing species with approximately one hour of irradiation compared to the 100 to 1000 hours required for optical studies.

While the resolution of the 1.96 line may have significant technical importance, the major effort has been directed to study of the required ratio of Fe II to Fe III and quantitative surface coverage for effective prevention of damage. These studies are not to optimize coating system formulation although they will be an aid to this end. The principal reason is to provide information leading to a test which will ascertain whether the additive is truly catalytic or some depletion reaction is involved.

Photo-conductance measurements on the ZnO system agree in general with the spin resonance work.

Attempts to apply the concept to other pigment materials (ZrO_2 and La_2O_3 have been selected for study) have so far been unsuccessful. The reasons are not understood at this time but electrical measurements aimed at selecting suitable recombination couples for these materials have produced anomalous results.

Ultraviolet irradiation has so far failed to produce detectable resistivity or ESR signal to evaluate candidate recombination couples.

PLANS

Due to contract delays, this effort will continue into FY 70; to be completed during the first quarter.

It is not clear that any measure of success can be achieved on other pigments for the reasons discussed above. A major portion of the remaining effort will be directed toward this end.

While the program concept and approach shows high potential productivity and technical merit, it is not currently planned to continue the work beyond the end of the existing contract period.

Development of S-13G Type Coatings (JPL Contract 951737)

A comprehensive report on the program was completed and distributed during the period. Included in the report was detail specification information for preparation of the treated pigment and coating formulation and application.

Materials for Active Temperature Control Devices

Material problems including generation of noncondensable gases in heat pipes, louvers to survive high intensity solar irradiation, and insulation for inner planet missions have been reviewed. No experimental investigations have been initiated since limited available manpower did not permit suitable survey of related efforts in other organizations.

A concept (and potential highly advantageous use) for a controllable solar energy absorber device has been developed. The idea, conceived approximately two years ago, incorporates a commercial coating with high solar transmission and low thermal emittance. The coating, normally applied to quartz, or preferrably, if applicable to a polymer film can be used over a highly absorbing surface or cavity to efficiently absorb solar energy. Equipped with a commandable or thermally activated "shutter" to vary the active area the system can produce reliable, lightweight active control for large power density vehicles or components such as the Viking propulsion module.

The active solar absorber concept will be pursued under project support during the next fiscal year. Problems associated with other devices will be investigated in relation to their utility and necessity for future program requirements.

PUBLICATIONS

Contractor Reports

1. Morrison, S. R., Freund, T., Sancier, K., "Effect of Environment on Thermal Control Coatings," Interim Report No. 2, SRI Project No. PAD 6146, Déc. 3, 1968, JPL Contract 951522.
2. Rogers, F. O. and Zerlaut, G. A., "Development of S-13G Type Coatings as Engineering Materials," IITRI Report U 6053-11, March 5, 1969, JPL Contract 951737.

TEMPERATURE CONTROL OF SPACECRAFT

NASA Work Unit 124-09-18-02

JPL 324-90501-0-3530

W. A. Hagemeyer
J. Schwartz

OBJECTIVE

The long-range objective of this work unit is to develop advanced test techniques and active thermal control devices for future spacecraft. For the current fiscal year, the objectives were: (1) to continue to monitor an out-of-house contract for research on transient thermal scale modeling at the University of Illinois, and (2) to continue research leading to an understanding of heat and mass transfer in heat pipes.

PROGRESS

Thermal Scale Modeling

Contract 951660 with the University of Illinois was successfully completed in March, 1969.

Final results indicate that the technique of electro-plating to modify lateral conductivity while not adversely affecting the heat capacity is a feasible if not optimum technique for thermal scale modeling a system where the conduction is two dimensional. Most spacecraft can successfully be represented as having two dimensional conduction, due to the thin sections used. This has been proven with electrical heating and under solar simulation. The technique is not optimum, since obtaining a uniform and predictable layer of electroplating is extremely difficult.

JPL is currently in negotiation with the University of Illinois for another contract to investigate a proposed technique for correcting test results from an imperfectly scaled model. This technique was submitted in an unsolicited proposal in January, 1969.

Heat Pipes

The heat pipe R/D effort in the past six months was divided into the following task areas:

(1) Heat pipe/radiator coupling studies.

(2) Performance map studies of the ammonia (NH_3) heat pipe.

(3) Life tests and the effects of non-condensible gases on the operational capabilities of the heat pipe.

(4) Flat plate heat pipe.

(5) Miscellaneous projects.

Heat Pipe/Radiator Coupling Studies

Data obtained from the last comparison test series (Ref. 124-09-18-06 January, 1969) indicated that the plate temperature profiles were flatter when the heater was not attached to it, compared to the case when the heater was attached to the plate. However, the empirical data of either of the above test runs did not compare to the temperature profiles obtained from a computer model. The main reason for this discrepancy is due to the physical difference between the test model and that selected for the computer model. Values for effective thermal conductivity of the heat pipe and contact resistance of the various interfaces which were assumed in the computer model were probably not realistic. Likewise, the plate's physical dimensions were not exactly the same in both models. As a result, a test model which resembles the computer model has been designed, built and is currently being instrumented. This model will be tested under the same conditions as those assumed for the computer model. Parametric studies of contact resistances will be performed in a parallel effort utilizing the computer model to determine the cause of the discrepancy between the empirical and analytical data.

Performance Map Studies

An ammonia (NH_3) research heat pipe is currently being tested. Preliminary data indicate that for vapor temperatures below 100°F, the ammonia heat pipe is capable of transporting approximately twice the heat load of the water heat pipe for the same surface temperatures. Between vapor temperatures of 100°F and 160°F (at which point dry-out occurred), the water heat pipe is more efficient than the ammonia heat pipe in the transfer of thermal energy at corresponding surface temperatures. This efficiency increases with increasing surface temperature. The data also reveal that the effective coefficient of thermal conductivity of the ammonia-saturated wick varies with temperature in a similar manner as that of the water-saturated wick. The effective thermal conductivity values of the former, however, are higher than the latter for the same temperature range.

Plans are to continue the present investigations which call for elevation tests, variable condenser tests, and multi-component fill fluid tests. The purpose of these tests is to map the performance of the ammonia heat pipe to determine its capabilities.

Life Tests and Effects of Non-Condensible Gas on Heat Pipe Operations

To date, three of the six life test heat pipes have undergone ten months of continuous operation. The data confirmed the previous findings that hydrogen, a non-condensible gas, was generated within the water heat pipes only. The gas accumulated in the cold region in what is believed to be an annulus within the wick, thus blocking the normal heat transfer process from taking place in that region. The hydrogen gas was the product of a chemical reaction which occurred between water (working fluid) and the metallic constituents of the heat pipe container such as iron, nickel, and chromium. The reaction apparently ceased after approximately three months of continuous heat pipe operation. The latest data indicate that hydrogen gas generation is a strong function of temperature. This is confirmed by the fact that the heat pipe operating at 325°F contained more than twenty times the volume of hydrogen gas compared to that operating at 85°F. In addition, the heat pipe whose internal gas generation ceased proceeded to generate more hydrogen when the operating temperature was elevated.

Plans are to continue the present life test. In addition, a number of heat pipes are to be built and instrumented for further tests. These units will be divided into three groups, each operating at a different temperature (100°F, 200°F, 300°F). One heat pipe from each group will be withdrawn periodically at the same time and its internal gaseous constituents analyzed spectographically. The purpose of this test is to further investigate the nature of non-condensible gas generation and accumulation within the heat pipe and the associated effects on its operation.

Flat Plate Heat Pipe

Efforts are currently concentrated on designing and building a flat plate heat pipe which will be composed of two welded plates with internal passage ways divided by lands. The passage ways are designed to be the heat pipe vapor core. The returning condensate will flow in grooves covered by a thin screen mesh. Because of the nature of this heat pipe, all high vapor pressure working fluids were ruled out and water was selected. A preliminary material compatibility study revealed that a beryllium copper alloy is the best candidate for the heat pipe container material. Plan's call for further test designed to determine the compatibility of this alloy with water. Likewise, investigations of machinability, strength, and weldability of this alloy are underway.

Miscellaneous Projects

An apparatus which will measure wick permeability is currently being built. Permeabilities of various wick structures such as screen, felt metal, and fused spherical particles are planned to be obtained and compared to similar data from various sources. In addition, a literature survey of all permeability and pore size data is contemplated in an attempt to categorize wick structures for heat pipe designs.

PUBLICATIONS

Contractor Report

B. T. Chao and M. N. Huang, "Transient Thermal Modeling with Simulated Solar Radiation," Final Report, ME-TR-JPL-951660-2, University of Illinois, March 1969, JPL Contract 951660.

CONDUCTION AND RADIATION IN SPACECRAFT TEMPERATURE CONTROL

NASA Work Unit 124-09-18-03

JPL 324-90601-0-3530

W. A. Hagemeyer
J. A. Hultberg

OBJECTIVE

The long-range objective of this work unit is to develop advanced analytical, design, and test techniques for the prediction of conduction and radiation heat transfer in spacecraft. The current fiscal year objectives are: (1) to improve computer analysis of temperature control, (2) to continue studies of real-surface radiation and computation techniques for practical solution, and (3) to experimentally verify that laboratory determined values of joint conductances versus pressure and analytically determined pressure loadings in plates can be combined to give the heat transfer across a given geometry.

PROGRESS

Real Surface Effects

In continuation of NASA Research Grant NGR 14-005-036, JPL has let NASA/JPL Contract 951661 to the University of Illinois starting September 1966. The contract has been extended until August 1969.

Work has progressed in the three major areas of research: (1) evaluation of radiant heat transfer analysis techniques, (2) development of analytical surface radiative property models for use in the heat transfer analyses, and (3) construction of a facility for measuring surface radiative properties.

Recent work has concentrated on the upgrading of the bidirectional reflectance measurement facility. An instrumentation system has been selected for collecting data with the facility. Measurements will be made of selected samples in order to validate the surface property models.

Computer Programs

The conversion of the thermal programs from the IBM 7094 to the UNIVAC 1108, EXEC8 System, has been completed. The programs that are now available on the 1108 are CONFAC II, CINDA3G, TASI, LHFPI, and LHFPII (Lockheed Heat Flux Program I and II). Although the programs functioned correctly for the test cases, some minor problems have been encountered during actual problem runs. Execution time comparison shows a two to ten times advantage of the UNIVAC 1108 over the IBM 7094.

The Users Manual for TASI has been written and is currently being edited.

Joint Conductance

All joint conductance tests have been completed. The data from these tests have been reduced and plotted. Examination of the data indicates that it is self consistent and trends are in the correct direction. A computer analysis is being performed to deduce the apparent joint conductance values from the experimental data. This is necessary since the physical geometry was such that the pressure distribution was not uniform. The nonuniform pressure distribution was used so that the tests more closely simulated the case of an actual bolted joint.

PUBLICATIONS

None

TEMPERATURE CONTROL MATERIALS APPLICATION DEVELOPMENT

NASA Work Unit 124-09-18-05

JPL 324-91601-2-3510

J. C. Lewis

OBJECTIVE

The objective of this work unit is to develop materials technology and processing information which can be used for application of temperature control materials to spacecraft or capsule surfaces where conventional methods are inadequate.

During FY 69 the approach has been to evaluate the use of temperature control coatings in forms such as pressure sensitive tapes and thin films applied with in-situ cured adhesives. The purpose was to evaluate the stability of these application methods with respect to the effective thermal performance of the coating.

PROGRESS

Two different commercially available tapes have been tested using the internally heated platen described in the previous semi-annual report. One tape was an aluminum foil - FEP Teflon laminate while the other was aluminized Kapton. Both tapes had pressure sensitive silicone adhesives that retained tack after exposure to temperatures exceeding 400°F.

The platen was designed to minimize conductive power losses so that all the applied energy could be assumed to be emitted by the tape. The tests were run in a vacuum chamber at less than 10^{-6} torr with a liquid nitrogen shroud maintained below -300°F.

The tests consisted of repeated cycles from approximately +400°F to -200°F to simulate spacecraft temperatures and thermal shock for severe but real conditions such as sun occultation at Mercury. Both tapes performed well with a degradation of about five percent for the aluminum-Teflon laminate and about ten percent for the aluminized Kapton. The total degradation occurred during the first 400°F cycle for both tapes and both tapes remained stable for repeated cycles to 400°F. The only apparent problem was entrapped air pockets and crinkled during application of the tape to the platen surfaces.

PLANS

This work unit ends in FY 69. No future work is planned. Results will be published in a forthcoming Space Programs Summary.

PUBLICATIONS

None

TEMPERATURE CONTROL ON A PLANETARY SURFACE

NASA Work Unit 124-09-18-06

JPL 324-91701-0-3530

W. A. Hagemeyer
D. Ting

OBJECTIVE

The objective of this work unit is to maintain cognizance of the state-of-the-art of temperature controlling a payload on a planetary surface and to develop means of deducing significant environmental parameters by use of commonly used engineering telemetry sensor. For this fiscal year the immediate objectives were: (1) by an out-of-house contract, investigate and experimentally measure values of free and forced convection coefficients for assumed Mars atmospheres, and (2) develop a "thermal model" of the Mars environment and investigate the effects of the controlling parameters.

PROGRESS

Heat Transfer in a Mars Atmosphere

Contract 952374 was initiated in November, 1968, with Purdue University to perform an analytical and experimental investigation of heat transfer in a simulated Martian atmosphere.

In February, 1969, the contract was modified such that the experimental work would be performed at JPL, while the analytical work would be accomplished at Purdue.

Two test models (cylinder and flat plate) were constructed with heaters and thermocouples installed, as were pressure and temperature probes and a multidirectional transfer mechanism. The probes and test models will be checked out prior to installation into the low density wind tunnel at JPL. It is anticipated that initial check-out runs will commence on or before July 1, 1969, at JPL's low density wind tunnel. Heat transfer experiments will be conducted to investigate the variation of convective heat transfer coefficient as a function of atmospheric pressure, wind velocity, and atmospheric temperature.

Completion of the experimental phase is scheduled for August 15, 1969. A comparison of analytical results and experimental data will be made to establish the validity of the analytical technique for computing heat transfer coefficients in a Martian environment. A final report will be published on or before October 1, 1969.

Thermal Model

This task will not be undertaken because of the redirection of the effort.

PUBLICATIONS

None

SOLAR SPECTRUM SIMULATION RESEARCH

NASA Work Unit 124-09-19-01

JPL 324-90701-2-3750

R. E. Bartera

OBJECTIVE

The purpose of this work unit is to improve laboratory predictions of spacecraft thermal performance in flight. In order to predict thermal performance of craft with no gray surfaces, it is helpful to determine the actual extraterrestrial solar spectrum and to duplicate it with sufficient accuracy in space simulation facilities. The unit objective has been to determine the actual solar spectrum, and the unit is now phasing into finding efficient ways to duplicate it.

PROGRESS

X-15 Flight Data

As reported one year ago the value of the extraterrestrial solar constant as measured above 80 km altitude is 1.95 cal/cm^2-min ± 1%. Values for the daily extraterrestrial solar irradiance have been computed for this Eppley-JPL solar constant by E. C. McCullough and the information is available from the Climatic Operations Branch, National Weather Records Center EDS, ESSA, Federal Building, Ashville, North Carolina, 28801.

The solar spectrum data have been reduced and the results transmitted verbally to JPL. We do not deem it proper to publish these numbers until the final report is received from Eppley Laboratory. This report, in preparation for several months now, will contain the methods of computation and a description of the calibration procedures.

Arc Spectrum Modification

During the past six months work has been concentrated on spectrum modification by the application of magnetic fields to short arc lamps. This was done in concert with the closely related Work Unit 124-09-19-04-55, Advanced Solar Simulation Research, and is partially described under that heading in this volume.

It appears possible that an intense axial magnetic field at the cathode of a short arc lamp can increase brightness, cause UV shift of the spectrum and be combined with an arc/rotating magnetic field near the anode. A cathode has been modified so that the central water tube is soft iron acting as the core of an electromagnet. The fields surrounding these magnetic electrodes are now being determined.

PUBLICATIONS

None

TEMPERATURE CONTROL FLUX MONITOR

NASA Work Unit 124-09-19-02

JPL 324-90101-0-3530

W. A. Hagemeyer
J. A. Plamondon

OBJECTIVE

The objective of this unit is to convert the Absolute Cavity Radiometer (ACRAD) from a laboratory to a flight instrument for implementation as an engineering experiment on the Mariner Mars 1969 spacecraft. The purposes of this experiment are to support temperature control engineering R/AD goals and to provide flight instrumentation for the spacecraft's temperature control subsystem. The flight version of ACRAD has been renamed the "Temperature Control Flux Monitor" or TCFM.

PROGRESS

Development of the TCFM

The TCFM has been built under NASA/JPL Contract 951792 with TRW Systems Group for a contract cost of $736, 934. Deliverable major items under Modification 8 of the contract are breadboard electronics and a transducer (radiometer); a flight prototype transducer; five flight electronics packages and seven flight transducers; and one laboratory test set and three system test sets.

Since the last report, the launch of Mariners VI and VII has taken place. During pre-launch test operation a single failure was experienced. This failure was traced to a faulty integrated circuit in the TCFM logic. The faulty unit was replaced with a spare unit.

Launch of the Mariners VI and VII occurred respectively on February 24 and March 27, 1969. Since launch, instruments on both spacecraft have operated flawlessly. Data from the two instruments are substantially in agreement. Reduction of the data taken two days after launch places the solar constant at 135.25 and 135.45 watts/cm^2, respectively, for each instrument. These values are believed to be accurate within a maximum error of ±1.5%. Data taken since launch indicates random variations in solar flux of ±0.2% maximum. However, correlation between the two instruments is not firm due to the lack of simultaneous, long term tracking coverage. Also noted since launch is a gradual decrease in corrected flux to 1 AU as the spacecraft moves outward from the sun. This gradual decrease correlates well between the two instruments, but no satisfactory explanation exists for the observed behavior.

With the exception of a final engineering report, Contract 951792 is complete. However, a follow-on contract with TRW is still in force to provide technical consulting as needed.

ANTICIPATED PUBLICATIONS

Mariner Mars 1969 TCFM.

PUBLICATIONS

None

MEASUREMENT TECHNOLOGY FOR
TEMPERATURE CONTROL MATERIALS

NASA Work Unit 124-09-19-03

JPL 324-90901-2-3510

W. F. Carroll

OBJECTIVE

The long range objective of this task is to provide spacecraft thermal designers and analysts with necessary data on surface properties of temperature control materials. To accomplish this, the following tasks must be undertaken:

(1) Requirements must be anticipated with the uncertainties and limitations associated with measurements understood and improved, and in some cases new methods developed.

(2) The uncertainties associated with processing reproducibility of the materials must be identified and reduced as required.

(3) Data must be available to designers and analysts in a concise usable form and must include uncertainty limits.

PROGRESS

This task was reprogrammed during the period due to lack of manpower. The follow-on program to experimentally evaluate error sources was eliminated since there was insufficient manpower to adequately review and plan for it.

During the second half of FY 69 support continued to NASA Headquarters on the contract with TPRC, Purdue University (NSR-15-005-037).

Analyzed Data Graphs (ADG) for Vol. VII, Metals and Alloys have been completed and were reviewed in detail. The modification in philosophy of presentation has produced several highly useful and illustrative ADG's utilizing plotting parameters other than reflectance, emittance temperature and wavelength. Vol VII is now ready to go to the publisher.

Methodology for retrieval, extraction, analysis and presentation of data on coatings was the subject of extensive study during the period. The large amount of available information, particularly related environmental test results and all too frequent ill-definition of samples would swamp the normal scheme. It will be necessary to apply analytical selection and organization during the retrieval and extraction process to achieve the required data summary in a reasonable time scale.

A simple handbook of radiative properties is being compiled at JPL from past project results and selected other sources. Data accumulation for this tabulation has been completed but formatting and publication were postponed during reprogramming due to lack of manpower.

PLANS

Portions of the activities in this work unit will be continued in FY 70 as part of a new, more general task, NASA Work Unit 124-09-18-35.

Support to the TPRC contract will continue during FY 70 and beyond. Future activity will include continued aid in evaluation of published data quality and organization, categorization, and presentation of radiative properties of nonmetallics and coatings.

Data accumulated from JPL and other selected sources will be reviewed, organized, assigned an order of merit or reliability, and issued for review in preliminary format early in FY 70.

Data from the experimental measurement program will be reviewed in detail and a continued experimental program plan developed for incorporation at a future date.

PUBLICATIONS

None

ADVANCED SOLAR SIMULATION RESEARCH

NASA Work Unit 124-09-19-04

JPL 324-91001-2-3750

R. E. Bartera

OBJECTIVE

The objective of this work unit is to develop systems and technology that will enable us to adequately simulate the effects of solar radiation on spacecraft. Although presently available lamps are close to the brightness of the sun, there is a need for sources of considerably higher brightness for near future accurate solar simulation testing. This additional higher brightness is necessary to obtain a true solar field angle in the test beam and to compensate for the system inefficiencies caused by the optical control elements. Furthermore, as the lamp brightness is increased, color filtration becomes practical so that the spectral distribution, the intensity, and the field angle of the sun can be simultaneously matched.

The performance attainable in a given solar simulation system, at a given level or irradiance, is a direct function of the brightness of the light source. This assumes, of course, that the system was sufficiently well designed to preclude any significant improvements in the efficiency of power transmission.

Therefore, our immediate objective is to develop ways to increase the brightness of high pressure arc lamps and to investigate other promising kinds of light sources.

PROGRESS

Multi-Anode Lamps

By having several anodes in a lamp and making the arc strike each sequentially, the total arc current can be significantly increased. Preliminary studies made of arc behavior with three-and six-anodes using carbon electrodes in air and 60 Hz, three-phase current showed good transfer between anodes and relative stability of the cathode spot. This latter was encouraging because the highest brightness and, therefore, the most useful portion of the arc is just off the tip of the cathode. A three-anode configuration (in tungsten) has been fabricated and evaluated in high pressure inert gas. The anodes were connected to the terminals of a 3-phase, 60-cycle wye-connected, current-limiting transformer with the cathode return connected to the neutral point of the transformer. The current flow went to each anode in turn during the passage of an electrical cycle, and only to that anode that had the momentary maximum (positive) potential, the others being inoperative during the part of the cycle when they do not have maximum positive polarity. Each anode thus has a duty cycle of 1/3 but each can handle its normal design maximum as a long-time average load.

The multiple-anode structure was built to operate in the JPL Variarc facility. A tungsten cathode was used with three tungsten, 1/4 inch diameter anodes, and set up to operate at 75 psig using argon gas. The lamp operated as expected with the cathode light spot being time-modulated to the extent of 16%, which corresponds to the current modulation in a 3-phase current. A 6-phase operation would give a 4.2% current modulation and presumably a 4.2% light modulation. Such modulations are quite acceptable as their fractional second periods are much faster than any conceivable thermal time constant of spacecraft elements to be tested in simulators.

The lamp was operated as a single-cathode, single-anode lamp by connecting all three transformer outputs to one anode which was raised to the melting point at 60A. This would normally be the operating limit of such a single-cathode, single-anode lamp. The three transformer outputs were then connected separately to each of the three anodes and the current needed to raise the tips of the tungsten anodes to the melting point was then 150A (50A in each anode leg and 150A through the single cathode). This current of 150A would then be the operating limit for the lamp as a single-cathode, 3-anode lamp. The fact that the limit was reached at 150A instead of 180A was attributed to the hot radiation anode tips giving additional heat load to the neighboring anodes.

Magnetic Steering of Arcs

A new method was tried to spread the heat load on the anode of an operating compact arc lamp, and thus to increase the power capability of a lamp. A single water cooled anode was modified to include three internal electromagnets parallel to the arc axis. When these were energized with three phase current during DC lamp operation, the anode attachment spot rotated continuously in a circle away from the anode tip, thus spreading the heat load, without appreciably disturbing the cathode spot location. High speed motion pictures were taken of the operation which showed the effects described.

Electromagnets external to the lamp showed a similar effect but also caused the cathode spot to move. We are currently trying to find an external magnet configuration which would allow the cathode spot to remain fixed while the anode attachment point is forced to rotate.

A single anode with embedded magnets, arranged to give magnetic fields perpendicular to the discharge axis instead of nearly parallel as in the work reported above is now being designed. This should be more effective in offsetting the arc anode attachment point. It will have a center-tube water inlet, annular outlet and have a very narrow water passage directly under the arc attachment circle. Thus it will be, in effect, a 3-dimensional Riise type anode, and will be adapted to be fabricated with circular symmetry so that it can be made by normal machinery techniques.

Arc Wall Cooling

Pending the use of the new anode, work is going on with the readying and installation of a peripheral-cooled-gas cathode, using Argon for the discharge gas and cooling the outside of the arc stream with helium.

PUBLICATIONS

JPL Publications

1. Youngberg, C., "Internal Pressures in a Water Cooled Anode," SPS 37-57, Vol III.
2. Miller, C., "High-Brightness High-Power Arc Lamp Light Sources," SPS 37-57, Vol. III.

COLDWELDING TEST REQUIREMENTS

NASA Work Unit 124-09-19-05

JPL 324-91401-0-2940

T. E. Gindorf
J. T. Wang

OBJECTIVE

The objective of this work unit is to develop a set of coldwelding test criteria for qualification of spacecraft hardware.

The phenomenon of coldwelding which causes spacecraft mechanisms to fail has been demonstrated in the laboratories. Recent examples include the infrared spectrometer (IRS) geartrain and the television (TV) shutter of Mariner Mars 1969 which failed during test in the JPL Molsink facility. In recognizing the seriousness of the problem for current as well as future spacecraft systems, an effort is being made to develop a set of test criteria for qualifying spacecraft hardware.

APPROACH

A research plan was formulated to achieve the following:

(1) Identify and evaluate the environmental parameters to determine the degree of influence they have on the coldwelding of materials.

(2) Compare the Molsink environment to the space vacuum.

(3) Perform experiments to determine the thresholds at which these parameters are to be maintained to produce an adequate coldwelding environment.

(4) Formulate coldwelding test criteria.

PROGRESS

Air Force Rocket Propulsion Laboratory (RPL) formally agreed to participate in the JPL-RPL joint effort in Coldwelding research. Necessary arrangements were made with RPL to provide JPL the friction module, liquid nitrogen (LN_2) and a contractor, Thompson-Ramo-Woodridge, Inc., (TRW) to assist in performing the experiments in the JPL Molsink.

Two friction modules were delivered to JPL in April, 1969 by TRW. The modules were calibrated after installation. Difficulty was encountered in the attainment of suitable environmental conditions due to leaks in the test chamber. The leaks were primarily in the loose flanges and feedthroughs which might be caused by the chamber temperature cycling.

After eliminating the major sources of leak (required approximately 6 weeks), the modules were recalibrated before the second pumpdown. The pressure decended to 10^{-10} torr. Since the Molsink has previously achieved a pressure of 10^{-12} torr, it was suspected that there might be a small leak between the guard vacuum and the inner chamber (Moltrap). A decision was made to perform the experiment under the existing vacuum condition.

The experiment was intended to provide a direct comparison between Molsink data and flight data. The flight data were secured over a one year orbital time on satellite ERS 20. Active runs were made intermittently while the two modules produced reciprocating sliding motion between 16 pairs of frictional surfaces each of a different material combination. The Molsink friction experiment was designed to duplicate the flight experiment except that the passive dwell time between active runs was scaled down. It was assumed that the cumulative vacuum exposure was not as strong a variable as cumulative sliding history. The ground experiment was completed on June 12, 1969. The data reduction began immediately and will be the subject of a future (classified) report.

The first draft of the friction experiment module operations manual has been completed. The manual provides the operational procedures and description for the ground test friction experiment hardware.

The primary objective for Phase II activities is to determine exactly what threshold environmental conditions must exist in order to achieve an adequate coldwelding test. Current effort is directed at finalizing the planning activity which will accomplish the objective of Phase II. Preliminary discussions with Langley regarding the usage of their ultrahigh vacuum chamber for exposure of the friction module to a high quality non-Moltrapped environment have been held.

PLANS

Tasks involved in the two phases of the program are as follows:

Phase I

(1) Establish the detailed requirements for the operation of two experiment modules (A and B) in the Molsink facility.

(2) Perform experiments to acquire comparison friction data corresponding to the test materials flown on the Environmental Research Satellite (ERS-20). The experiment run profiles used will conform to the mechanical sliding history incurred during Environmental Research Satellite (ERS-20) in-space tests.

(3) Perform data reduction of the coefficient of friction values.

(4) Perform analysis and comparison of the results obtained in space and Molsink.

(5) Prepare an interim report for Phase I.

Phase II

(1) Determine adequacy of environments which are degraded from that of the Molsink type environment by performing experiments similar to those in Phase I.

(2) Determine adequacy of conventional chamber types of environments.

(3) Determine parameter thresholds in a conventional chamber if (2) is adequate.

(4) If the conventional chamber type of environment is inadequate, determine parameter thresholds in the Molsink.

(5) Develop valid methods of accelerating tests.

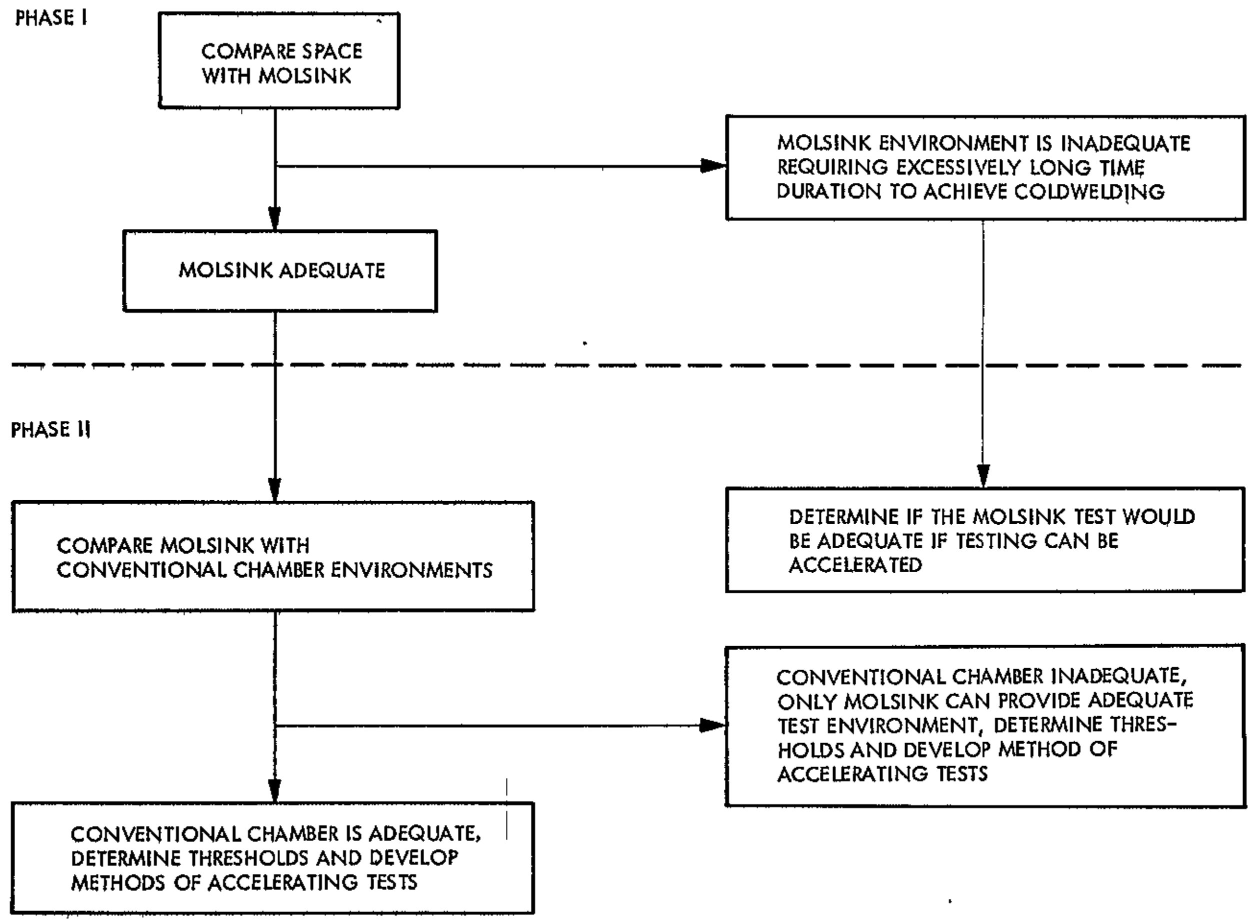

Figure 1. Phase I and Phase II Flow Diagram

(6) Establish coldwelding test criteria.

(7) Prepare final report.

PUBLICATIONS

None

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MOLSINK RECONTAMINATION RATIO EXPERIMENTS

NASA Work Unit 124-09-19-07

JPL 324-91801-2-3750

R. E. Bartera

OBJECTIVE

The objective of this work unit is to provide an understanding of the unique environment produced in the JPL 10-ft MOLSINK facility which was designed and built as a medium for developing the technology necessary for simulating the molecular sink of space. This facility has been operational since June, 1968.

It is estimated that in this test facility, even with a very "dirty" (high outgassing rate) object, the molecular flux impinging on that object will be a reasonable approximation to that which would occur in space. If so, it is possible to do a wide range of surface effect experiments not previously possible as conventional extreme high vacuum chambers cannot maintain an adequate vacuum when testing dirty hardware, thus seriously comprising results. Included in this class of problems are coldwelding of certain kinds of spacecraft bearings, viability of biological specimens and degradation of thermal control surfaces.

Time is being scheduled in the MOLSINK and funding obtained for this kind of work but, before meaningful experiments can be performed, the environment must be defined. Because the environment is a direct function of the kind and amount of material emitted from an experiment, the facility must be calibrated in a particular manner. This calibration could also yield, in a very effective way, information useable for modifying the design or building more effective molecular sink simulators.

PROGRESS

This work unit was planned as a second quarter effort but, due to press of unexpected Mariner 69 tests requiring the MOLSINK, the experimental work had been rescheduled for later in the year. However, a helium refrigerator malfunction and the appearance of a significant leak between the guard vacuum and the inner vacuum have kept the MOLSINK out of service since January, 1969. Corrective actions have partially restored performance so that we can maintain a "pressure" reading of 10^{-10} torr for a few days but only 10^{-8} torr after one week: original performance was 10^{-11} torr indefinitely. We have procured a special leak detector which will be used to attack the elusive leak problem during July, 1969.

At one point in the series of leak checks, fixes and trial runs (which were our primary occupation during the past six months), the recontamination ratio apparatus was installed and operated. We found that the MOLSINK could absorb several grams per second of nitrogen for long periods of time. The heat of condensation of the gas on the cryogenic quartz crystal microbalances (CQCM) used caused a transient frequency shift of similar magnitude to that caused by mass accumulation. While we now have CQCM's with much lower temperature sensitivity, it may be necessary to make the recontamination ratio measurements with short gas pulses. The CQCM oscillators and other electronic circuits which must operate at about 10°K are being redesigned by our instrumentation section for better signal characteristics and increased reliability.

PUBLICATIONS

Meeting and Symposia Papers

1. Stephens, J. "A Space Molecular Sink Facility," 4th Aerospace Mechanisms Conference, Santa Clara, California, May, 1969.

SPACE VEHICLE DESIGN CRITERIA (124-12)

SPACE VEHICLE DESIGN CRITERIA PROGRAM SUPPORT

NASA Work Unit 124-12-01-02

JPL 324-20601-0-3500

H. Bank

OBJECTIVE

The objective of this work unit is to support the design criteria program of NASA Langley, Lewis, Goddard, and Electronic Research Centers which are developing design criteria documents for all of NASA's space programs. The JPL role in this activity is to provide (1) technical information concerning NASA projects assigned to JPL for the development of appropriate design criteria, (2) technical support for establishing the scope and content of design criteria documents, and (3) technical review and comment on acceptability of completed document drafts.

PROGRESS

Activities during this period included participation in the formulation of document content as well as review for official criteria approval. Reports involved include:

Structures (Under LRC cognizance)

(1) Radiation Hazard (Final Review)

(2) Buckling of Thin Walled Doubly Curved Shells (Final Review)

(3) Propellant Slosh Suppression (Final Review)

(4) Natural Vibration Model Analysis (Final Review)

(5) Sterilization Effects on Structure

(6) Transportation and Handling Loads

(7) Mechanical Surface Interactions

Environment (Under GSFC cognizance)

(1) Meteoroid Environment Model 1969 (Near Earth to Lunar Surface) (Final Review)

(2) Surface of Mars 1968 (Final Review)

(3) Magnetic Fields - Earth and Extraterrestrial (Final Review)

(4) Interplanetary Meteoroid Model Monograph

(5) Spacecraft Magnetic Torques (Final Review)

Propulsion (Under LeRC cognizance)

(1) Solid Rocket Motor Metal Cases Design Monograph

(2) Solid Rocket Motor Igniters Design Monograph

(3) Solid Rocket Motor Performance Analysis & Prediction

Guidance and Control (Under ERC cognizance)

(1) Spacecraft Radiation Torques

(2) Stabilization and Control for Translational Space Maneuvers

(3) Spacecraft Sun Sensors

(4) Spacecraft Star Sensors

(5) Single Degree of Freedom Gyros

(6) On Board Computing for Spacecraft

PUBLICATIONS

None

VENUS ATMOSPHERE ENVIRONMENTAL
DESIGN CRITERIA MONOGRAPH

NASA Work Unit 124-12-03-01

JPL 324-20201-0-2940

R. A. Schiffer

OBJECTIVE

The objective of this work unit is to synthesize existing state-of-the-art knowledge pertinent to the Venus atmosphere as required to prepare environmental requirements engineering monograph for use in space vehicle design. This monograph is intended to be a guide to Venus atmosphere environmental criteria and not as a NASA requirement, except as may be specified in formal project specifications.

As a part of the NASA Space Vehicle Design Criteria Program sponsored by the NASA Headquarters Office of Advanced Research and Technology, JPL was assigned the responsibility for the preparation of a Venus atmosphere environmental criteria monograph. Additional scientific measurements and theoretical studies are required before a clear understanding of the structure of the Venus atmosphere can be evolved. In the meantime, Venus atmosphere engineering models reflecting the best current knowledge are still needed for space vehicle design and mission planning. Accordingly, this monograph is intended to provide an interim set of standard models based on the latest scientific data. They should not be considered as new scientific models of the Venus atmosphere, however.

This progress report covers the activities in this task through the fourth quarter of FY 69.

APPROACH

The approach taken in accomplishing this task was to determine what information should be included in an atmospheric model for use in space vehicle design, collect and review the principal scientific Venus data, examine the compatibility of the various theoretical atmospheric models appearing in the literature with the measured data, and specify a set of consistent atmospheric models suitable for engineering purposes.

PROGRESS

The monograph, which appears as NASA SP-8011, "Models of the Venus Atmosphere (1968)," has been published. This task is completed.

PUBLICATIONS

Meeting and Symposia Papers

1. Schiffer, R. A., "Engineering Models of the Venus Atmosphere Based on an Interpretation of Recent Space Vehicle Observations of Venus," presented at the AIAA 7th Aerospace Sciences Meeting, New York, January 1969.

JPL Publications

1. Schiffer, R. A., "Engineering Models of the Venus Atmosphere," SPS 37-53, Vol. III, 1968.

2. "Models of Venus Atmosphere," National Aeronautics and Space Administration, NASA SP-8011, December 1968.

MARS SURFACE ENVIRONMENTAL DESIGN CRITERIA

NASA Work Unit 124-12-03-02

JPL 324-20301-0-2940

A. J. Beck

OBJECTIVE

The objective of this work unit is to synthesize existing state-of-the-art knowledge pertinent to the Mars surface as required to prepare a Mars surface environmental requirements engineering monograph for use in space vehicle design. This monograph is intended to be a guide to Mars surface environmental criteria and not as a NASA requirement, except as may be specified in formal project specifications.

As a part of the NASA Space Vehicle Design Criteria Program sponsored by the NASA Headquarters Office of Advanced Research and Technology, JPL was assigned the responsibility for the preparation of a monograph covering the Mars surface. This progress report covers the activities in this task through the second half of FY 69.

APPROACH

The approach taken in accomplishing this task was to determine what information should be included in a planetary surface model for use in space vehicle design, collect and review the principal scientific Mars surface data, examine the compatibility of the various theoretical surface models appearing in the literature with measured data, and specify a set of consistent surface parameters suitable for engineering purposes.

PROGRESS

The final JPL draft of the Mars surface environmental design criteria document was forwarded to NASA Headquarters during the third quarter FY 69. Upon receipt of this draft, a review copy was prepared by GSFC reflecting the style appropriate to the overall space vehicle design criteria program.

The version, "The Surface of Mars (1968) NASA SP-8020," will be distributed to the NASA Centers during June, 1969 for final review prior to publication. Comments from this final review will be incorporated in the monograph and publication will proceed under the direction of GSFC. With the publication of the document, the JPL effort involved in this task will have been completed and hence no effort is expected on this task during FY 70.

PLANS

It is expected that this task will be completed at the end of FY 69. Consequently, no future effort is anticipated.

PUBLICATIONS

None

MERCURY ENVIRONMENTAL DESIGN CRITERIA

NASA Work Unit 124-12-03-03

JPL 324-20401-0-2940

A. J. Beck

OBJECTIVE

The objective of this work unit is to prepare a Mercury environmental criteria monograph which contains a synthesis of pertinent state-of-the-art knowledge relative to the planet Mercury.

As part of the Space Vehicle Design Criteria Document program sponsored by the NASA Headquarters Office of Advanced Research and Technology, JPL has been assigned responsibility for the preparation of a monograph on the environment of the planet Mercury. This progress report covers the activities carried out in support of this task during the second half of FY 69.

APPROACH

The approach followed to accomplish this work unit consists of collecting and reviewing all pertinent state-of-the-art knowledge, examining the capability of observational data, and preparing a set of environmental engineering models which reflect the latest scientific knowledge of the planet Mercury.

The environmental criteria generated from these engineering models will be published in a Mercury Environmental Criteria Monograph.

PROGRESS

The effort to prepare a Mercury space vehicle design criteria document has continued at the previously reported low level of effort. A literature survey was initiated and a current bibliography of literature pertinent to the planet Mercury has been compiled. Published literature which has been gathered as a result of this search has been partially reviewed. As a part of the initial review of the atmospheric data of Mercury, some gross modeling for the atmosphere has been accomplished. This modeling currently considers the atmosphere to be composed primarily of carbon dioxide with possible traces of Argon. The atmospheric pressure at the surface is probably less than 4×10^{-2} mb and the temperature is probably about 100°K at the antisolar point and 600°K at the subsolar point.

In addition, a preliminary outline for the monograph has been composed and a schedule to completion of the monograph has been developed (Fig. 1). This schedule assumes that the funding level during FY 71 will be at a sufficient level required to complete the remaining effort by June, 1971.

PLANS

The future activity to completion of the Mercury space vehicle design criteria document is outlined in the schedule shown in Figure 1. The effort will continue at a low level of effort during FY 70 during which time the literature survey will continue and the observation data and the theoretical model will be reviewed. Selection of environmental parameters will be completed early during the first quarter of FY 71 and a draft of the document will be completed during the second quarter. Following reviews of the resulting document by JPL and NASA Centers, publication is expected during June, 1971.

PUBLICATIONS

JPL Publications

1. Schiffer, R. A., "Atmospheric Environmental Criteria for Mercury," SPS 37-56 Vol. III, April 1969.

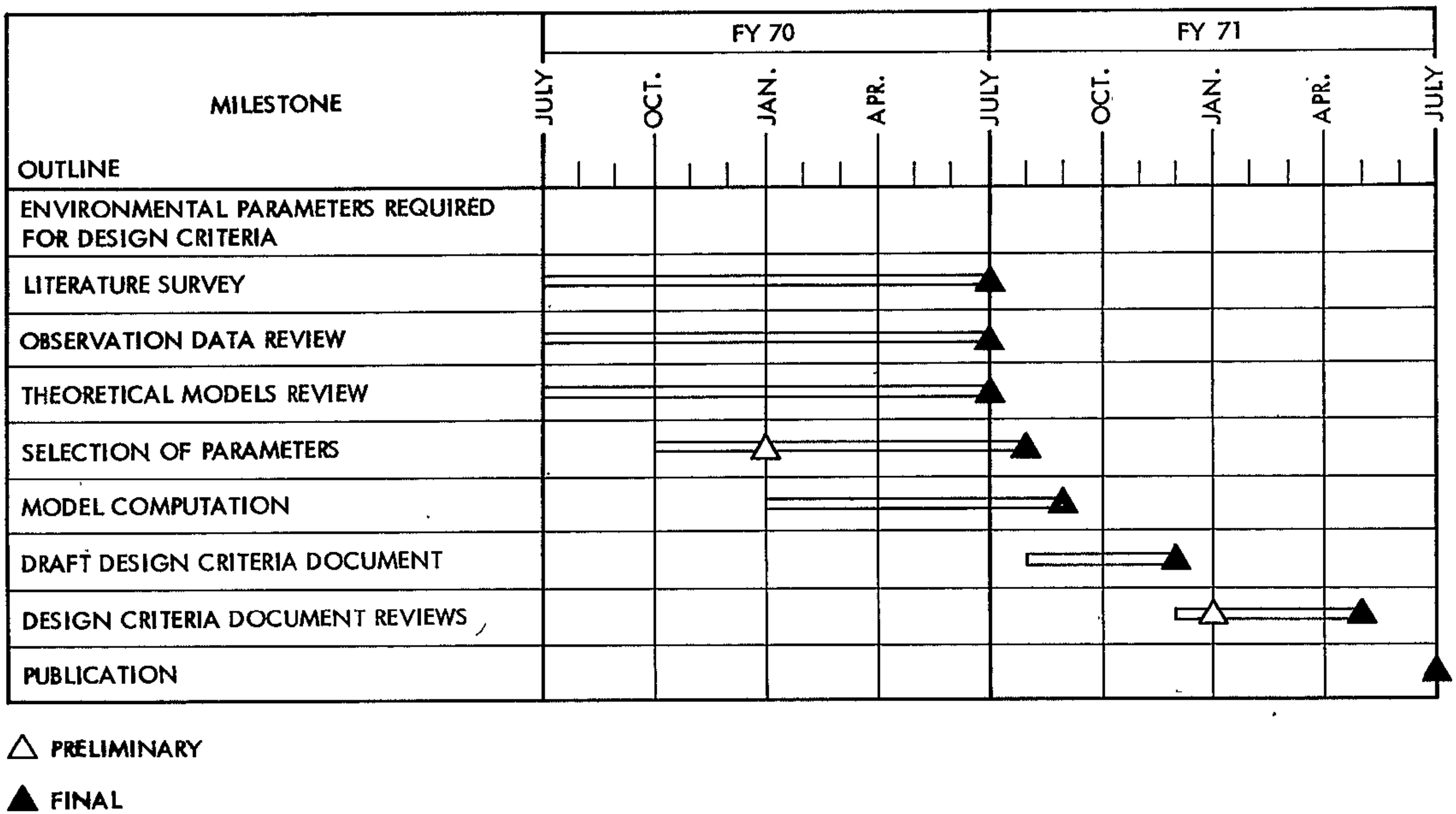

Figure 1. Mercury Monograph Plan

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JUPITER ENVIRONMENTAL DESIGN CRITERIA

NASA Work Unit 124-12-03-04

JPL 324-20501-0-2940

N. Divine

OBJECTIVE

The objective of this work unit is to prepare a Jupiter environmental criteria monograph which contains a synthesis of pertinent state-of-the-art knowledge relative to the planet Jupiter.

As a part of the Space Vehicle Design Criteria Document program sponsored by the NASA Headquarters Office of Advanced Research and Technology, JPL has been assigned responsibility for the preparation of a monograph on the environment of the planet Jupiter. This progress report covers the activities carried out in support of this task in the last two quarters of FY 69.

APPROACH

The approach adopted for this task anticipates the compilation of a comprehensive bibliography of recent published work relating to Jupiter, the assimilation of pertinent material, and the synthesis of current qualitative and quantitative information into a consistent description of the Jupiter environment. Space vehicle environmental design criteria will be generated from this description and published by NASA in a Jupiter environmental design criteria monograph.

PROGRESS

A program of interviews with spacecraft subsystem designers has been completed, resulting in the preparation of detailed matrices which describe the level of subsystem interaction with possible Jupiter environment topics. On the basis of this information a monograph outline, which anticipates fifteen topical subsections in each of the "State-of-the-art" and "Criteria" sections, has been prepared and attached (Table I). Determination of the scope and depth of the monograph coverage for each of these subsections has been completed.

A bibliography of Jupiter-related publications, essentially complete for 1965 through 1968, with some earlier citations, has been published (Ref. 1). The bibliography, in which the abstracts for most of the papers cited are categorized by topic, has been used to select the most pertinent reference material for the monograph subsections. That material has been reviewed for each subsection prior to assembly of the information into the best state-of-the-art description of the environment.

A contract (pursuant to Procurement Requisition 042982 and Purchase Order GP-506185) has been completed which calles for the assistance of Dr. James W. Warwick (Dept. of Astrogeophysics, Univ. of Colorado, Boulder) in the preparation of the monograph sections relating to the Jovian radio emission, magnetic field, and trapped radiation belts.

PLANS

A schedule which is consistent with that presented in the May 15, 1969, RTOP submission, and which anticipates completion of a monograph draft in December, 1969, and publication at the end of FY 70, has been prepared as Table II.

From the literature reviewed as described above the best state-of-the-art description of the Jupiter environment, including uncertainty specifications, will be developed, and then modified according to the results of discussions with Jupiter experts at JPL, the several NASA Centers, and elsewhere. On the basis of this description the pertinent design criteria parameters will be evaluated and incorporated into a draft text of the monograph, which will become available for JPL and NASA reviews in the third quarter of FY 70. A final draft will be prepared after the completion of the review procedures, and publication of the monograph is anticipated at the end of FY 70.

PUBLICATIONS

JPL Publications

1. Sterkin, Carol K., "Jupiter and the Jupiter Environment," Jet Propulsion Laboratory Literature Search No. 886, 563 pp., Pasadena, California, January 13, 1969 (also Supplement No 1, 11 pp., May 26, 1969).

TABLE I

OUTLINE for JUPITER ENVIRONMENTAL DESIGN CRITERIA MONOGRAPH

FOREWORD
Standard monograph program summary and acknowledgments

TABLE OF CONTENTS

1. INTRODUCTION
   Definition of the environment
   Environment-spacecraft interactions
   Related monographs in series

2. STATE OF THE ART

   2.01 Gross Physical Properties

2.02 Gravity Field 2.03 Magnetic Field 2.04 Electric Field 2.05 Electromagnetic Radiation Field	Field Environments
2.06 Satellites and Meteoroids 2.07 Exospheric Gases 2.08 Charged Particles 2.09 Radiation Propagation and Transfer Properties (beyond atm.)	Particle Environments
2.10 Atmospheric Structure 2.11 Visible Cloud Features 2.12 Atmospheric Motions 2.13 Radiation Propagation and Transfer Properties (within atm.)	Fluid Environments
2.14 Surface 2.15 Interior	Solid Environments

3. CRITERIA

   3.01 Gross Physical Properties

   3.15 Interior

4. RECOMMENDED PRACTICES (if any)

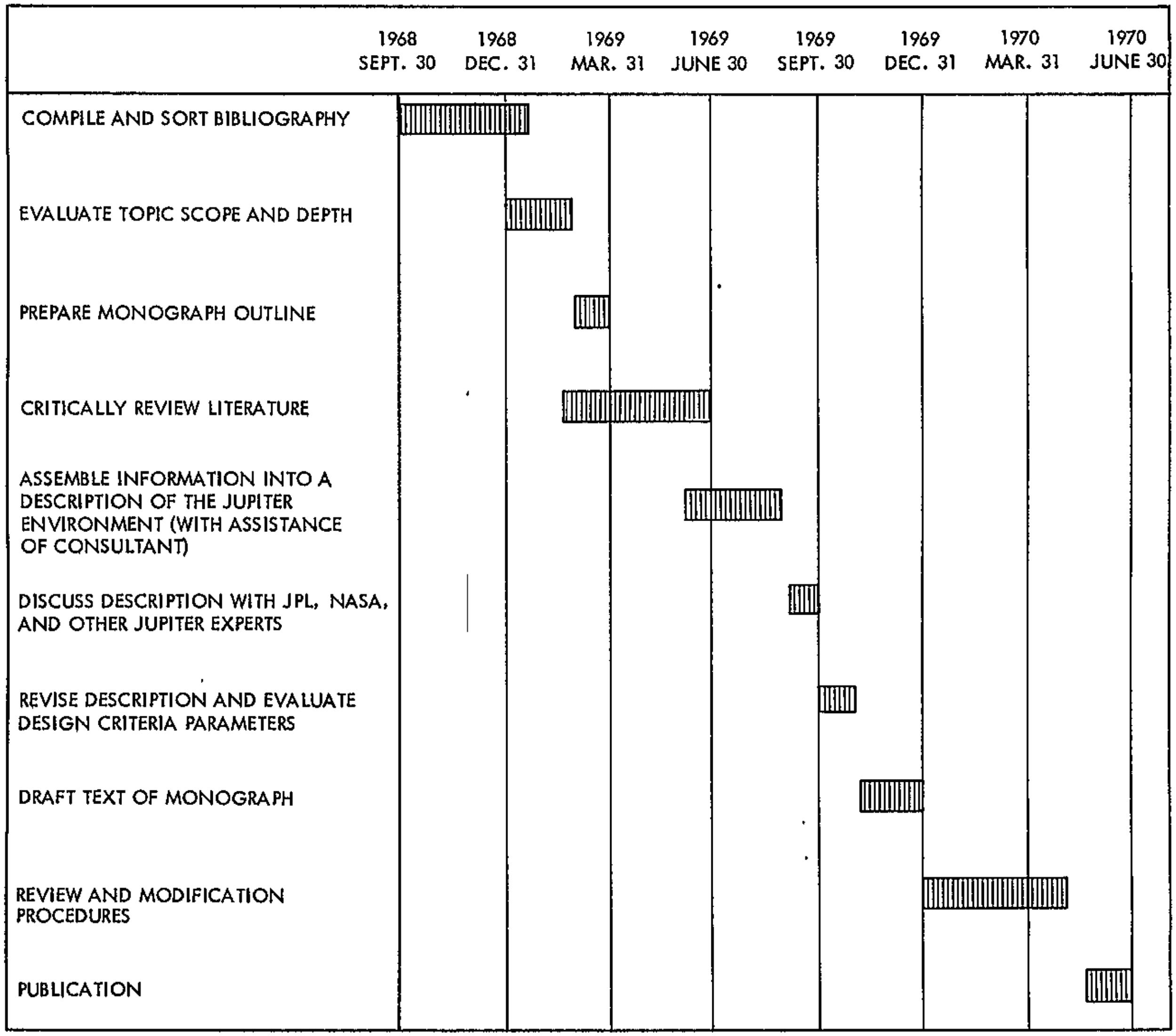
REFERENCES

APPENDIX A. Definitions of Symbols

APPENDIX B. Mathematical Formulations (if any)

APPENDIX C. Glossary

Table II. Schedule of Development Activities for Jupiter Environmental Design Criteria Monograph



ELECTRONICS SYSTEMS SRT (125)

EXTREME TEMPERATURE REQUIREMENTS FOR ELECTRONIC PIECE PARTS

NASA Work Unit 125-06-02-01

JPL 325-60101-0-2940

T. E. Gindorf
T. Hutchinson

OBJECTIVE

The objective of this work unit is to determine temperature and life requirements for survival and operation of electronic components which will be used as criteria for development of electronics piece parts for future space missions.

APPROACH

The Extreme Temperature Requirements study is being done in several phases. The approach selected assumes that some form of thermal control (requiring a finite amount of weight and power) would be used on all future missions. The missions considered can then be classified as flyby, orbiter, or lander missions (in ascending order of thermal control complexity) and according to the temperature requirements for the extreme cases of each mission type. The last year's effort dealt with the determination of what temperature extremes were likely to be encountered by electronics parts on future outer planet space missions.

Previously, it was shown that the spacecraft bus could be thermally decoupled from the solar environment for flyby missions. Once this is done, a reasonable amount of thermal control (typically less than 4% of total weight and power) is sufficient to maintain acceptable electronics temperatures inside the bus. Therefore, the extreme temperature problem is reduced to considering only the effects on items which cannot be included in the bus such as science experiments and attitude control sensors.

For any particular spacecraft using such thermal control methods, the problem of discovering which electronics parts types will experience severe temperature environments is evaluated by accomplishing the following tasks:

(1) Parts identification - listing the electronics parts types contained in each spacecraft subsystem, along with the present temperature capability of each parts type to be used.

(2) Thermal studies - estimating the temperature extremes to be encountered during the mission for all subsystems, and evaluating the penalty (in weight and power) imposed by the thermal control approach.

The class of missions selected for study in FY 69 was JPL's Thermoelectric Outer Planets Spacecraft (TOPS). The primary mission of TOPS is the Grand Tour Flyby of Jupiter, Saturn, Uranus and Neptune during the unique 1976-79 launch opportunity. Such a mission was considered to be the limiting cold-temperature case for any flyby missions planned for this century.

PROGRESS

Both the parts identification and thermal studies tasks listed above have been completed. A draft of the final report describing FY 69 activity has been prepared, with publication of the report to take place shortly.

The following conclusions were reached:

(1) Development of special low temperature electronics parts is not necessary to insure a successful TOPS mission, but the price that must be paid for using currently existing parts types is increased thermal control power and weight for the science experiments, tighter thermal design, and perhaps constraints on mission operations.

(2) These constraints could be eased considerably by use of electronics parts types capable of surviving temperatures as low as -100 to -125°C (about 45°C lower than quoted capability of most current parts).

(3) Since the actual lower limit of many parts is not established, if development of new parts types is chosen to avoid paying the weight and power penalties of using current parts types attempts should first be made to qualify existing parts types for lower temperature levels.

(4) The minimum electronics likely to be mounted at a non-bus location would consist of a detector element and pre-amplifier (containing linear bipolar and MOS IC's, metal film and wire-wound resistors, ceramic capacitors, inductors/transformers and discrete semiconductors such as transistors, diodes, FET's, zeners and thermistors). If qualification of existing electronics at lower temperatures proves fruitless, development of new parts should begin with these types.

PLANS

FY 70 will be concerned with applying the same study techniques to the extreme high temperature case (inner planet flybys). Also to be examined will be the problems posed by orbiter and lander missions.

PUBLICATIONS

None

GUIDANCE SYSTEMS (125-17)

INERTIAL SENSORS—ELECTRICALLY SUSPENDED GYROSCOPE

NASA Work Unit 125-17-01-02

JPL 325-70501-X-3440

T. J. Donlin

OBJECTIVE

The objective of this work unit is to develop a strapdown, electrically suspended gyroscope (ESG) to be an inertial, two-axis, angular reference sensor for spacecraft and capsule attitude control. The objective during this reporting period was to complete the evaluation of the remaining ESG test data and to terminate the effort.

PROGRESS

The test program was successfully completed with the test data analyzed for ESG performance. No further testing will be performed. The final report on JPL Contract 951149 has been submitted for approval.

ESG Drift Testing

The drift testing and data analysis during this final period have been directed toward correlating the ESG performance with the math model and theory. As stated in the previous report, six drift tests were conducted on the ESG to verify the math model calibration procedure developed from the simulation study. During this reporting period, additional drift tests were conducted to evaluate the math model torque coefficients' sensitivity to changes in the suspension preload voltages, the rotor speed, and the gravity vector. Two of the six original tests were used as control tests for the second test phase. These two tests gave the best fit of the math model to the data for the calibration procedure. These two tests had identical test conditions except for the spin axis location. The spin axis locus was 60° from the Earth's Polar Axis (EPS) for the first case, and for the second case, the spin axis locus was 120° from the EPS. The Y force axis was North East, the X force axis was South East and the Z axis was vertical.

Six tests were conducted to evaluate the gravity vector influence on the ESG. Three groups of two tests were made, each group repeating the spin axis loci used in the control test. The first group of tests was conducted with the Z axis up, the second group was made with the Y axis up, and the third set with the Y axis down. A group of two tests was conducted to evaluate the effect of changing the suspension voltage. The two control tests were again repeated with the suspension voltage at the 15-g pre-load level, rather than the 4-g pre-load level of the control tests. One of the two tests was conducted with the spin-axis locus in the plane of the housing split and parallel to the earth equatorial plane. This test was then used as a prediction of the gravity vector math model solution for the drift coefficients.

Two additional tests were conducted repeating the control tests but with the rotor speed at 180 RPS. All other tests were conducted at 200 RPS rotor speed.

Test Results

Gravity Vector Sensitivity

According to theory, the mass unbalance and third harmonic torque coefficients are linear functions of the gravity vector, while the fourth harmonic and ellipsoidal rotor torque coefficients are quadratic functions of the gravity vector. Comparison of the torque coefficients from the tests where the Y axis was up, with the torque coefficients from the tests where the Y axis is down, gave an indication of agreement between ESG torque theory and experimental results. A set of torque coefficients developed from these four tests was used for a prediction of the drift error compensation. The ratio of residual error to uncompensated error was approximately 25 percent using this prediction.

Suspension Preload Sensitivity

The results of the testing showed no preload sensitivity of the mass unbalance and the third harmonic rotor shape torque coefficients. The sensitivity of the fourth harmonic rotor shape torque coefficient to the force voltage, was determined to be proportional to the square of the force voltage.

These results are in agreement with the ESG torque theory. However, the rotor translation torque coefficients were found to increase with increased preload which does not agree with theory. This non-correlation was attributed to electrode assembly errors.

Rotor Speed Sensitivity

The change in rotor operating speed had no discernable effect on the mass unbalance or on the third harmonic rotor shape torque coefficients. A significant speed sensitivity was noted in the changes to the ellipsoidal rotor shape coefficients at the reduced rotor operating speed. These changes to the torque coefficients are in agreement with ESG torque theory.

PLANS

The current objectives have been completed and this work unit will not be continued in FY 70.

ANTICIPATED PUBLICATIONS

Contractor Reports

Honeywell, Inc., "Strapdown Electrically Suspended Gyroscope Development," Final Report, 20-302, JPL Contract 951149, to be issued.

PUBLICATIONS

JPL Publications

Donlin, T. J., "Strapdown Electrically Suspended Gyro," SPS 37-55, Vol. III, February 1969.

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SEAN SYSTEM DEVELOPMENT

NASA Work Unit 125-17-01-04

JPL 325-70901-0-3410
JPL 325-70902-0-3430
JPL 325-70903-0-3440
JPL 325-70904-0-3440

B. M. Dobrotin
G. Paine
E. Imlay
G. T. Starks
R. E. Williamson

OBJECTIVE

The Strapdown Electrostatic Aerospace Navigation (SEAN) System program is a joint NASA/JPL/USAF cooperative effort to determine the feasibility of a strapdown navigator incorporating electrostatically suspended gyros (ESG).

JPL is responsible for the system design and development, system analysis, integration, and test. The Air Force Avionics Laboratory is providing the gyros, the inertial measurement unit (IMU) and support electronics (IMU console). The JPL effort is divided into four major task areas within the Guidance and Control Division. Implicit in the SEAN program (though not included as a separate activity) is the task of system integration and test. As an aid in understanding the interrelation of the tasks, the SEAN functional diagram may be referred to in JPL Report 701-23.

PROGRESS

System Testing

System navigation has begun, using the one available ESG. Qualified results have been obtained in the 3 to 4 knot range. The qualifications are in the use of one uncalibrated and uncompensated gyro and simulating a perfect second gyro. The ESG was positioned with the spin vector in a polar orientation. An automatic alignment and initialization was performed and the system automatically switched to the navigate mode. Runs of several hours have been obtained. Typical plots of down-range and cross-range error are shown in Figure 1.

These tests are made by positioning the ESG in a low-drift configuration, thus, minimizing the effects of gyro drift on system performance. This type of navigation test allows performance of the remainder of the navigation system to be evaluated under actual navigation conditions. This includes computer program roundoff, accelerometer errors, etc.

The results of these tests indicate that the ultimate performance of SEAN will be determined by the compensated drift rate of the ESG's. This is indicated in two ways. First, the system drift rate is low enough that individual source errors may be observed. Second, for the ESG drift obtained during these tests, the analytical prediction agreed with the actual system performance.

The IMU was calibrated for system testing. It was the first time both ESG's were installed in the IMU and the IMU was used as a complete inertial sensor, measuring both acceleration and attitude. Calibration consisted of installing the ESG's in the IMU, aligning them to the IMU reference axes and performing the calibration tests. This consisted of measuring the pickoff misalignments and performing a series of 30 hour drift tests on both ESG's. During the drift testing, the data reduction program indicated apparent changes in the spin axis, when the ESG optical pickoffs were switched, of up to 8 arc-min. The problem was resolved by an extensive ESG calibration program, involving efforts by both the Inertial Sensor and Analytical Groups.

Inertial Sensors

As mentioned above, the ESG's were installed in the IMU and drift tested. Upon discovery of the apparent changes in the spin axis position when the pickoffs were switched, a series of special tests was instigated to determine the cause of these shifts.

During these tests, suspension power was removed from ESG 1 and the rotor was dropped, destroying the rotor assembly. The ESG was returned to the manufacturer, Honeywell, Inc., and the rotor assembly was replaced

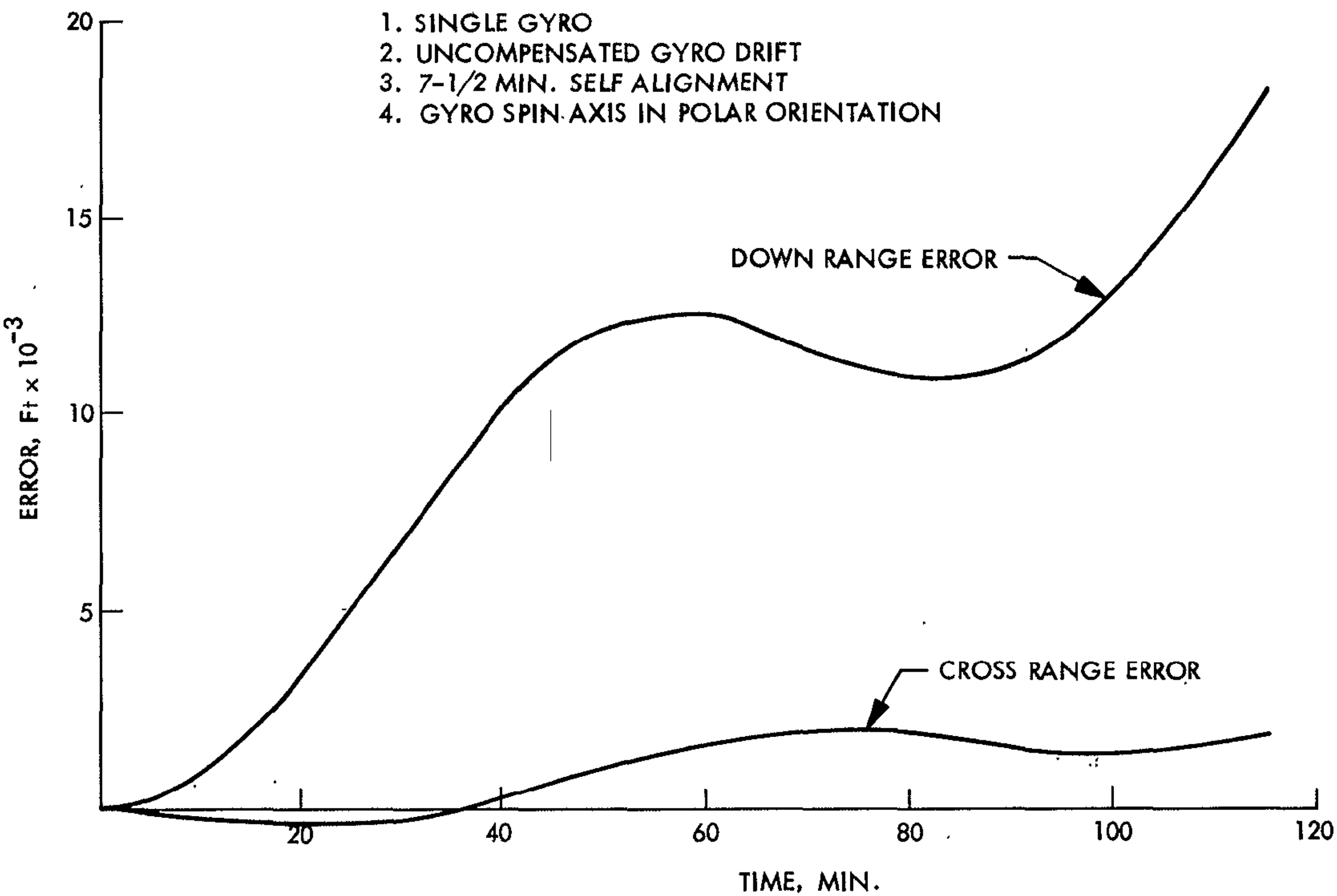

Figure 1. SEAN System Performance

by a spare assembly, S/N 3. After return to JPL the housing assembly developed a vacuum leak, and is now at Honeywell for repair. Delivery should be at the first of FY 70.

Testing eliminated the test equipment as a source of error and both ESG's (S/N 2 and S/N 3) were recalibrated in the single-gyro test fixture and the IMU. It was shown that two problems existed. First, there was the difference in environment between the IMU and the single-gyro calibration procedures. The calibration of the ESG at the component level is now done at JPL and simulates the IMU environment as closely as possible. This not only minimizes mechanical distortion, but also eliminates any variations in the pickoff electronics due to component thermal coefficients.

A second and perhaps predominant reason for the spin axis steps is the difference in the ability of the optical pickoffs to read the double width rotor pattern. A line calibration for each pickoff was made.

During the initial IMU calibration the position of the ESG within the IMU was found to vary by as much as ±20 arc-sec. Repeated measurements have shown that this is due to thermal cycling of the IMU during operational periods. This has accounted for many of the inaccuracies noted when attempting to do component level testing in the IMU.

The shock and vibration isolation cradle ordered during the last reporting period have been received and acceptance tested. After rework by the vendor, the units met the original specifications which were to reduce a combined 10g shock and 3g vibration environment to less than 3g total.

SEAN System Analysis Task

During the last half of FY 69, substantial progress has been made in four distinct areas: gyro calibration techniques; development of a flight computer program; development of a basic data reduction program; and specification of a complete set of laboratory tests to isolate individual system errors. The work performed in the first area mentioned was not anticipated in earlier schedules and became necessary with the appearance of various anomalies in the gyro test data as previously described.

ESG Analysis

Several advanced calibration techniques have been developed during the last two quarters of FY 69. These techniques were necessitated by anomalous gyro behavior. Fundamentally the problem appears as an apparent shift of the gyro spin axis as different sets of pickoffs are used to sense its position. A partial cure has been found. The shift can be minimized by calibrating the rotor pattern three times, once per pickoff, rather than just once. Previously a single set of coefficients had been used to read out each gyro, now three sets are used. As part of this work the sensitivity of the pickoff to angle of incidence between the pattern and the case axis was tested and found to be low.

These calibration techniques required the development of several new computer programs for test data reduction and verification. The apparent spin axis shift has been reduced from a maximum of 8 arc-min to 2 arc-min at the check points. The flight math model has not been completed.

System Analysis

A set of system tests has been developed to aid in the isolation of system errors. These tests are to be performed in a laboratory environment with the first computer navigation program and make full use of the optical alignment data available, as well as the low background noise. These tests are systematic in nature and require the use of simulated sensor data. The tests first show the computation errors using simulated DVM's and ESG. Next, the DVM's are tested while employing simulated gyro data. Finally, the full system is tested and the simulated data are used only for comparison purposes. By this procedure, which requires several navigation runs with the IMU in different positions for each test category, it is expected that the DVM errors and the ESG errors can be factored out of navigation results.

Flight Computer Program Development and Support

During this reporting period, a complete navigation program for laboratory usage has been developed. This program is made up of the segments reported in the previous period coupled with some new ones. The program is capable of self-contained alignment, navigation, making data available to the DRS, and has a built-in inertial sensor simulator which allows the program to perform the system tests discussed above. In addition, programs have been developed for both the IBM 7094 and the Univac 1108 to allow rapid reduction of the data placed on the DRS tape. These programs have been used for flight computer debugging and the production of quick-look down and cross-range errors rather than for systems error analysis.

CAD and Computer

The environmental testing of the Honeywell Alert computer has raised the MTBF from 20 hours to 100 hours. This last figure is acceptable if repairs may be made quickly, so that little computer down time is experienced. To enhance the repair capabilities, an assortment of spares has been ordered from Honeywell and diagnostic equipment is being fabricated. Both tasks are expected to be completed during the first quarter of FY-70.

During the last reporting period, the Alert memory has failed completely and been repaired, the central processor has had several IC failures and the power supply has failed twice. However, due to the immediate response of Honeywell field service, the computer has been available for system support when needed.

The CAD buffers which receive the ESG HIT signals have been reworked to improve noise rejection. Two IC's in the CAD have failed and a component failure analysis has indicated that the IC's contained manufacturing defects.

Van-System

During this reporting period, the van system was completed and is now ready for a van installation of the SEAN system. This includes installation of the air conditioners, addition of 60 Hz generators to power the air conditioners, fabrication and installation of the console support cradles and completion of a Safety Analysis Program.

Power Subsystem

The un-interruptable power conversion unit was returned to the manufacturer for extensive rework. Upon completion of the rework, which was to provide satisfactory operation on 400 Hz, the power unit was extensively tested at JPL on dummy loads. Upon re-integration with the SEAN system, it was discovered that the power supply could not handle starting transients, necessitating rework of the IMU console. The unit was used to power the SEAN system until a component failure caused shutdown of the power supply. The unit was repair, retested and is undergoing integration with the SEAN system.

Digital Recording System (DRS)

Acceptance testing and integration of the DRS has occupied all of this reporting period. At present, the DRS is supporting the laboratory tests, but is not suitable for van testing due to a connector problem. This problem is being resolved with the vendor.

Altimeter

The altimeter has been returned to the vendor three times for rework. Delivery is expected during the first quarter of FY 70.

Cabling

All cabling was finished and has been delivered during this reporting period.

PUBLICATIONS

Meeting and Symposia Papers

Dobrotin, B. M., "SEAN, a Strapdown Electrostatic Gyro Aerospace Navigator," ION Space Navigation Conference, April 24, 1964.

JPL Publications

Williamson, R. E., "SEAN OSE," SPS 37-57, Vol. III.

Dobrotin, B. M., "SEAN System Testing," SPS 37-56, Vol. III.

Starks, G. T., "SEAN IMU Task," SPS 37-58, Vol. III.

OPTICAL APPROACH GUIDANCE ANALYSIS AND DESIGN

NASA Work Unit 125-17-02-01

JPL 325-70802-2-3430

T. C. Duxbury

OBJECTIVE

The objectives of this task are to demonstrate near planet encounter orbit determination using spacecraft-based optical measurements, and to show that these measurement data can be processed by earth-based computing equipment to provide a trajectory estimate within the time constraint of near-encounter operations.

PROGRESS

Mariner Mars 1969 Optical Orbit Determination

The feasibility of using spacecraft-based measurements in near-real-time for estimating the spacecraft trajectory is to be demonstrated during the near-encounter phase of Mariner Mars 1969 mission. The on-board measurements will be obtained from the far-encounter planet sensor (FEPS), attitude control (A/C) sensors, scan platform (SCAN), and television, and will be combined to give Mars' direction as the observable for the orbit-determination process. The measurements will be ground-processed and used to estimate the spacecraft trajectory prior to encounter. The ground software system to process these spacecraft measurements is 90% complete.

A study has been performed to determine the expected accuracy of the trajectory estimate based on the on-board data. It was determined that the limiting accuracy of the trajectory estimate was a function of the ability of the spacecraft-based instruments to yield planet direction information: approximately 150 km (1σ) for the FEPS and approximately 100 km (1σ) for the TV.

Mariner Mars 1971 Optical Orbit Determination

An orbit determination accuracy study has been performed based on expected characteristics of TV data that can be obtained during the approach to Mars. It was found that viewing the natural satellites of Mars could yield more accurate information about the direction to Mars than that obtained by viewing Mars itself. TV science data could be used to reduce the uncertainty in the spacecraft trajectory to approximately 60 km (1σ) at one day prior to Mars encounter.

Thermoelectric Outer Planet Spacecraft (TOPS) Project

The MM '69 and MM '71 efforts directly support the TOPS-related approach guidance activities being performed under Work Unit 125-17-05-55 (Guidance Studies for Future Missions) and Work Unit 186-68-02-21-55 (Guidance and Control Subsystem Integration for Future Missions). The knowledge and experience gained from processing on-board optical flight data will form a basis from which the definition and requirements of an outer planet on-board guidance instrument will be derived.

PLANS

Mariner Mars 1969 Optical Orbit Determination

The ground software system will be completed and the near-real-time orbit determination demonstration will be performed. Post-encounter analyses of the spacecraft data will include both a comparison of the near-real-time trajectory estimate with the earth-based post-encounter estimate, and an in-flight pointing calibration of the science package. The use of land-marks as navigation observables will be investigated.

Mariner Mars 1971 Optical Orbit Determination

An orbit determination accuracy study will be performed based on TV data expected to be taken while orbiting Mars. The software system to process MM '71 pre- and post-insertion data will be defined. Data interfaces will be established with the MM '71 project.

PUBLICATIONS

Meetings and Symposia Papers

Breckenridge, W. G., Duxbury, T. C., "Investigation of Planetary Navigation Using Spacecraft-Based Measurements," ION National Space Meeting, Houston, Texas, April 1969.

Duxbury, T. C., "Spacecraft Navigation Using Science Television Data," AIAA/AGU Astrodynamics and Related Planetary Sciences, Washington, D. C., April 1969.

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DEVELOPMENT OF ADVANCED ELECTRO-OPTICAL SENSORS

NASA Work Unit 125-17-02-02

JPL 325-71101-X-3440

W. C. Goss

OBJECTIVE

This work unit provides for studies of new sensor requirements and for the development of new concepts into advanced electro-optical sensors. These sensor developments are directed toward advanced mission applications. The tasks to be performed are (1) star tracker improvement studies, based on the MM '69 Canopus Tracker as a baseline, and (2) obstacle avoidance sensor studies based on an active laser radar mapping concept.

This work unit had planned an additional objective of developing an optical sensor as part of a subsystem for the pointing of a high gain radio antenna toward earth. The subsystem effort has been discontinued and so the optical sensor development has not been pursued.

Star Tracker Signal Processing Study

This subtask is in support of the technology development needed for outer planet missions. Study results completed this period were: (1) an evaluation of the response of signal processing circuit components to signals large enough to cause non-linear operation and saturation, including response to frequency components outside the fundamental modulation frequency; (2) an evaluation of the response of the signal processing circuits to large noise inputs, as would occur with heavy illumination backgrounds in the field of view or with anomalous noise inputs; (3) an optimization of the preamplifier design; (4) a definition of typical image dissector tube performance and noise characteristics; (5) an evaluation of demodulator frequency stability; and (6) a recommendation for modifications to the M '71 Canopus Star Tracker.

Several study elements listed in the last semi-annual report were not completed for the following reasons. The relative advantages and disadvantages of fixed electron-multiplier voltage versus an automatic gain control (AGC) to maintain a constant star signal current was found to lie simply in favor of the AGC approach, which limits anode current to a safe value and allows use of relatively simple pre-amplifier and demodulator circuits. Response of circuitry to time and temperature was not undertaken because recent data, from a nine month life test on a flight model MM '69 tracker provided the needed information.

The radiation environment definition and circuit response study has been re-scheduled as a task for FY 70 under NASA Work Unit Number 186-68-02-19, entitled Optical Sensor Techniques and Components. These efforts will include the definition of a probable radiation profile for the star tracker and the exposure of a residual MM '69 tracker to representative radiation levels to determine prompt and long term effects.

Obstacle Avoidance Sensor

This task is in support of future unmanned landed operations for which an automatic obstacle recognition and avoidance technique will be needed.

Accomplishments this period were more fundamental than we had projected last period. The manpower allowed was largely absorbed in the efforts of getting facilities, equipment and building block components together.

During a preliminary study phase, it was found that the question of source/modulator/detector combinations was not significant compared with the basic problem of suitable techniques for obtaining the measurements needed. A single basic approach was conceived of using passive mode-locking to generate a nanosecond duration optical pulse inside a low loss laser cavity, and extracting the relatively high-powered pulse at intervals of about one microsecond with an optical switch. In this way a laser beam modulated with frequencies from megacycles to gigacycles will be generated, thus, providing the inherent capability of optical measurements of distances to targets up to hundreds of feet in range with resolution of much less than a foot. Passive techniques for pulse switching may be possible, as an alternative to the optical modulator.

Efforts then were directed toward getting a mode-locked helium-neon laser operating as a test vehicle for development of components. Accomplishments include:

(1) Completion of the laser test area, including safety precautions to the satisfaction of the JPL safety representatives. Controlled access with warning lights and an entry alarm are used.

(2) Fabrication of a solid-state detector assembly having response at least to 400 megacycles. This detector will be used with a spectrum analyzer to determine signal frequency content and, with a sampling oscilloscope, to look directly at the pulse structure in the time domain.

(3) Fabrication of vacuum-bases for the precision equipment to be used on the granite slab. The bases lock solid to the granite upon application of the vacuum without changing optical alignment.

(4) Design of a Brewster-angled neon gas cell to mode-lock the helium-neon laser. This technique promises the advantages of passive mode-locking without the depletion problems associated with saturable dyes, for example. Assembly of the cell and mode-locked laser operation are expected to occur this reporting period.

(5) Lithium Niobate crystals for the optical switch have been ordered. The crystals will be selected for low scattering and absorption loss, since they will operate in the cavity. A preliminary design of the optical switch mount has been made. A passive switch driving circuit is being evaluated. This would involve a gated high-current photomultiplier tube, excited by leakage flux through the laser reflectors, close-coupled to the optical switch.

(6) A photomultiplier detector with sub-nanosecond response time has been placed on order. A detector mount providing for matched impedance coupling and electrostatic and magnetic shielding has been designed and is being fabricated.

(7) An optical spectrum analyzer, to display laser mode structure has been procured. This will be a principal diagnostic tool in the evaluation of mode locking techniques.

PLANS

Plans for the Next Period Include:

(1) Study of the neon mode-locking cell with respect to the basic mechanism of operation, optimization of design from the viewpoint of weight and power and optimum techniques for integrating into a packaged laser.

(2) Study of the mode-locked laser operation to determine relative electrical to optical power conversion efficiency, mode stability and transient characteristics of a mode-locked laser used in a pulse-sampling mode.

(3) Assembly and preliminary tests of the optical switch.

(4) Assembly and use of the sub-nanosecond response photomultiplier detector.

ANTICIPATED PUBLICATIONS

JPL Publications

SPS Contributions R. H. Burns, Spurious Canopus Tracker Outputs, SPS 37-57, Vol. III, July 1969.

PUBLICATIONS

None

GUIDANCE COMPUTER ORGANIZATION

NASA Work Unit 125-17-04-02

JPL 325-70401-0-3410

D. A. Rennels

OBJECTIVE

The objective of this work unit is the development of designs and design techniques for ultrareliable spacecraft guidance computers to be used in unmanned space vehicles with missions of several years. The major effort is the design and construction of an experimental self-testing and repairing (STAR) computer. When completed, this machine will be used to verify its predicted performance in case of failures and to study the effects of transient errors. Software for this machine, as well as a mathematical investigation of the reliability of fault-tolerant machines, is being carried out under a related work unit: System Programming for STAR Computer Work Unit 125-17-04-03.

PROGRESS

Construction of the memory interface unit, control processor, and a subset of the test and repair processor is complete and these functional units have been debugged and are operating satisfactorily. These units have been interconnected and are functioning as a programmable (STARLET) computer. Approximately 50 of the 216 STAR operation codes are now functioning and a number of programs have been run on this limited system.

The bootstrap I/O system has been completed and allows loading of programs into the computer via rotary switches or an incremental card reader. Construction of interface logic for an electric typewriter has been completed and it is expected to be operating in the system in approximately one month.

Design and construction of new functional units to be added to the computer system has begun. A logic processor is currently being built which will allow the programmer to perform logical operations such as AND, OR, EXCLUSIVE OR, and TEST of data words and will also perform the operations ADD, SUB and, by use of subroutines, MULTIPLY and DIVIDE. Since error detection codes are not maintained under logical operations, two of these processors will be constructed, and error detection will be performed by comparing their outputs.

A second memory interface unit is being constructed which will allow expansion of memory capacity from 4096 to 8192 words.

These units are designed (as were the previous units) for convenience of error analysis and testing. All internal registers are displayed with lights on the front panel, and special switches are provided to allow offline testing.

Design of a new arithmetic processor is continuing. The processor is being designed in such a way as to allow the programmer the option of floating point and multiple precision arithmetic. Design is also continuing on the STAR computer central controller, the test and repair unit.

PLANS

Construction of the logic processor and memory interface unit is continuing and should be complete in the fall of 1969. Construction of the arithmetic unit will be undertaken and the current test and repair processor will be expanded to provide error detection and localization. The study of medium scale integrated circuits applicable for use in a STAR prototype system will be continued. Some low power bipolar MSI devices are currently being used in the logic processor and will be used in future functional units.

A design effort is currently under way to construct the filters and other electronic circuits necessary to integrate the magnetic power switches into the STAR system.

Detailed design of the interrupt and I/O processors will begin in the next few months. These units will be designed to provide a highly flexible I/O system which will be capable of handling simulated spacecraft inputs as well as conventional I/O devices such as typewriter, magnetic tape, etc. The I/O processor will be different from the interim bootstrap I/O system.

A series of tests will be conducted on the STAR computer to validate fault detection and recovery procedures and provide information for their future refinement.

PUBLICATIONS

Meetings and Symposia Papers

1. A. Avizienis, "Design Methods for Fault-Tolerant Navigation Computers," National Space Meeting of The Institute of Navigation, Houston, Texas, April 23, 1969.

2. A. Avizienis, "Digital Fault Diagnosis by Low-Cost Arithmetic Coding Techniques," Purdue Centennial Year Symposium on Information Processing, Purdue University, Lafayette, Indiana, April 28, 1969.

3. A. Avizienis, "A Real-Time Diagnosable Arithmetic Processor for Product ("An") Coded Operands," IEEE Workshop on the Theory of Computer Arithmetic, Minneapolis, Minnesota, June 16, 1969.

4. A. Avizienis and D. A. Rennels, "Automatic Maintenance Aspects of Data Processing in Unmanned Spacecraft," Joint National Meeting of the American Astronautical Society and the Operations Research Society, Denver, Colorado, June 19, 1969.

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SYSTEM PROGRAMMING FOR STAR COMPUTER

NASA Work Unit 125-17-04-03

JPL 325-71001-0-3410

F. P. Mathur, J. A. Rohr, J. J. Wedel

OBJECTIVE

The objective of this work unit is the development of software for the STAR computer. This computer is being developed under the Guidance Computer Organization Work Unit 125-17-04-02 to which reference should be made for overall objectives.

The primary objective is the development of system software including an assembler, a STAR simulator, and an executive program. It is also expected that the work unit will support applications programming during the period when the STAR is under development and the primary users are the STAR computer personnel.

The work unit is also investigating the problems of estimating and quantifying the reliability of fault-tolerant computer configurations. This work will lead to the development of a mathematical reliability model of the STAR as well as other configurations which may become of interest to the Guidance Computer Organization work unit. Concurrently, a software package for supporting this reliability study is being developed on the UNIVAC 1108 at the JPL scientific computer facility and is known as CARE (Computer-Aided Reliability Estimation). The ultimate purpose of the CARE program is to provide a computer-aided reliability design tool for designers of ultrareliable computers.

The work accomplished in these three tasks will be reported separately below.

PROGRESS

The analytic effort is concerned with several interrelated tasks. One is the development of reliability equations which represent the reliability of STAR-like fault-tolerant organizations. The second is to analyze, with respect to significant parameters, the various redundancy techniques that have been utilized. The third critically compares the various redundancy techniques available and determines figures of merit and guidelines for their optimum usage. The task of designing for fault-tolerance is that of considering all anticipated classes of faults. The task of reliability analysis is to estimate and predict quantitatively the reliability (i. e., the probability of survival for a given mission) of the resulting design and, thus, to give a measure of the effectiveness of the fault-tolerance capabilities. The procedure of designing a fault-tolerant configuration followed by its reliability evaluation is not, in general, a two step procedure but an iterative one. The insight obtained by the formulation of the mathematical model and the derivation of its representative reliability equation is followed by the analysis of the behavior of the reliability as a function of the several variables of design. This process leads to refinements in the original design and suggests new approaches to the problem of designing for ultra-reliability.

As a starting point in this study, a thorough literature search was performed. Besides the well known publications where papers on reliability and self-repair are published other periodicals such as Technometrics, Journal of the Operations Research and Naval Research Quarterly Journal were scanned for relevant material. A large number of papers on the subject of self-repair, failure distributions, and the underlying probabilistic mathematics of reliability were found to be in the Journal of the Operations Research. A comprehensive bibliography has been generated.

The well known reliability concepts and models of self-repair were looked into and their applicability to the modeling of the STAR computer were investigated. Specifically, the TMR (triple modular redundancy) class of systems were investigated in depth and various new results pertaining to the asymptotic behavior of such systems under limiting or boundary conditions have been established.

Replacement systems (RS) using selective or dynamic redundancy have also been investigated, and a comparison between them and the systems using massive redundancy (such as TMR) is being made. A configuration which is a hybrid of the aforementioned two systems was developed. This hybrid system uses the TMR concept with spares as standby replacements. The mathematical model of TMR/Spare system has been derived along with the representative reliability equations and expressions for mean time to failure.

Systems using standby spares have been investigated for the three cases of being in the active, dormant or inert mode. These designations indicate whether the standby unit is undergoing relatively greater, lesser, or equal failure stress as compared to the powered unit. A spare unit is said to be active if its failure rate is identical to the failure rate of the powered unit; it is said to be inert if the failure rate of the unit is zero, and it is dormant if its failure rate lies between the active and the inert values. Reliability estimation when the standby units are considered active yields a conservative estimate of the reliability and gives a lower bound on the survival probability. The condition of inert standby units yields an optimistic estimate and provides an absolute upper bound of reliability.

A first-cut reliability estimate of the STAR computer was derived. This estimate was based on the following reliability model: The functional processors comprising the STAR are considered to be in series reliability. The TARP unit which is the "hard-core" of the STAR organization is a majority triplicated configuration with a number of spares. The remaining functional processors are in a replacement mode utilizing standby spares. The reliability model reflecting this organization was extended by incorporating additional parameters to reflect dormancy effects of the spare units.

The body of information referred to above is being placed on computer files, and a library of reliability subroutines is being written on the UNIVAC 1108 multiprocessor system; these subroutines will form an integral part of the CARE program.

The interrelated tasks described in the opening paragraph are all being worked on concurrently. It is anticipated that the effort on developing new mathematical models and equations and refining the well known ones will continue, along with the task of making critical comparisons and developing figures of merit. The effort on the CARE program has just been initiated and a considerable amount of work has yet to be done before it becomes operational. Further work will also be done in estimating the reliability of the STAR computer with greater exactitude.

System Software

The STAR simulator has been completed up to the present status of the STAR command repertoire. The simulator is modular in construction and modifications to or additions to the command list of the STAR may be implemented by writing additional subroutines. A software manual has been completed which describes the design philosophy and provides a functional description of the system for users.

The STAR software is presently written in assembly language for the IBM 7094 computer. The conversion of the Scientific Computer Facility at the Laboratory to a UNIVAC 1108 system has progressed to the point where the UNIVAC is available and conversion of the STAR software to the 1108 assembly language has been started. This work will be completed during the next quarter. Following its completion, work will start on the resident executive for the STAR. This program is in the STAR memory and correlates the various functions performed by the STAR. A major part of its normal work is scheduling and interrupt processing. It will also be concerned with the recovery from transient errors and from failures.

Applications Programming

The STAR computer is to be used for the Central Computer and Sequencer (CC&S) subsystem in the thermoelectric outer-planetary spacecraft (TOPS) project at the Laboratory. In this spacecraft it will, among other things, monitor various subsystems and undertake certain remedial action if the data received indicate a problem or failure in the monitored equipment. The development of programs for the TOPS version of the STAR is the first specific applications programming work. It is expected that the results of this work may be used to further improve the STAR computer itself.

During the present period, the people concerned with the STAR software have met with representatives of other subsystems on the TOPS to discuss capabilities and implementation of the subsystem interfaces. A general presentation of the STAR software (and the machine itself) has been made to TOPS personnel.

Although no direct STAR programs have been written, preliminary flow charts have been developed under another Work Unit 186-68-02-08-55, Flight Computers and Sequencers Advanced Development, and it is expected that programs will be written for STAR during the next reporting period under this work unit.

A subset of the STAR computer is now operational and test programs have been written to aid in debugging it and studying its performance.

PUBLICATIONS

Meetings and Symposia Papers

A. Avizienis, F. Mathur, D. Rennels, and J. Rohr, "Automatic Maintenance of Aerospace Computers and Spacecraft Information and Control Systems," to be presented at the AIAA Aerospace Computer Systems Conference, Los Angeles, California, September 8-10, 1969.

JPL Publications

J. A. Rohr, STAR Computer Simulator and Executive Program, Space Programs Summary 37-55, Vol. III, February 28, 1969, pp. 90-92.

PROGRAM MEMORY FOR STAR COMPUTER

NASA Work Unit 125-17-04-04

JPL 325-71201-0-3410

J. J. Wedel

OBJECTIVE

The objective of this work unit is to obtain a read-only program memory (ROM) for the JPL self-testing and repairing (STAR) digital computer. The overall objectives of the STAR computer are considered in the report for the Guidance Computer Organization Work Unit 125-17-04-02.

APPROACH

The ROM uses a magnetic core rope in which the presence or absence of a wire threading a core, is used to store a 1 or a zero. A single core is used for many bits. A complete description of this memory may be found in the contractor's Phase I Report E-2266 of Instrumentation Laboratory of Massachusetts Institute of Technology entitled "The Braid Read-Only Memory for the JPL-STAR Computer," by John McKenna, May 4, 1968.

PROGRESS

During this report period, the contract modification referred to in the last report has been negotiated. The contractor will furnish a single rope (or braid); the electronics for the memory have already been constructed. The information for this rope will be provided in standard STAR word format on punched cards and converted by the contractor to the necessary format to operate the loom which weaves the rope. The cost of these changes if $3,097.

The punched cards for the rope have been prepared by JPL for the contractor. The contents of the memory will consist of a set of pseudo-random numbers together with a sequence of integers. Such a set of words will permit the memory performance to be evaluated. For test purposes, it is not desirable to place a program in a read-only memory because it is impossible to modify it except by reconstructing the rope.

PLANS

The remaining work on this contract is to construct the rope and test it with the electronics. This work is expected to take about three months. For this reason the present work unit has been terminated at the start of FY 70 and future reporting on the read-only memory will be accomplished in Guidance Computer Organization work unit.

PUBLICATIONS

None

AUTOMATIC ROVING VEHICLE COMPUTER DEVELOPMENT

NASA Work Unit 125-17-04-06

JPL 325-71501-0-3410

L. Y. Lim

OBJECTIVE

The objective of this work unit is the development of computer techniques for the operation of an automatic roving vehicle. The work applies to an on-board vehicle computer and, therefore, emphasizes procedures using a minimum amount of computer storage. Currently, the objective of the work is the development of data processing algorithms for processing sensory input data and providing information for the pathfinding algorithm previously developed. Recommendations for desirable sensors will be a result of this work although the development of sensors is outside its scope.

PROGRESS

During the present reporting period, various obstacle detection methods have been considered. A survey of published literature was conducted and is being evaluated. The fields of pattern recognition and electronic aids for the blind contain much relevant information.

A proposed method of obstacle detection using optical ranging with a vertically scanning laser beam is being investigated. By comparing the range at two beam angle positions, the presence of obstacles or holes can be determined. The processing of information from such a sensor and its optimum deployment are being investigated.

In the next period the evaluation of the literature will be continued. The complete data processing problem associated with the laser obstacle sensor previously mentioned will be studied. This work includes the requirements resulting from vehicle vibration, limitations on the maximum time for processing a scan, optimum storage of data in the computer, etc.

PUBLICATIONS

Meetings and Symposia Papers

D. E. Kirk and L. Y. Lim, "A Pathfinding Algorithm For An Autonomous Roving Vehicle." The Second Hawaii International Conference on System Sciences, January 22, 23, 24, 1969.

GUIDANCE STUDIES FOR FUTURE MISSIONS

NASA Work Unit 125-17-05-01

JPL 325-70301-2-3430

T. C. Duxbury
J. W. Moore

OBJECTIVE

The long-range objectives of this Work Unit are to determine and specify the guidance system requirements for future missions; to develop functional descriptions of guidance system configurations; and to analyze and evaluate system performance of the configurations. The near-term objective is to develop and demonstrate the approach guidance capability required to perform the Grand Tour type mission. The effort described by the near-term objective is in direct support of the Thermoelectric Outer Planet Spacecraft (TOPS) project.

PROGRESS

Guidance studies for the TOPS project have been performed during the reporting period. The studies were performed using updated TOPS spacecraft trajectory parameters. The results have led to the definition and functional requirements of the approach guidance subsystem. Currently, the effort in the Work Unit is directed toward the development of the approach guidance subsystem functional design.

Activities in this Work Unit are directly related to those in Work Units 186-68-02-21 and 125-17-02-01 respectively, "Guidance and Control Subsystem Integration for Future Missions" and "Optical Approach Guidance Analysis and Design." In the former, the objectives have been modified to support TOPS and the tools and technology developed in the latter directly benefit TOPS.

PLANS

Future effort in this Work Unit will be concerned with the completion of the approach guidance functional design. Specific studies in the area of natural satellite theory will be performed to determine the depth to which the motion of the outer planet natural satellites must be modeled to yield satisfactory spacecraft navigation results.

PUBLICATIONS

None

MANEUVER STRATEGY AND NAVIGATION ANALYSIS

NASA Work Unit 125-17-05-02

JPL 325-70701-1-3910

P. Dyer
T. H. Elconin
J. F. Jordan
S. R. McReynolds
T. Nishimura
R. K. Russell

OBJECTIVE

The objective of this work unit is to conduct navigation and maneuver strategy analyses associated with advanced lunar and interplanetary trajectories.

PROGRESS

The continuous estimation program (CEP) continues in service as a tool for applied research in the field of orbit determination. Studies have been conducted in order to determine the advantages of employing ranging data as well as counted doppler data for orbit determination purposes. Empirical formulas for expressing the information content of a few successive passes of both data types have been set forth in Ref. 1.

The Continuous Linear Orbit Determination (CLOD) Program has recently been programmed by Melba Nead. The purpose of the program is to describe the inherent accuracy of doppler and ranging data, when taken over long periods of time. The program is essentially an extension of the Hamilton-Melbourne data compression technique to include long data arcs. The capability to consider both random and bias process noise and both random and bias station locations is included in the program. Checkout is being performed by comparison to DPODP.

Plans are made to determine the inherent accuracy of doppler and/or ranging data, when processed with a least squares filter, when random process noise is acting on the spacecraft. Applications are to M '71 and future low thrust missions.

The Sequential Orbit Determination Program (SOD) for a satellite has been designed and programmed. The program is presently running but has not been completely checked as of this date. This program has the capability of estimating the six state parameters and the mass of central body for an elliptic or hyperbolic orbit. Cross checking of the program with the Continuous Estimation Program (CEP) is progressing.

Optimal Stochastic Transfer Problems

During this period, the study on the orbit transfer strategy has been reviewed and coordinated with other elements of the Laboratory. The applicability of this work to M '71 mission was studied although no conclusion has been reached yet. The extension of the program to the insertion maneuver has been temporarily delayed because the expansion of the dynamic programming computer program requires much more memory space as well as computer time which might become a limiting factor. However, the analysis along this line will be continued to the next period, and the feasibility study of the program to the M '71 mission will be pursued.

Estimation Theory

An analytic Planetary Satellite Orbit Estimation Accuracy Study has been completed, relating to planetary orbit estimation accuracy characteristics. Utilizing a rudimentary tracking model and basic linear estimation theory, the orbital element estimation standard deviations are determined as functions of tracking duration and the orbital parameters. The results are felt to be new, as previous studies have not to our knowledge, isolated estimate accuracy parametric trends, without recourse to numerical procedures.

The results of this study have been issued as an internal document. On the basis of the equations cited herein, a computer program (dubbed SOMA) is being developed. This routine will compute estimate error covariance matrices for various input planetary satellite orbits and tracking situations. The program should provide a convenient means for doing exhaustive parametric studies of planetary estimation capabilities.

A study on the Sensitivity Analysis of Kalman Filters was completed. It will be Chapter IV of the forthcoming book "Theory and Applications of Kalman Filtering" (Ref. 2). A lecture on "Modeling Errors in Kalman Filters," was given at UCLA, in a short course in Optimization Problems Associated with Control Estimation and Smoothing of Stochastic Dynamic Systems, organized by Professor Aoki, June 12, 1969.

A sensitivity analysis of modeling errors of exponentially correlated noise (both data noise and process noise) was published in the SPS article (Ref. 3). A paper on smoothing problems submitted to IEEE Transactions was accepted for publication (Ref. 4).

In addition to these sensitivity analyses, a computer program (NSEP)— Nonlinear Sequential Estimation Program— Encounter phase—for the planetary approach and encounter phase was designed, but it is still under the process of coding and the results on this program will be reported during the next period.

As a result of studies into the accuracy of estimation techniques the Householder algorithm is now being implemented into the DPODP. An SPS article specifying the formulation for this new estimation link is being prepared. In the near future the DPODP will be modified to include a sequential filter as outlined in Ref. (5) and (6). A short article discussing an approach to non-linear estimation was published in the SPS (Ref. 7) Work is being initiated on the study of more sophisticated algorithms.

Optimal Control

A book review by T. Nishimura on the book, Advances in Control Systems, edited by Professor Leondes, will appear in IEEE News Letter, July issue, 1969.

The Second Hawaii International Conference on System Science, Honolulu, Hawaii, January 22-24, 1969, was attended in conjunction with the work described in this task area.

REFERENCES

1. Jordan, J. F., "The Influence of Range Measurements on the State Information Contained in a Few Passes of Counted Doppler Data," SPS 37-57, Vol. II, May 31, 1969.

2. Leondes, C. T. (editor), "Theory and Applications of Kalman Filtering," Chapter IV, Nishimura, T., "Modeling Errors in Kalman Filters." NATO-AGARD.

3. Nishimura, T., "Sensitivity Analysis of Noise Correlation Time in Sequential Filters," SPS 37-57, Volume II, May 31, 1969.

4. Nishimura, T., "A New Approach to Estimation of Initial Conditions and Smoothing Problems," IEEE Transactions on Aerospace and Electronics, to be published in September issue, 1969.

5. Dyer, P., and McReynolds, S. R., "The Extension of Square Root Filtering to Include Process Noise," Accepted for publication in J. of Opt. Theory and Applications.

6. Dyer, P., and McReynolds, S. R., "On the Computational Accuracy of Square Root Filtering," SPS 37-54, Vol. III, December 31, 1968.

7. Dyer, P., and McReynolds, S. R., "A Simplified Approach to Non-Linear Estimation," SPS 37-57, Volume II, May 31, 1969.

PUBLICATIONS

Journal Articles

1. Nishimura, T., "A Review of the book 'Advances in Control Systems' C. T. Leondes, ed.," IEEE News Letter, July 1969.

2. Dyer, P., and McReynolds, S. R., "The Extension of Square Root Filtering to Include Process Noise," Accepted for publication in J. of Opt. Theory and Applications.

3. Nishimura, T., "A New Approach to Estimation of Initial Conditions and Smoothing Problems," IEEE Transactions on

Aerospace and Electronics, to be published in September issue, 1969.

JPL Publications

1. Dyer, P., and McReynolds, S. R., "A Simplified Approach to Non-Linear Estimation," SPS 37-57, Volume II, May 31, 1969.

2. Jordan, J. F., "The Influence of Range Measurements on the State Information Contained in a Few Passes of Counted Doppler Data," SPS 37-57, Volume II, May 31, 1969.

3. Nishimura, T., "Sensitivity Analysis of Noise Correlation Time in Sequential Filters," SPS 37-57, Volume II, May 31, 1969.

LANDED OPERATIONS

NASA Work Unit 125-19-03-02

JPL 325-90401-X-3440

Y. E. Sahinkaya
R. Sridhar

OBJECTIVE

The long-range objective of this work unit is to develop advanced control systems for planetary entry vehicles and surface exploration vehicles. Previous progress in this work unit resulted in the theoretical design of a minimum energy controller for a planetary surface roving vehicle electric drive system. Work was initiated in the implementation of the theoretical results into a laboratory test model.

PROGRESS

The following control circuits of the minimum-energy controller have been built and tested in the laboratory: (1) Pulse-width modulator which supplies the desired firing signals to the main and commutating SCR gate circuits of the step-down and step-up d-c to d-c SCR voltage converters. (2) Armature-current direction sensor which controls the motoring and generating modes of operation. (3) SCR step-down and step-up voltage converters. (4) Prototype speed, load, and minimum energy circuits.

These circuits have been assembled into a complete control system breadboard model, ready for the testing of a laboratory demonstration model, to prove the feasibility of the general concept.

Future work will consist of a quantitative comparison of the actual laboratory system with the theoretically derived results. Following this, a design study will be initiated to determine if a minimum energy drive system can be adapted to an existing roving vehicle model at JPL. If so, actual circuit design will be initiated. It is expected that the system design will be completed during the next reporting period.

Research Contracts - California Institute of Technology

Under this work unit, a contract was given to the Electrical Engineering Department of CIT to develop ways of applying modern control theory to planetary atmospheric entry problems. For FY 69, the total funds allocated are $26,000 on JPL Work Order Number 69822.

The primary research effort in the past six months has been concerned with a satisfactory completion of the investigation concerning the variable lift control of a space vehicle during the re-entry into the Martian atmosphere. The first part of the investigation was concerned with the feasibility of determining open and closed loop controls using a deterministic formulation. This formulation requires that the characteristics of the atmosphere are precisely known and no random disturbances are acting on the space vehicle. It was shown that it is possible to determine satisfactory approximate control laws for the deterministic problem. The second phase of the study was concerned with the determination of the control law when atmospheric parameters were not well known. This requires the implementation of an estimator and controler for success of the mission. It was shown that approximate controller determined from the deterministic formulation of the problem yielded satisfactory performance. The third phase of the study was concerned with allowing stochastic disturbances on the space vehicle (typically due to wind gusts). A first order correlated model was used for the disturbance. This led to the control problem being formulated as a stochastic optimization problem. It was shown using Monte-Carlo simulations that approximate decoupling of the estimation and control problems led to satisfactory terminal guidance of the space vehicle. The particular investigation is now complete, and no further work relating to this problem is proposed within the framework of the contract.

The next investigation which was initiated during the last month is concerned with methods of evaluating the performance of approximate non-linear filters. The structure of the filter is often constrained by hardware considerations. The only known method of determining the performance of the filter is by the Monte-Carlo methods. This is very time consuming computationally, and hence expensive.

A new formulation of the approximate filtering problem adjoins the equation of the filter to the original process equation after eliminating the observation variable. With suitable assumptions, it can be shown that the enlarged vector is a Markov process which satisfies a Langevin equation. The transition density of this process satisfies the Fokker-Planck equation. The estimation error is the difference between certain components of the enlarged vector. The density function of the error can be obtained as marginal density from the density function of the enlarged vector which satisfies the Fokker-Planck equation.

Approximate equations that the mean and the covariance of the error satisfy can be readily determined. These are ordinary differential equations which can be directly solved numerically.

The current investigation is concerned with numerically evaluating the performance of some of the nonlinear filters whose structures were determined by digital experimentation in earlier investigations on this contract. It is expected that this work will be completed within the next three months.

PUBLICATIONS

JPL Publications

(1) Bejczy, A. K., "Time and Fuel-Optimal Bounded Retro-Thrust Controls for Nonlifting Bodies Subject to Drag", Space Program Summary 37-55, Vol. III, February 28, 1969.

(2) Bejczy, A. K., "Fuel-Optimal Retrothrust Control Programs for Soft Landing Maneuvers in the Presence of Drag", Technical Report 32-1361, June 1969.

Contractor Reports

(1) Contractor Reports for W. O. 69822 dated Dec. 1968 and June 1969.

CONTROL SYSTEM SYNTHESIS UTILIZING FLEXIBLE BODIES

NASA Work Unit 125-19-04-01

JPL 325-90501-X-3440

G. E. Fleischer

OBJECTIVE

The objective of this work unit is to investigate alternate or new control techniques for future JPL missions, and to develop ways to analyze these control systems, especially with respect to flexible structures, rotating devices, and articulated members.

PROGRESS

During the fiscal year, an excellent opportunity was provided, by the Thermoelectric Outer Planet Spacecraft (TOPS) Program, to test some of the techniques being developed. Initially, efforts were concentrated on obtaining a simple description of the spacecrafts' dynamics and combining it with a linearized, single axis, control system transfer function for root-locus studies. The simplified dynamic model assumed a three-body rigid system with connections provided by discrete joints. While this simple configuration had been analyzed previously using a Lagrange (energy) approach to deriving the equations of motion, the barycenter formulation (of Hooker-Margulies) was applied as well and quickly showed that certain terms that were dropped from the Lagrange derivation (by decoupling translation from rotation) significantly changed the form of the structural transfer function. Restoration of the terms, of course, resulted in identical results. However, the barycenter method also proved to be a faster and more straight-forward way of deriving the equations of motion, dispensing with the need to write energy expressions and execute the many subsequent differentiations.

Results of computer root-locus studies on a single-axis autopilot for TOPS showed negligible structural effect due to the large science and RTG supporting booms (4Hz), but very significant effect due to a pair of 30-ft magnetometer booms (0.5 Hz), i.e., a reduction in critical loop gain from 6.3 (for the ideal regid case) to 2.6. Hand calculations using the barycenter derivation also were able to show that magnetometer boom deflections would not exceed specifications (±1 deg) either under the influence of gas jet unloading forces or the sudden application of thrust (25 lb) by the midcourse motor.

In addition to single-axis studies of the TOPS autopilot, a three-axis computer simulation of the system was accomplished using a relatively detailed structural model developed by the JPL Applied Mechanics Section. Using the approach of Likins, developed under this work unit, the structural model was represented using hybrid coordinates, i. e., a combination of the usual three rigid-body rotations θ_x, θ_y, and θ_z and a number of modal coordinates η_i describing the system's normal modes of vibration. Specifically, the configuration 12C model exhibited 4 magnetometer boom modes ranging from 0. 804 Hz, an antenna torsional mode at 1. 006 Hz, and many additional modes at 3. 77 Hz, 4. 09 Hz, etc. Modal damping was set at 0. 5%.

Results of the three-axis simulations showed definite autopilot instability for a loop gain of about 2. 3, but acceptable performance at a reduced gain of 1. 0. Gyro outputs were well within limits. While some modification to magnetometer boom stiffness could be made to improve performance, results generally point to an autopilot (Mariner '71 design) which is compatible with TOPS structural characteristics. Further, the analytical methods developed for and finally brought to bear on this type of mission have proven to be invaluable.

PLANS

Activities in the next six months should see some refinement of the structural model as the baseline TOPS design is finalized. Further verification of autopilot performance will take place as well as studies of structural response due to cruise control operations (such as momentum wheel unloading).

PUBLICATIONS

None

COMMUNICATIONS (125-21)

COMBINATORIAL COMMUNICATION

NASA Work Unit 125-21-01-01

JPL 325-10701-X-3310

E. R. Rodemich

OBJECTIVE

The objective of this work unit is to provide a fund of combinatorial and algebraic theory and techniques for use in the design of coded spacecraft and ground communication systems. In addition, theoretical yardsticks are developed against which the performance of such systems can be measured.

PROGRESS

A study of the proposed DSN teletype code was made (Ref. 1). It was discovered that in the proposed decoding technique there is a substantial probability of error due to channel deletions or insertions, indicating that the decoder should be modified. Proposals for modification were made.

A simplified method for computing shift-register correlation matrices was found (Ref. 2), of use in designing ranging coders.

The weight spectra of second order generalized Reed-Muller codes were determined (Ref. 3). This information is useful for computing error probabilities when such codes are used for telemetry.

An exponential function generator was designed for use in the slope-threshold method of data compression (Ref. 4).

All cosets of maximal comma-free index for the Reed-Muller (16, 5) code used in the high rate telemetry project were determined (Ref. 5). Many of these can be easily generated. One of these was chosen for use in the high-rate telemetry decoder.

It was shown (Ref. 6) that there are arbitrarily long nonlinear binary block codes at all rates which simultaneously satisfy the Gilbert bound on minimum distance and admit large permutation groups. The presence of a large permutation group is helpful for decoding purposes.

PLANS

It is planned to make a study of the use of non-binary block codes in future telemetry systems, using the well-developed techniques of algebraic coding theory, in order to preserve bandwidth.

A study of the capabilities of convolutional codes will be made with emphasis on the explicit construction of good codes.

A new method of construction of non-linear codes is being developed. This work has already led to simplified constructions of known non-linear codes with good properties.

A comprehensive report on difference sets has been completed (Ref. 7) and will be published as a JPL technical report. Difference sets provide codes with good cross-correlation properties.

REFERENCES

1. McEliece, R. J., "The Synchronization of Reed-Solomon Codes", SPS 37-55, Vol. III, pp. 38-41.

2. Golomb, S. W., "Shift Register Correlation Matrices", SPS 37-55 Vol. III, pp. 42-43.

3. McEliece, R. J., "Quadratic Forms over Finite Fields and Second Order Reed-Muller Codes", SPS 37-57, Vol. III.

4. Anderson, T. O. and Hurd, W. J., "Digital Quasi-Exponential Function Generator", SPS 37-57, Vol. III.

5. Baumert, L. D., "Cosets of Maximal Comma Free Index for the Reed-Muller (16, 5) Code", SPS 37-56, Vol. III.

6. McEliece, R. J., "On the Symmetry of Good Nonlinear Codes", submitted to IEEE Transactions on Information Theory.

7. Baumert, L. D., "Difference Sets", SIAM J. Applied Math 17 (1969).

PUBLICATIONS

None

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SEQUENTIAL DECODING

NASA Work Unit 125-21-01-02

JPL 325-10201-X-3310

S. Butman

OBJECTIVE

The objective of this work unit is to develop simple and efficient convolutional coding-decoding systems to improve the performance of deep space communication links. In particular, methods are sought to generate convolutional codes with the best possible error correcting capabilities. In addition, methods of decoding convolutional codes, such as sequential decoding and maximum-liklihood decoding, are compared to determine their appropriateness for various missions.

PROGRESS

Design Consideration of a Viterbi Decoder

Simulation studies of the Viterbi decoder were made to determine a) memory requirements and b) quantization effects.

Memory Requirements for Various Path Lengths

The Viterbi decoder makes a final bit decision only after all 2^{k-1} path decisions agree in the given bit position. Here "k" is the code constraint length. In theory, the memory per path can be infinite, and the time necessary for a bit decision is random. Decisions are forced, however, in a practical system with finite memory. It has been found, by simulation, that for error probabilities in the range 10^{-2} to 10^{-4}, negligible degradation from the theoretical optimum performance can be obtained with a memory size per path of about 4 times the code constraint length.

Quantization Effects

The simulation study has also revealed that the received data can be quantized to 8 levels (3 bits) with negligible loss compared to infinite quantization.

Buffer Overflow in Sequential Decoding

Simulation studies of buffer overflow in sequential decoding have been made. The results indicate that in many cases of practical interest previous theoretical predictions of buffer overflow probability are unrealistic. A more complete model of this overflow problem has been devised and reported (SPS 37-56, Vol. III). This model can be used to predict overflow probability by numerical methods for various decoder and channel parameters.

Proposed High-Rate Telemetry System for Viking Using Convolutional Codes

An extensive simulation study was carried out to determine the effectiveness of short constraint length convolutional codes for a 16 K bps telemetry channel with a bit error probability of 5×10^{-3} using either a Viterbi decoder or a sequential decoder. The results indicate that a constraint length 8 code and a Viterbi decoder would save 1.3 db over a 32-6 (6 bit) bi-orthogonal code. A sequential decoder would save 1.0 db and could be used as a back up decoder.

Hard Wired Viterbi Decoder

The feasibility of a high rate, hard wire Viterbi decoder was investigated. It was determined that a constraint length 8 decoder could be built using available TTL chips for rate up to about 150 K bps. The decoder could switch to shorter constraint lengths with a doubling of rate possible at K = 7 and a further doubling for K = 6. The decoder would consist of several registers in an arithmetic unit and a high speed 5000 bit random access memory.

PLANS

Efforts will be made to study algebraic and other properties of convolutional codes with the aim in mind of obtaining codes with the best possible error-correcting capabilities for given constraint lengths and rates.

Also, work will be done on concatenating convolutional codes, i.e., on using more than one level of coding in a system. The aim here is to reduce the error probabilities attainable with one level of convolutional coding still further without increasing system complexity prohibitively.

Further studies of the erasure probability in sequential decoding are planned. For FY 70, this work unit is merged with 125-21-02-03, "Decoding and Synchronization Research".

REFERENCES

1. Heller, J. A., "A Model for Buffer Overflow in Sequential Decoding", SPS 37-56, Vol. III, Feb-Mar. 1969.
2. Heller, J. A., "Improved Performance of Short Constraint Length Convolutional Codes", SPS 37-56, Vol. III, Feb-Mar. 1969.
3. Heller, J. A., "Short Constraint Length Convolutional Codes", Presented at the IEEE International Conference on Communications, June 1969, Denver, Colo.

PUBLICATIONS

None

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ADVANCED SOLID STATE RF TECHNOLOGY APPLICATIONS

NASA Work Unit 125-21-01-03

325-10301-2-3360

B. Conroy

OBJECTIVE

The objective of this work unit is to improve spacecraft communication capability through the application of recent developments in advanced solid state technology. If properly applied, the properties of several recently discovered devices can provide a means of achieving significant improvements in spacecraft transmitter reliability, life time, and efficiency. In addition, the inherent small size and weight characteristics offer advantages for planetary landed capsules or other size and weight-limited probes.

Specific areas of new technology being considered include (1) basic devices, such as new high power, high-frequency transistors and bulk effect oscillators such as the Gunn and L.S.A. Diodes, (2) circuit configurations and (3) media for microwave circuit construction.

PROGRESS

Basic Devices

The most practical solid-state devices for spacecraft transmitters are still high-power transistors and varactors. The capabilities of high-frequency transistors are expanding very rapidly, and, to stay abreast of the technology, communications have been maintained with device designers at TRW, RCA, and United Aircraft. Specific transistor performance data are reported under Work Unit 160-21-02-01, UHF FM Transmitter Investigation. Construction and packaging methods of various manufacturers have been compared.

As reported in the last semi-annual review, the most promising high efficiency power generating device is an IMPATT diode operating in the "Anomalous Avalanche" mode. This mode has been theoretically analyzed and computer-simulated by D. L. Scharfetter and R. L. Johnston of Bell Labs.

They have given it the name TRApped Plasma Avalanche Triggered Transit (TRAPATT) mode.

Circuit Configurations

The configuration of the distributed amplifier continues to be investigated. The basic approach was to build four individual amplifiers with 50-ohm input and output impedances, join the amplifiers with halfwave coupling sections, and then match the input and output with quarterwave sections. Two versions (each with a nominal frequency of 860 MHz) of this approach have been designed and tested: one with United Aircraft S-1050 stripline transistors and the other with RCA 2N5470 coaxial transistors.

The first version (stripline) used the S-1050 transistors and was plagued with instability problems. Since experience had shown that the 2N5470 tended to be the more stable transistor, the first version was modified to accept this device. However, testing proved this modification inadequate; because of parameter differences and added series inductance, the amplifier would not tune. The second version was then built.

The second version (lumped constant model) was designed for the 2N5470 transistor. This circuit was tested with 12.5-ohm and 50-ohm coupling sections. The data are presented in Table 1.

These data confirm previous data in which there is a loss of gain in the distributed configuration. Tuning was quite critical, and equal load sharing was very hard to obtain. In regard to this configuration, the conclusion is that some sort of inter-amplifier isolation, such as provided by a hybrid tree or Wilkinsen Summer, is mandatory for a practical UHF amplifier.

Media for Circuit Construction

Breadboard filters and amplifiers have been designed and constructed using two different configurations, stripline and microstrip.

One three-section stripline filter was constructed with adhesive-backed copper tape on Z-tron "G" dielectric. Agreement between the desired and actual performance was quite good in spite of the fact that the lines were cut by hand and spacing between lines was as small as 0.006 inch. The comparison is shown in Table 2.

Additional design information on aluminum oxide microstrip has been compiled, and several filter and amplifier designs have been completed. The circuit board has been completed for a hybrid integrated-circuit amplifier using an unpackaged transistor chip on aluminum oxide ceramic.

PLANS

This work unit was terminated at the end of FY 69. Work on the aluminum oxide microstrip amplifier will continue under Work Unit 160-21-02-01, UHF FM Transmitter Investigation. Additional work on the ceramic filters will continue under Work Unit 125-21-09-05, Multi-Mission Spacecraft Radio Research.

PUBLICATIONS

None

Table 1

Performance Data on Distributed Amplifier Using 2N5470

Test Item	Gain, dB	Power Out, W	Efficiency, %
Individual amplifier stages	6 to 6.3	1 to 1.2	60 to 63
Distributed amplifier with 12.5-ohm coupling section	4.8	3.2	60
Distributed amplifier with 50-ohm coupling section	4.6	3.1	59

Table 2

Test Results of Three Section Stripline Filter

Performance	Center Frequency, MHz	Band-width, %	Ripple, dB	Loss, dB
Design goal	860	5	0.5	---
Measured	854.5	7.5	0	1

LARGE SPACECRAFT ANTENNAS

NASA Work Unit 125-21-02-02

JPL 325-11001-2-3330

P. W. Cramer

OBJECTIVE

The purpose of this task is to develop the technology of large light-weight erectable antennas for Thermoelectric Outer Planet Spacecraft (TOPS) and other spacecraft. Specifically, the R. F. aspects of erectable antennas will be investigated to establish design parameters and support trade-offs between antenna gain and weight.

PROGRESS

In the design of unfurlable antennas with reflectors composed of mesh materials stretched between radial ribs, one of the problems is the determination of deviations of the mesh surface from an ideal paraboloid. To calculate this deviation at points on the antenna mesh, a Fortran IV digital computer program was developed to find the equilibrium shape of the mesh for any radial rib antenna, given the tension in the two orthogonal directions and the shape of the radial ribs.

The mesh surface is assumed to be a membrane with negligible bending stiffness, with all forces assumed to be acting in the plane of the membrane. The solution of the membrane equilibrium equation is approximated by applying an iterative relaxation process to a finite difference approximation to the equation.

In order to minimize the electrical performance degradation due to the deviation of the mesh surface from the ideal paraboloid, a program was developed which optimizes the shape of the radial ribs. To define the rib shape in terms of a few variables, Chebyshev polynominals are superimposed on the original parabola to define the new rib shape. The variables are then optimized using the simplex method to obtain a rib shape that produces a membrane deflection with the least weighted RMS error. The existing computer program is able to take a desired RMS error, outside diameter, hub diameter, and output the minimum number of ribs and the rib shape that gives the desired RMS error.

Work has been started on cassegrain configurations which would apply to erectable antennas and have application to TOPS.

PLANS

Further work will be done in the area of allowing the optimized ribs to be distorted by either thermal gradients or external loading. By calculating the mesh shape and RMS error at these extremes, the initial rib shape can be varied to compensate for the expected deflections.

A special jig has been designed and is in fabrication to simulate a section of an erectable antenna. During the next half year this jig will be used to simulate surfaces with boundary conditions identical to those inputted into the program to calculate the antenna surface shape. The measured surface shape will be compared with the calculated surface shape to establish the accuracy of the developed computer program.

Also, cassegrain configurations will be evaluated for TOPS and work will be started to develop a far field antenna pattern calculation program utilizing inputs from the surface shape calculation program. These calculations will apply to erectable cassegrain type antenna configurations.

This work will be closely coordinated with another JPL OART work unit in the Engineering Mechanics Division, "Advanced Spacecraft Antenna Technology," #RTOP 124-08-26- and JPL OSSA work unit "Space Antenna Pointing Techniques," #186-68-04-24 which is responsible for developing the feeds used with this type of antenna.

PUBLICATIONS

None

CODING AND SYNCHRONIZATION STUDIES

NASA Work Unit 125-21-02-03

JPL 325-10601-X-3310

S. Butman

OBJECTIVE

The objective of this work unit is to develop advanced techniques of carrier and symbol synchronization and tracking systems for deep space telemetry, command, and ranging.

PROGRESS

A simulation study of cycle slipping in phase-locked loops has been made. The results and conclusions are reported in SPS 37-57, Vol. III. Analysis of a fast fading channel model is in progress. Quantization effects due to A-D conversion on the performance of the multimission command system are under investigation. The results should determine the most economical quantizer for the desired system performance. The effect of amplitude uncertainty on tracking error in ranging systems has been analyzed and reported in SPS 37-57, Vol. III.

PLANS

A detailed study of the performance of bi-orthogonal codes as a function of the number of quantization levels in the A-D converter will be carried out. Analysis of the fast fading channel will be continued in order to study the performance of non-coherent detection now being considered for the Viking project. Design considerations for a more efficient ranging transponder will be initiated, to provide a "clean-up loop" on board the spacecraft.

This work unit will be entitled, "Coding and Synchronization Research" in FY 70, and will absorb 125-21-01-02, "Sequential Decoding".

REFERENCES

1. Holmes, J. K., "A Simulation Study of the First Slip Times vs Static Phase Offset for the First and Second Order Phase-Locked Loops, SPS 37-58, Vol. II, June and July 1969.

2. Butman, S., "The Effect of Amplitude Uncertainty on Estimating Phase of a Square Wave, SPS 37-57, Vol. III, April-May 1969.

3. Butman, S., "On Estimating the Phase of a Square Wave in White Noise", presented at IEEE International Symposium on Information Theory, Ellenville, N. Y., January 1969.

PUBLICATIONS

None

PROPAGATION STUDIES

NASA Work Unit 125-21-02-04

JPL 325-10801-3310

G. A. Morris Jr.

OBJECTIVE

The purpose of this work unit is to determine the effects of deep space transmission media, planetary atmospheres, and lunar and planetary surfaces on deep space communication systems.

PROGRESS

Recent radar ranging of Mars with rms accuracy of 1 μsec offers promise of an improved ephemeris for Mariner 69 encounter. Topography and albedo are also being obtained. Reduction of Venus radar mapping data with improved resolution is possible with mathematic techniques recently developed. Pulsar observations have continued with most periods now known to .1 nsec and most positions to .1 sec of arc. A slip was observed in the period of pulsar PSR 0833-45. Two pulsars were observed as they passed near the sun; resolution was enough for a test of General Relativity. Mathematical techniques have been developed to search for pulsars with unknown periods.

PLANS

Reduction of Venus radar data will yield a map with better resolution. Observations of pulsars will continue on a regular basis. Data now available indicates improvements to the ephemeris and astronomical constants are possible. Effects of General Relativity on an Earth-based atomic clock will be analyzed. Equipment presently under procurement will enable pulsar arrival times to be measured with a precision great enough that clock synchronization may be possible.

REFERENCES

1. Pulsar Observations at 12.5 cm and 3.5 cm Wavelength, AAS meeting, Dec. 13, 1968, Austin, Texas. (Downs, Morris and Reichley)
2. Average Pulsar Energies at Centimeter Wavelengths, Nature, in the press. (Downs, Morris, and Reichley)
3. An Observed Decrease in the Period of Pulsar PSR 0833-45, Nature, 222, 229 (1969). (Reichley and Downs)
4. Pulsar Astrometrics, URSI Meeting, April 22, 1969, Washington, D.C. (Reichley, Downs, and Morris)

PUBLICATIONS

None

RF TECHNIQUES RESEARCH

NASA Work Unit 125-21-03-04

JPL 325-10901-1-3330

W. Higa

OBJECTIVE

The objective of this work is to develop technology to provide a basis for evaluating the potential of frequencies above S-band for data dump telemetry and for application to antenna and microwave scale model work. Emphasis is placed upon the capability of designing, improving, and operating the radio frequency hardware of experimental equipment, especially low-noise receivers, at these frequencies.

PROGRESS

Two maser materials, ruby and iron-doped rutile, have been investigated for application to a 15.3 GHz maser. The effort to obtain computer analyses of the maser characteristics of these two materials has been successful, and experimental cavity masers, built and operated in the laboratory with these materials, have provided information necessary for the construction of a prototype maser.

Further laboratory investigations are being conducted on crystals of chromium-doped rutile and iron-doped zinc tungstate.

JPL Contract (#952210) with the University of Southern California

The 90 GHz radio sextant with optical sun tracker was successfully used during 15 days of clear weather to measure atmospheric attenuation at 90 GHz. The zenith atmospheric attenuation measured approximately 1 dB. Attenuation through clouds could not be measured due to the inability of the optical sun tracker to function properly under those weather conditions.

PLANS

A 15.3 GHz low noise maser will be constructed for laboratory testing.

No further use of the 90 GHz radio sextant and optical sun tracker is anticipated and they will be turned over to the contractor. This work unit will absorb "Quantum Electronics Research," 125-22-02-01.

ANTICIPATED PUBLICATIONS

1. Slobin, S. D., and Rusch, W. V. T., "A Case Study of Phase-Center Relationships in an Asymmetric Cassegrainian Feed System," in the IEEE Transactions of the Group on Antennas and Propagation.

PUBLICATIONS

JPL Publications

1. SPS 37-54, Vol. III, "Atmospheric Effects on Millimeter Wave Propagation," T. Sato, p. 205.
2. SPS 37-55, Vol. II, "Microwave Maser Development," R. Berwin, pp. 44-45.
3. SPS 37-56, Vol II, "Microwave Maser Development," R. Berwin, R. Clauss, E. Wiebe, pp. 101-105.

TRACKING AND DATA ACQUISITION (125-22)

MULTIPACT AND IONIZATION STUDY

NASA Work Unit 125-22-01-02

JPL 325-20501-2-3330

R. Woo

OBJECTIVE

The objective of this task is to study RF voltage breakdown in order to obtain information helpful in avoiding voltage breakdown in RF components designed for space applications. Another objective is to study the effects of a plasma environment on the performance of spacecraft antennas, especially high-gain unfurlable antennas.

PROGRESS

Experimental data have been obtained for voltage breakdown in coaxial transmission lines whose characteristic impedances are 70Ω and 90Ω. Utilizing the idea of similarity parameters developed earlier, these data are presented in compact and useful plots. The data cover values of frequency times separation distance ranging from 50 to 400 MHz-cm. It has been shown that no definite advantage results from the use of transmission lines whose characteristic impedances are higher than 50Ω. These conclusions hold for breakdown in argon and carbon dioxide gases, as well as in air.

Data have also been obtained for voltage breakdown in the parallel plates geometry in the range of 10 to 250 MHz-cm. These have been combined with existing data gathered elsewhere into a compact plot. The plot is very extensive and covers frequencies varying from UHF to K-band and pressures varying from atmospheric down to hard vacuum. Thus, the plot should be useful to engineers designing not only spacecraft RF components but high power RF ground equipment as well.

Multipacting in the coaxial configuration for large frequency times separation distance values has been studied, and the presence of higher order modes identified. These higher order multipacting modes occur at power levels above 1 kw and for values greater than 500 MHz-cm.

Ray-tracing and geometrical optics have been used to study radiation from an antenna in an inhomogeneous plasma. Such studies are necessary in order to determine the performance of antennas located on a blunt-body capsule as the capsule enters an extraterrestrial atmosphere such as that of Mars. Few studies have been made of radiation through inhomogeneous plasmas because explicit solutions are very difficult. The use of geometrical optics represents a different approach. The idea consists of tracing the various rays through the inhomogeneous plasma and accounting for phase, amplitude, and polarization of the field through the laws of geometrical optics.

PLANS

Voltage breakdown experimental work for the coaxial transmission line geometry will be completed. Antenna breakdown experiments will begin. Finally, the study of radiation from antennas located in inhomogeneous plasmas will continue.

This work will continue in FY 70 under the 125-21 program, under the title "RF Breakdown and Plasma Studies."

PUBLICATIONS

Meetings and Symposia Papers

1. Woo, R., "RF Voltage Breakdown in Coaxial Transmission Lines," Second Workshop Voltage Breakdown in Electronic Equipment at Low Air Pressures, March 5-7, 1969.

Journal Articles

1. Woo, R., "RF Voltage Breakdown in Coaxial Transmission Lines," Proceedings of the IEEE, Vol. 57, No. 2, February 1969, pp. 254-256. Also published as JPL Technical Report 32-1379, February 1969.

JPL Publications

1. Woo, R., "RF Breakdown in Carbon Dioxide and Argon Gases in Coaxial Transmission Lines," SPS 37-55, Vol. III, pp. 47-48.

2. Woo, R., "Radiation from a Dipole Antenna Located in an Inhomogeneous Cylindrical Plasma," SPS 37-56, Vol. III, April 30, 1969.

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QUANTUM ELECTRONICS RESEARCH

NASA Work Unit 125-22-02-01

JPL 325-20101-1-3330

M. S. Shumate

OBJECTIVE

The principal objective of this task was to maintain a continuing feasibility study on optical deep space communication based upon a laser as a transmitter. The study had both a theoretical and an experimental phase.

The theoretical study has attempted to answer the questions:

(1) Which optical communication system, if any, appears likely to have application to the deep space communication problem?

(2) How can this system be most efficiently utilized?

The experimental study is devoted to the investigation of two rather critical fundamental problems:

(1) the design and construction of an appropriate low noise heterodyne receiver for use at carbon dioxide laser wavelengths, 10-11 μm; and,

(2) the atmospheric turbulence effects on the wavefront distortion of a 10 μm signal during a transit from space to the Earth's surface.

PROGRESS

The most important part of this effort is to keep an up to date compilation of data on possible laser communication systems and to continually assess and update estimates of feasibility. The major contribution of this effort is a report, currently being published as JPL Technical Report No. 1392, devoted to a discussion of high frequency, high data rate communication systems. The report considers the basic dichotomy of maintaining reliable communication with a deep space probe and operating at an acceptably high data rate. Both microwave and optical wavelengths for a high data rate link are discussed, and a performance comparison of each system is presented.

The major conclusion is that high rate (10^7 bits/sec) data dump type deep space communication systems could be built at either X-band or carbon dioxide laser wavelengths that would have similar penalties on the spacecraft (weight, power consumption, etc.). Hence, the decision as to which system to use would have to be based upon other considerations, with the final choice being a trade-off between cost effectiveness and reliability.

Experimental Study

1. Carbon Dioxide Laser Heterodyne Receiver

The carbon dioxide laser heterodyne receiver in the laboratory has been modified to incorporate a 5 watt Sylvania Model 948 CO_2 laser as a local oscillator, and to provide for testing of two detector/dewar systems at the same time. The receiver is provided with a second laser, at 100 milliwatt maximum power, and calibrated attenuators. This laser can be frequency locked to the local oscillator frequency plus or minus the intermediate frequency, and is used to simulate a distant transmitter.

This receiver is being used to evaluate three separate detector/dewar systems at the present time, and will be used to compare the several different types of detector mounting schemes. New detector elements and a closed cycle refrigerator have been ordered.

2. Atmospheric Turbulence Study

This effort is completely experimental, and is directed toward two separate goals:

(a) measurement of atmospheric turbulence effects upon a light beam from an extraterrestrial source at several infrared wavelengths; and,

(b) determination of methods to evaluate telescope sites by direct measurement of atmospheric turbulence.

The first activity is being conducted jointly by Cal Tech and JPL (Cal Tech-JPL Internal Work Order No. 69818, $14,919 in FY 69, J. Westphal, Cal Tech, principal investigator). The experiment measures the astronomical "seeing" or point spread function of a source simultaneously at the visible and at one of several selectable infrared wavelengths (Ref. 1). A photometer built for this experiment has been successfully used on two occasions on the 200" Hale telescope at Mt. Palomar. Data has been accumulated for the 10-14 μm wavelength range. Results to date indicate that the visible point spread is 1.5 arc sec when the 10 μm spread is 1.0 arc sec.

The second activity is utilizing conventional microthermal turbulence measurement apparatus to evaluate the NASA-SAO* Mt. Hopkins observatory which is being coordinated by NASA-ERC. The appropriate apparatus is being fabricated and tested at the present time. Similar microthermal apparatus has just been flown on a tethered balloon to an altitude of 1000 ft. above Mt. Palomar, in order to determine the scale height of the turbulence.

During FY 70, data on atmospheric turbulence will be accumulated for several infrared wavelengths from 1.6 μm to 14 μm, and for a variety of elevation angles and atmospheric conditions. An attempt at direct measurement of the 10 μm coherence diameter will also be made.

The microthermal turbulence apparatus will be installed at Mt. Hopkins early in FY 70 on the 100 ft. towers being erected for the purpose. The data from the 1000 ft. balloon flight will be evaluated.

This work unit was terminated at the end of FY 69, and will continue at a reduced level of effort under "RF Techniques Research," 125-21-03-04. The emphasis will be on laser communication as a competition to microwaves.

PUBLICATIONS

JPL Publications

1. Shumate, M. S., Westphal, J. A., "Infrared Astronomical Seeing Study," JPL Space Programs Summary, 37-55, Vol. III, pg. 44.

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*Smithsonian Institution Astrophysical Observatory

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THERMAL AND STRUCTURAL ANALYSIS OF A PHOTOHELIOGRAPH SYSTEM

NASA Work Unit 125-22-02-04

JPL 325-20701-0-3550

J. M. F. Vickers

OBJECTIVE

It is proposed to conduct an extensive review of the presently developed techniques for making micro-strain measurements and to evaluate the feasibility of modifying these methods, if required, to provide the data for the analysis and design of a near-diffraction-limited primary mirror for the telescope. If it is determined that it is feasible to develop suitable techniques, these will be developed, proved, and used to obtain micro-strain property data on some candidate materials.

PROGRESS

Work during the past 6 months has been concentrated on preparing criteria for a statement of work relative to testing the micro-yield and precision elastic-limit properties of certain candidate mirror materials for photoheliographs. Telephone conversations have been conducted with Mr. Hoffman of Langley Research Center to discuss his work in this field. A visit has been made to the Boeing Company, Seattle, to discuss with Messrs. Wood and Eul the work which they are carrying out for Langley Research Center under the direction of Mr. Hoffman. A visit was also made to Dr. Moberly, of Stanford Research Institute, to discuss his work, both in the area of micro-yield property measurement and his techniques for producing highly isotropic iron-beryllium and copper-beryllium alloy billets for telescope mirror blanks. While these can only be made in small sizes at present, the materials are very good candidates for telescope primary mirrors. In the coming fiscal period, trips will be made to other firms and institutions who have been active in the field of micro-strain in order to determine the best approach for obtaining good design data.

PUBLICATIONS

None

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ADVANCED SPACECRAFT TRANSMITTERS

NASA Work Unit 125-22-03-01

JPL 325-20601-2-3360

L. Derr
H. Detweiler

OBJECTIVE

The objective is to improve the efficiency, life time, and reliability of microwave tubes to meet the requirements of future space missions. The specific activities being pursued are: (a) a study of the life and electron production capabilities of hot cathodes; (b) development of an automatic cathode replacement mechanism and; (c) a theoretical investigation of the large-signal performance of traveling-wave amplifiers.

PROGRESS

Cathode Life and Emission Study (JPL Contract 951810 at Raytheon)

Life test evaluation of dispenser and oxide cathodes continues. Sixteen dispenser cathodes have now operated at current densities from 200 to 1600 ma/cm^2 for 14,280 hours, with heavy evaporation of barium being evident. Most units, however, have maintained their original emission levels, if not actually improving, over this test period. Sixteen oxide cathodes have been life tested for an average of 12,000 hours. Units operating at greater than 150 ma/cm^2 show current declines to 50%. Those operating below that limit have shown declines ranging from 0 to 25% during the same period.

CPC coatings have been processed on Cathalloy A-33, Ni-pure and 220 nickel bases, to test the effects of the base metal activators upon cathode emission. The A-33 nickel has been shown to be superior and four such diodes will be life tested at current densities from 275 to 830 ma/cm^2. Twelve other CPC diodes fabricated during this evaluation will be life tested at lesser current levels.

Automatic Cathode Replacement Mechanism (JPL Development)

Mechanical improvements have been made at JPL to the package design of this long-life electron gun. A mechanical model using an axial configuration has been completed and a suitable test set circuit is being fabricated. The axial design will be used in a pending study and fabrication program which will be conducted by a traveling-wave tube vendor.

That program provides for a selection of the materials to be used for the component parts of the electron gun, the fabrication and evaluation of a vacuum diode test model with operating oxide cathodes, and the fabrication of a complete traveling-wave tube using this electron gun design. A contract for this work will be issued during the next report period. This traveling wave tube with the automated electron gun will be evaluated at JPL for possible application to space missions of 10 to 15 years duration.

Theoretical Investigation of TWT Performance

Programming of a simplified version of the two-dimensional large-signal TWT interaction equations for solution on the digital computer has been completed. The interaction equations which are employed in the analysis are based on a deformable-disk model (DDM) for the electron beam; they are valid for large values of the gain parameter, C, and take into account the effects of distributed loss on the circuit.

This program is operational and can be used to obtain space-charge-free solutions for uniform-circuit traveling-wave tubes (no circuit-velocity tapers or velocity jumps). Logic has been included which enables this program to provide solutions for one-dimensional (no radial field variations and confined electron flow) as well as for two-dimensional cases. With this flexibility, check calculations can be easily made for comparison with results appearing in the literature. Also included are theorems which describe the conservation of power and momentum for the beam-wave interaction that takes place in the TWT. These are useful in checking the accuracy of the solutions obtained with the computer.

RF space-charge effects can be especially important in traveling-wave tubes designed for high-efficiency operation. Thus, recent efforts have been directed toward including space-charge forces in the computer calculations. Because of the prohibitively large amount of computer time and storage which would be required to solve for the Coulomb fields exactly, an alternative approach using space-charge weighting functions is being employed. In this procedure, the interaction space is divided into a number of annular regions, and functions which indicate the influence of representative charge groups upon one another according to their radii and spatial (or phase) separation are evaluated. These weighting functions are then used to calculate the inter-electron space-charge forces during the execution of the large-signal TWT program.

A series of computer programs, separate from the TWT program, have been developed to generate the space-charge weighting functions, which depend upon the device geometry and electrical parameters. The last program yields weighting-function tables which are read into the computer memory and used each time calculations are performed with the large-signal TWT program. The TWT program is currently being modified to include the space-charge-force calculations.

Various phase-focusing techniques, such as velocity tapers and jumps, are often employed to improve TWT efficiency. The necessary modifications will be made in the TWT program during the next period so that these efficiency-improvement techniques can be studied. When these efforts are completed, programming of the general large-signal interaction equations, in which a ring model is used to represent the electron beam, will be initiated.

PLANS

This work unit was terminated at the end of FY 69. The work will continue in FY 70 under 125-21-09-05, "Multi-Mission Spacecraft Radio Research."

PUBLICATIONS

Contract Reports

1. Hill, F. T., "Thermionic Cathode Evaluation Study," Raytheon Company, Interim Report No. 5, October 31, 1968, JPL Contract No. 951810.

2. Hill, F. T., "Thermionic Cathode Evaluation Study," Raytheon Company, Interim Report No. 6, March 19, 1969, JPL Contract No. 951810.

DATA HANDLING AND PROCESSING (125-23)

DIGITAL VIDEO PROCESSING TECHNIQUES

NASA Work Unit 125-23-02-01

JPL 325-30101-2-3240

F. C. Billingsley

OBJECTIVE

The long-range objective of this task is to develop methods and techniques for the recording, scanning, interpretation and manipulation of video information. These are to include consideration of digital processing, analog electrical processing, optical processing or suitable combinations thereof. This is a long-range task which is expected to continue as long as digital processing development is required.

This is a continuation of part of the FY 68 effort emphasizing the development of advanced imaging processing techniques, i.e., algorithms and software. Computer and hardware development are being co-supported by the Mariner 69 flight project and by the Digital Video Processing Equipment task (NASA 186-68-03-10). As this job continues to support computer associated advanced developments, they will be reported.

The primary objective this fiscal year is the further development of the special purpose operating system (VICAR), which has been developed to facilitate the processing of pictures and the writing of processing programs.

PROGRESS

As part of this task and co-supported by the flight projects, a complete Image Processing System has been defined in a previous report (JPL Technical Memo 33-353, Vol. 2, page 271). A brief discussion of the criteria involved in the design of an operating software system was given in that reference. This task is primarily supporting the continued development of that software system.

IBM Programming System, PS-IV

The IBM PS-IV has been assembled and installed to replace the previous version of the system.

Initial study of the system requirements for the user-interchange operation to be used with the interactive console and the acquisition devices has begun.

VICAR (Video Image Communication and Retrieval) System

This is the special purpose supervisor which has been developed to facilitate the processing of pictures and the writing of processing programs. VICAR III is in operation. Development of VICAR to include further functions and to simplify the job of the using programmer is continuing.

The complete set of image processing programs has been submitted to COSMIC.

During this period while VICAR is being used, a modification to VICAR is being designed to incorporate the conversational mode of operation. This mode of operation is required to facilitate the use of the live display which allows the analyst to interact with the processing. This mode will also enhance the efficiency of the system in both processing and program development.

Minor technical problems in the debugging of programs have been overcome as encountered. There have been no major problems.

PLANS

During the remainder of the year, the user-interchange mode of operation will be defined, and a prototype live-display installed for user-interaction with processing. This will eliminate the last remaining major cause of slow turn-around in the image processing, and greatly facilitate both alogorithm development, parameter selection and experimental processing.

In addition, software development will be begun to provide inter-active display of alpha-numeric and graphical data on the live console, and for continuous graph plotting with grey shades and color on 35-mm or 70-mm film.

ANTICIPATED PUBLICATIONS

The complete set of image processing programs has been submitted to COSMIC.

PUBLICATIONS

Journal Articles

1. Billingsley, F. C., "A Digital Image Processing Rationale," Journal of the Association for the Advancement of Medical Instrumentation, January 1969, p. 31-45.

ADVANCED SCIENCE DATA SYSTEM TECHNIQUES

NASA Work Unit 125-23-02-02

JPL 325-30201-2-3240

M. Perlman

OBJECTIVES

The general objective of this task is to advance the state-of-the-art in system and logical design techniques applicable to future spacecraft science data systems. Pursuant to this are the following specific objectives:

(1) Development of formal mathematical characterization of finite-state machines.

(2) Maximization of scientific information transferral.

(3) Reliability enhancement through circuit redundancy and/or signal redundancy.

(4) Development and application of algorithms for minimizing simultaneous Boolean functions.

(5) Development and application of algorithms for selecting state assignments which minimize overall logical complexity of a sequential network.

PROGRESS

Theory of Cubical Complexes

Another phase of a research study contract has been completed by the IBM Thomas J. Watson Research Center. The study "A Formal Theory of Cubical Complexes" focuses on the analysis, synthesis, and fault diagnosis of irredundant logical automata. Results covering the period from September 1, 1968, to April 30, 1969, includes the following:

(1) An APL program, Multiple Output Minimization Algorithm, for two-level multiple-output combinational logic circuits. The letters APL designate the programming language that is the outgrowth of

the work of K. E. Iverson. (The initials APL correspond to the title of Iverson's book, A Programming Language, published by Wiley in 1962. APL is a "conversational" language by which a programmer communicates with the computer via the keyboard. It enables one to check the feasibility of an algorithm before converting it to a more efficient machine language.)

(2) Progress to date on the development of F-notation, a high-level language for the description of algorithms and programs. A formal syntax for the F-notation has been developed.

(3) An algorithm and an APL program for fault diagnosis or irredundant asynchronous sequential circuits. This is termed C-alg which denotes a fault diagnosis algorithm for cyclic logical circuits. The C-alg is given in F-notation.

Theory and Design of Reliable Spacecraft Data Systems

A research study contract was awarded to the University of Michigan in the "Theory and Design of Reliable Spacecraft Data Systems." The technical focus of the study is the mathematical characterization of finite-state machines with redundant memory elements which mask memory element failures. Investigations will be undertaken to relate the redundant machine to its irredundant equivalent in order to determine the amount of memory redundancy required to mask a specified class of errors. Also fault diagnosis algorithms will be formulated for finite-state machines with redundancy in the structure.

Quarterly Progress Report No. 1 covering the period from February 10, 1969, to May 9, 1969, has been received and includes a survey of technical literature in three proposed areas of investigation. These are:

(1) Design and analysis of redundant combinational and sequential networks.

(2) Fault diagnosis of redundant systems at the component and subsystems level.

(3) Data system reliability analysis.

It was agreed by JPL and the University of Michigan to exclude area 3 in favor of more concentrated effort in areas 1 and 2.

Sequential Networks

A search for r^{th} degree tetranomials with periods of $2^{r-1}-1$ and $2^{r-1}-2$ was completed through degree r equal to 34. Each tetranomial may be expressed as $(x + 1)\,\phi(x)$ or $(x + 1)^2\,\theta(x)$ where $\phi(x)$ and $\theta(x)$ are primitive polynomials of degree r-1 and r-2 respectively. These tetranomials characterize a 3-tap linear feedback shift register capable of generating pseudo-noise sequences of length $2^{r-1}-1$ or $2^{r-2}-1$. The FSR plays a central role in the analysis and synthesis of autonomous linear sequential machines.

Signal Redundancy

Investigations of algebraic codes are continuing, particularly, the cyclic polynomial codes. Signal redundancy techniques are being considered where long term reliability requirements are beyond the state of the art technology, e.g., the TOPS program. Encoding and decoding is confined to data to be transferred within the spacecraft science data system.

PLANS

Development of fault diagnosis algorithms for irredundant asynchronous sequential networks will continue at IBM Watson Research Center.

Application of the multiple output minimization program MIN-6 will be applied to monotonic voltage curve generation by digital techniques.

The University of Michigan will formulate and explore the model of a finite-state machine with redundant memory which masks a specified class of memory failures.

The search for r^{th} degree tetranomials which contain an $r-1^{th}$ or $r-2^{th}$ degree primitive polynomial as a factor will continue. A special purpose, 3-tap, linear 44 stage FSR is being designed to operate at 120 MHz. This will enable the search to be extended to degree 44.

The study of algebraic codes and their application to enhancing the reliability of spacecraft science data systems will continue.

ANTICIPATED PUBLICATIONS

1. Publication A in condensed form has been accepted for publication in the IEEE Transactions on Aerospace and Electronic Systems in August 1969.
2. Perlman, M., "The Decomposition of the States of a Linear Feedback Shift Register into Cycles of Equal Length," accepted subject to suggested revision by IEEE Transactions on Computers.

PUBLICATIONS

JPL Publications

1. Roth, J. P., and Perlman, M., "Space Applications of a Minimization Algorithm," JPL Technical Report 32-1385, April 1969.
2. Perlman, M., "PN Sequence Generation with 3-Tap Linear Feedback Shift Registers," JPL Technical Report 32-1432 in preparation.

VIDEO INFORMATION EXTRACTION

NASA Work Unit 125-23-02-09

JPL 325-30901-2-3240

T. C. Rindfleisch

OBJECTIVE

The long range objective of this work unit is to develop video data compression techniques achieving compression factors in excess of 100. Implicit in this goal are the development and improvement of methods to enhance, extract, and encode various types of image information.

The objectives for this fiscal year have been the continued in-house development of two-dimensional digital processing techniques for noise suppression and the enhancement and extraction of various types of video information. An R/AD contract was let to USC for the study of Fourier transform approaches to data encoding.

PROGRESS

In-House

Since the last report, efforts have concentrated on both the preprocessing of video data to suppress random noises relative to significant information and the automated extraction of quantitative pattern characteristics from enhanced pictures. Sample imagery for testing these techniques has been derived from radioisotope scanner pictures and spacecraft television pictures.

The problem of suppressing random noises in imagery with a minimum associated loss in resolution has been under continuing investigation. The filter described in the last report which dynamically adjusts its passband has been applied to a larger sample of imagery. The results continue to be encouraging although considerable hand analysis is required to optimize externally accessible parameters of the program to produce the best subjective image. It is the intent to develop methods for automating this entire enhancement procedure.

Techniques for the automated extraction and analysis of isolated object patterns are being developed. Current investigations include the study of methods for incorporating an internal learning process in the computer software as well as methods for exploiting pattern characteristics to distinguish the pattern from noise. A test problem for these techniques is the tracking of the quasi-rectangular reticle pattern in multi-gray level spacecraft imagery. The pattern is only approximately stationary due to various physical limitations of the camera system and the reticles are on the order of the resolution limit of the system so that noise and image data produce many false "reticles". The algorithm provides for a memory of previous pattern location experience which is used to eliminate obviously inconsistent objects in the new pattern and which is continuously updated using the new reticle locations. The final selection of actual reticles from noise is made using two-dimensional correlation and clustering techniques which exploit the quasi-rectangular characteristics of the array. The program has been able to sort the 35 correct reticles from a total of over 2000 possible objects detected in the image.

Contract

The first phase ($9000) of a study contract with USC for the investigation of Fourier transform processing and encoding of images has been completed. As mentioned in the previous report, the Fourier along with the Hadamard transformations, while computable using a very efficient algorithm, are periodic transforms and as such are not well suited to random natural scenes. It has been possible to compress video information using these techniques only with the loss of some information. The work in this phase of the contract has provided a basis for answering more general and encompassing questions regarding transform encoding of imagery. These problems will be pursued in an extension of the contract.

PLANS

In-House

During the coming fiscal year, there will be continued development of noise suppression algorithms. These will emphasize dynamically adaptive filters and will combine more specifically elements of pattern recognition with the noise removal process. There will be continued work on multi-gray level pattern extraction and analysis techniques as related to the noise reduction problem.

Contract

The current contract with USC will be extended to the study of general transform techniques for the processing and encoding of imagery. Emphasis will be placed on developing computable transforms which approximate the optimal Karhunen-Loeve transform for image representation.

PUBLICATIONS

JPL Publications

1. Selzer, R. H., "Improving Biomedical Image Quality with Computers", JPL TR 32-1336, October, 1968.

Contractor Reports

1. Pratt, W. K., and Andrews, H. C., "Transform Processing and Coding of Images", USCEE Report 341, Final Report, March, 1969.

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EFFICIENT SPACECRAFT DATA SYSTEMS

NASA Work Unit 125-23-02-13

JPL 325-31301-0-3340

R. A. Easton
E. E. Hilbert

OBJECTIVE

The purpose of this work unit is to discover, understand, and demonstrate advanced techniques for the efficient design of planetary spacecraft telemetry data systems. These systems must adapt to future missions without the necessity for long lead times and expensive redesign as the profiles of these missions change. The on-board treatments considered include buffering, multiplexing, formatting and measurement selection, data compression, etc. The techniques worked on are principally aimed at the "post-Mariner" generation of planetary spacecraft. The Thermoelectric Outer Planetary Spacecraft mission will be given emphasis as a special customer, useful as a demonstration vehicle, because its long life and complexity require the telemetry data system to be substantially more powerful and flexible than those of the Mariner class. Multimission ideas and implementation are stressed so that any deep-space mission can use the concepts and techniques developed under this work in procuring its spacecraft data system equipment and software.

PROGRESS

Determination of TOPS Engineering Telemetry Requirements

A survey was made of the TOPS engineering telemetry requirements and a baseline telemetry system was designed using minimum change from Mariner techniques. This system does not provide the flexibility or high sampling rates desirable for TOPS but does provide a basis for comparison with more advanced designs such as the one described below.

A Computer Accessed Telemetry System (CATS).

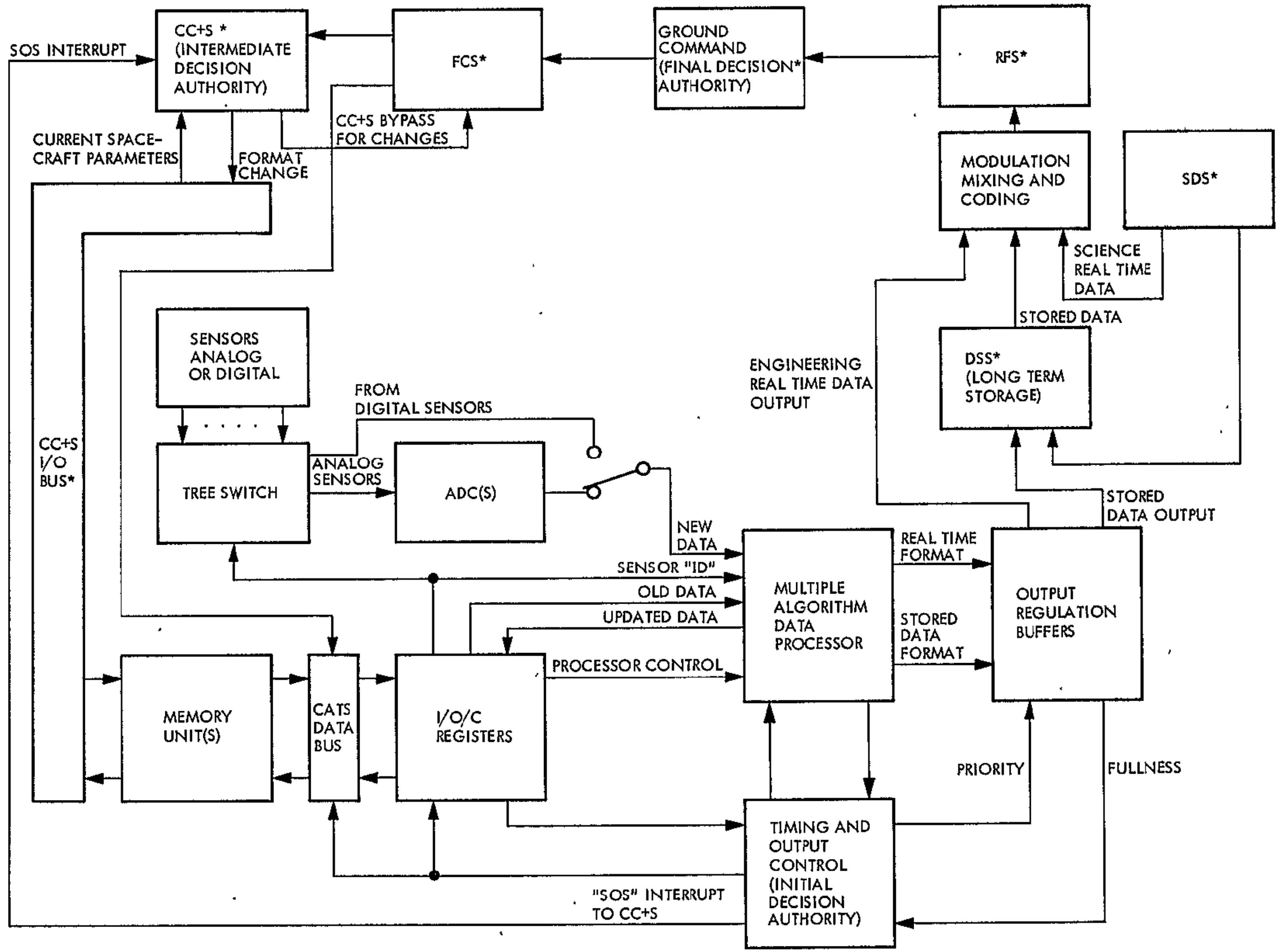
As the name implies, the traditional approach of a more or less fixed sampling sequence derived from a clock-controlled commutator has been set aside in favor of an approach which allows the commutator to be "set" to any desired position by loading in any desired sequence of numbers. Different sampling rates can be obtained for different sensors by loading the numbers corresponding to some sensors more often than those corresponding to others. One way to do this is by using nested DO loops in a computer. The format can then be changed by changing the numbers being loaded and/or their loading frequency.

Figure 1 shows the general organization of a system to accomplish this. Comparison data plus information to control the format, the processor algorithm, and the allowable degree of sensor activity are stored in a memory of approximately 2n words, where n is the number of sensors. The information for one sensor at a time is loaded into the I/O/C (input/output/control) registers; this information interacts with the control circuitry and with new data in the data processor. The result is that any significant data changes are read back into the memory and to the storage buffers. The buffers remove gaps due to compression and timing equalization. Sampling rates and data processing can be tailored individually to each sensor and can be changed at will. Circuit redundancy and error detecting and correcting codes are easily implemented to allow reliability exceeding that easily obtainable with conventional approaches.

Detailed flow diagrams of the system have been drawn and a simulation program is nearly completed. Detailed logic design is starting on a breadboard of the system. Information gained from running the simulation program will be used to guide the logic design. These action items will run in parallel during the coming months.

Improving the FTS Commutator/Programmer

New commutator/programmer configurations have been investigated. These provide greatly improved reliability with reduced power, weight, and volume requirements. Reliability can be improved if the sensor selection



* INDICATES SYSTEMS EXTERNAL TO THE FTS

Figure 1. TOPS CATS FTS Block Diagram

FETS are connected in a self decoding tree structure so that fewer drivers and no decoding gates are required. For a "minimum change from Mariner," small trees can be used as a 1 to 1 replacement for the Mariner subdecks, since they generate their own fixed sequence and require only a clock for a driver. However, with a programmable sequence generator such as CATS, it would be desirable to use a large random access tree for the whole system instead of using several smaller trees as subdecks. This holds because there is no subcommutation required within the commutator with the sequence loaded from a computer memory in the latter configuration. This is the most reliable of the methods considered. High reliability is achieved because the tree has very few components common to a large number of sensors, and these components can easily be made redundant. This is not the case with the Mariner approach.

A four sensor Random Access Tree was constructed and successfully operated. Parts have been ordered to build a full size breadboard. Circuit design studies have been focused on the driver circuit which must interface between the low level logic and the FETS in the tree. These driver designs show that the power dissipated in the driver unit itself can be made negligible compared to that in the load. Such drivers have been breadboarded and successfully operated. Thick film hybrid versions of the drivers and trees will be constructed by the JPL hybrid circuits facilities in the near future. Feasibility of a monolithic IC version is also being studied.

PUBLICATIONS

JPL Publications

1. R. A. Easton, E. E. Hilbert, "Efficient Telemetry Data Systems," SPS 37-55, Vol. III, pp. 52, 53, 54, February 28, 1969.

AUTOMATED LABORATORY INSTRUMENTS

NASA Work Unit 125-23-02-18

JPL 325-32101-2-3240

R. H. Nixon

OBJECTIVES

The work unit objective is to provide a facility which will enable the technology for computer-automated experiments to be evaluated on actual hardware and to reduce to practice those techniques which may be successfully applied to a remote planetary laboratory.

The immediate objective is to automate the control and data-acquisition functions of a light microscope. The IBM 1130 and the IBM 360-44 computers will be interfaced with a light microscope to ultimately provide a completely automated analysis capability. The automated functions include: translation, focusing, magnification change, search, video data acquisition, and data analysis.

PROGRESS

The mechanical modifications to the light microscope have been completed. These modifications include stepping motor control of the following functions:

(1) X and Y Translation

(2) Focus

(3) Eight-Position Filter Wheel

(4) Four-Position Magnification

In addition, the optical bench which the microscope is mounted on has been shock mounted to prevent any building vibrations from interfering with high resolution optical measurements.

As was stated in the previous report, the Surveyor breadboard vidicon would not meet the requirements as an image detector. Instead, an image plane scanner (IPS) will be used. The IPS is a device which physically rotates mirrors to scan the image past a pinhole and into a photomultiplier detector. The IPS was originally to have been purchased from the Perkin-Elmer Corporation, but it has now been decided to fabricate the mechanical portion of the IPS at JPL using drawings obtained from the National Institute of Health who have an IPS which was developed for them by Perkin-Elmer.

The scan control electronics for the IPS have been designed under consultation with Mr. S. R. Pedersen. This portion of the electronics will be fabricated and tested during the first quarter of fiscal year 70. The electronics will be fabricated under contract with Mr. Pedersen.

The motor control electronics have been designed, fabricated, and are in the process of being checked out.

The computer interface equipment for the IBM 1130 has been installed and is operational. A cycle steal function has been designed as an addition to this equipment and the modifications are presently being made to accommodate it.

PLANS

The software for controlling the microscope will be developed during the first quarter of FY 70. Program subroutines will be written to provide the greatest flexibility possible for control and data acquisition. Because of core limitations in the IBM 1130, most of the video processing will be accomplished after the data is stored on magnetic disc. Some processing jobs will be larger than the 1130 computer can handle. In these cases the processing will be done by the IBM 360-44. A link between the two computers will be accomplished during FY 70 to accommodate this data transfer.

The scan control electronics will be installed and checked out during the first quarter of FY 70. It is anticipated that all hardware will be functional by October, 1969, and that the second quarter of FY 70 will be devoted to software development and system testing.

PUBLICATIONS

None

INSTRUMENTATION (125-24)

ADVANCED SIGNAL CONDITIONING

NASA Work Unit 125-24-01-08

JPL 325-41001-2-3220

J. A. Daniels
J. R. Locke

OBJECTIVE

The long range objectives of this task are to conceive, design, develop and demonstrate signal conditioning circuitry having application to planetary and landed scientific instrumentation and the maintenance and advancement of in-house technology. FY 69 efforts are directed at the support of gas chromatography and mass spectrometer instrumentation. These efforts include: (1) a logarithmic electrometer, (2) charged particle counting, (3) power law compression, and (4) microminiaturization of the peak detector-analog-to-pulse width converter (PD-A/PWC).

PROGRESS

Logarithmic Electrometer

Efforts to develop a solid state logarithmic electrometer were successfully concluded during the first half of FY 69.

Charged Particle Counting Technique

This technique is being developed for use with a lunar mass spectrometer. The need for this approach stems from the need to measure the low ion currents (associated with mass spectrometer analysis of the rarefied atmosphere of the moon) which are below the practical limits of present spaceborne electrometers.

A test system has been designed, fabricated and assembled that will be used in evaluating the detection efficiency of the particle detector (a Channeltron) used in this instrument. This system will also be used to simulate the performance of the mass spectrometer for system testing the charged particle counting instrument.

Detail design of the eleven digital submodules, required by the system, has been concluded and a request for quotation has been issued for wiring sixteen of the twenty circuit boards.

Auxiliary electronics have been designed for read-out and control of the counting instrument and wiring details and layout of this system have been started. Supporting instrumentation (digital recorder, high-voltage power supplies, etc.), fabricated parts, electronic components and accessories required for the instrument and its testing have been acquired and construction and assembly are proceeding.

Planned future efforts include: (1) Channeltron testing and concurrent development of pulse processing circuitry, (2) complete wiring details and layout of read-out and control electronics, (3) complete construction and assembly, and (4) test and evaluate counting technique, redesign and develop as required.

Power Law Compression

Power Law Compression has application to a mass spectrometer. The technique utilizes the current gain relationship of an electron multiplier which shows the gain to be a power function of the applied supply voltage. The advantages of the technique are: (1) a wide dynamic range that can be tailored for specific applications, (2) it permits use of a single range AC coupled electrometer, (3) eliminates the DC drift problem, (4) has a fast response and, (5) is amenable to signal/noise filtering techniques.

The Power Law Compression system using a discrete dynode electron multiplier has been successfully built and operated. Due to the capacitance coupled feedback transformer, special attention was required for system stability.

The low-level pulse signals, that such a system looks for, are imbedded in noise and are often completely obscurred using conventional methods of detection. Statistical design techniques for extracting these low-level pulse signals of unknown amplitude from noise have been studied and will be applied in developing filters.

Computer aided design analysis methods are being employed in analyzing the results of the filter synthesis.

Filter circuitry will be developed based on the results of the statistical techniques of signal detection.

Calibration techniques will be developed and built to test the accuracy of the overall system.

Microminiaturization of the Peak Detector-Analog to Pulse Width Converter (PD-A/PWC)

The PD-A/PWC was developed under this task at an earlier time for use with mass spectrometers and gas chromatographs. In such applications it serves the key functions of marking peak time of occurrence and conversion of the peak amplitude into a corresponding pulse width suitable for digital encoding. Since only the desired data points are encoded, data compression is achieved.

Fabricating the circuit in the microminiature form will optimize the performance of the circuit because it will minimize the thermal gradient seen by the components of the circuit. The significance of this property lies in the circuit design emphasis on input symmetry. Additional advantages associated with the hybrid version are: minimal circuit volume and weight, and increased circuit reliability.

After soliciting requests for competitive proposals from six capable organizations, Motorola's Government Electronics Division was awarded a $19,600 contract to design, fabricate and test one prototype and five proof test models in hybrid form. A later supplemental contract for $9,300 increased the number of proof test models to twenty.

Motorola's approach to converting the PD-A/PWC to hybrid form has been to break the circuit into two parts which are packaged in two separate hermetic TO-8 metal cans. A molybdenum manganese thick film conductive network is screened on to the two ceramic substrates to form a basic conductive network to which are attached chip diodes, transistors, a monolithic and thin film nichrome resistors. Wire interconnections are accomplished using aluminum wire and thermocompression bonding. To improve repairability (and thus yield) an intermediate bonding pad is used with all wired interconnects when possible.

The contractor is presently on schedule and has delivered the prototype unit. This unit was subjected to: heat soak, thermal stress, humidity, vibration and shock, and survived these environmental conditions without any signs of degradation. In addition, the unit surpassed, by a substantial amount, the performance criteria on the thermal stability of peak height-to-pulse width conversion.

PUBLICATIONS

None

RADIOMETRY INSTRUMENTATION DEVELOPMENT

NASA Work Unit 125-24-03-05

JPL 325-40801-0-3710

M. Berdahl
J. M. Kendall, Sr.
R. C. Willson

OBJECTIVE

The long-range objectives of this task remain as last reported. These are to:

(1) Develop the art of quantitative radiometry to the degree required for testing spacecraft in simulators. This has not yet been done elsewhere. Methods of measuring total energy flux and its spectral distribution will be studied.

(2) Develop standard procedures for calibrating radiometric devices and to set up a laboratory, which, on a routine basis, can maintain a family of calibrated devices.

(3) Develop certain radiometric experiments which can be used to check the actual performance of space simulators, and which can be used to test the radiant energy transfer properties of spacecraft surface coatings.

The current objective is to establish the JPL cavity type radiometers as primary standards of total irradiance measurement. If this can be accomplished, it will provide an absolute scale rather than an arbitrary scale to which irradiance measurements may be referred. Since the arbitrary scale is defined by an Angstrom Pyrheliometer presently held in Stockholm, preliminary comparisons will be made with locally held instruments of this type under various levels of solar irradiance prior to a comparison with the Stockholm instrument. A secondary objective (one that automatically falls out of using a solar source at low air mass) is the determination of the solar constant.

PROGRESS

Primary Absolute Cavity Radiometer, PACRAD

Testing and analyzing the Primary Absolute Cavity Radiometer to increase our confidence in its performance constituted the main portion of work performed in the last half of FY 69. A series of tests were made at the JPL Table Mountain Facility in which the newly constructed standard radiometer for use at ambient pressures was compared with the prototype PACRAD, a cooled cavity type radiometer and two secondary standard International Pyrheliometric Scale Eppley Angstrom Radiometers. Tests made in April, in which extensive data were taken with all instruments, indicated consistency between JPL cavity types in the order of one quarter of a percent but disagreeing with the I. P. S. as determined by the Angstrom Radiometers by two and one half percent. The JPL cavity types gave higher readings consistent with previous Angstrom Radiometer comparisons and tend to confirm the scale relationship between the two types. The new JPL PACRAD proved to be easy to set up and operate and tracked the Sun accurately for several hours without adjustments. It provided a large sample of data with which to make our comparisons. The short time constant of this instrument in following changes of irradiance level permitted almost instantaneous readings to be taken, thus helping to provide the high confidence level which was achieved.

A thorough electrical, mechanical and heat transfer analysis has been performed on the PACRAD with the result that our certainty of agreement with an absolute scale of total irradiant energy is well within one half of one percent. Heat transfer analysis is still being done and should either reveal any discrepancies or serve to further strengthen our confidence level. NBS and GSFC are making blackness tests of surface coatings for us which will further narrow our uncertainties.

Liquid Cooled Heat Sink Radiometer

A prototype variation of the cavity radiometer using a water referenced heat sink is now in the development stage. It will provide a radiometer with essentially an infinite heat sink (one whose temperature is constant regardless of irradiance level). Such an instrument will be useful in making measurements over long periods of time such as are encountered in long solar-thermal tests of spacecraft. Interest has recently been shown in this version of cavity radiometer by Lewis Laboratory who wish to use such an instrument as a reference standard for calibration of other types of radiometers. We are working closely with both Lewis Laboratory and the National Bureau of Standards. in the development, testing, and use of this instrument.

Solar Constant Measurement

A second related activity is participation in a joint effort with Division 34 on R. F. Greenwood's Solar Cell Standardization Program, NASA Work Unit 120-33-01-03-55 in which balloons are used to carry instruments to higher altitudes. The instruments for the upcoming balloon flight are again slight modifications of the standard JPL cavity types which operate in ambient atmosphere. The modifications consist of use of a platinum wire resistance bridge heat flow sensing circuit and a built in amplifier suitable for flight telemetry. It is expected that we will obtain a better figure for the solar constant at an altitude of 120, 000 feet than was obtained on the previous balloon flight which was at an altitude of 80, 000 feet.

PLANS

Future activities include further analysis and comparisons until the opportunity arises to make the comparison with the Stockholm Held Angstrom Pyrheliometer representing the International Pyrheliometric Scale. Early in FY 70 the JPL radiometer will be used as a reference scale for calibration of instruments used on the Nimbus Satellite in connection with Earth resources determination program. Later a comparison will be made with a somewhat similar radiometer of cavity type owned by the National Physical Laboratories (NPL) in England. The experiment will take place at the Eppley Laboratories in September and use a standard light source furnished by NPL. Later comparisons may be made at Table Mountain using the same radiometers.

There will be a need for radiometers of both high sensitivity (for far distant planet solar intensities) and for high levels (such as Venus and Mercury intensities). Methods of optical irradiance amplification will be studied for the former and possible variations in construction studied for the latter.

Other plans, time permitting, will include investigation of a new type instrument to measure upper atmosphere aerosol properties and its possible use in meteorological work. A study of need for and the present state-of-the-art in connection with ESSA and other NASA facilities will be made prior to proposing any action on this work.

ANTICIPATED PUBLICATIONS

Journal Articles

1. Willson, R. C., "The Active Cavity Radiometric Scale, The International Pyrheliometric Scale and the Solar Constant," Journal of Applied Optics (in process).

2. Kendall, J. M., Sr., and Berdahl, C. M., "SACRAD and PACRAD "Black Body" Radiometers of High Absolute Accuracy," Journal of Applied Optics (in process for January 1970).

JPL Technical Reports

1. Willson, R. C., "A Comparison Study of JPL Absolute Radiometric Methods" (in process).

2. Willson, R. C., "High Altitude Measurement of the Solar Constant and Spectral Distribution" (in process).

PUBLICATIONS

JPL Technical Reports

1. Willson, R. C., "Experimental and Theoretical Comparison of the JPL Active Cavity Radiometric Scale and the International Pyrheliometric Scale," TR 321365, February 1, 1969.

ELECTRON MICROSCOPE
NASA Work Unit 125-24-03-06
JPL 325-41101-2-3240
R. Nathan

OBJECTIVE

The objective of this work unit is to investigate the feasibility of improving the normal 10 A resolution of a commercial transmission electron microscope to a 1 A resolution (atomic distances) thereby revealing molecular geometry of biological materials. An image-intensifying system also becomes necessary for reduction of exposure times and improvements of contrast.

PROGRESS

The SEC intensifier camera has proven to be very difficult to bring into reliable operation. We have temporarily abandoned it in favor of a 3-stage image intensifier coupled to a vidicon via fiber optics. This change in directions was recommended by Dr. Ando who was having similar difficulties in his advanced space camera work.

We were very successful with the new intensifier from VARD, but arcing from the high voltage supply of the intensifier partly destroyed the equipment. We have since developed a better mounting to avoid a repeat of the damage and should have the repaired tube ready for reinstallation early in July.

PLANS

This task will not continue in FY 70. The efforts will continue, however, as part of an NIH grant titled "A Computer Resource for Pictorial Data Processing". Since the loss of NASA support was not anticipated, and the NIH grant funding for hardware development is very limited, progress will be much slower than planned.

ANTICIPATED PUBLICATIONS

A report "Computer Processing for Electron Micrographs" has been completed and will be submitted to an appropriate journal. (See JPL Announcements of open literature articles, since this task will not be reported on again.)

PUBLICATIONS

None

ELECTRONICS TECHNIQUES AND COMPONENTS (125-25)

FAILURE MODES IN MULTI-FUNCTION SEMICONDUCTOR DEVICES

NASA Work Unit 125-25-02-01

JPL 325-50501-0-3540

L. W. Wright

OBJECTIVES

The long range objective of this effort is to identify and investigate the fundamental physical and chemical phenomena underlying degradation and failure processes in Multi-function semiconductor devices. The results from these studies will then be used as a basis for (1) improvement of device reliability and (2) prediction of device reliability with minimal need for large scale test programs.

PROGRESS

The program to investigate problems associated with the bonding of large area silicon wafers has been completed and the final report received. Throughout the program, five bonding techniques received attention. The three techniques showing the greatest promise were diffusion bonding, amalgam bonding and anodic bonding. Reliable bonds were made for wafers up to two inches in diameter. Additional work, however, will be necessary to further develop these techniques before they can be implemented in a production operation.

PUBLICATIONS

Contractor Reports

1. Final Report on Bonding Large Area Silicon Wafers, Motorola, Inc., Semiconductor Products Division, Contract 952022.

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ADVANCED DEVELOPMENT OF ELECTRONIC INTERCONNECTIONS

NASA Work Unit 125-25-03-01

JPL 325-50101-0-3570

E. R. Bunker, Jr.

OBJECTIVE

The long range objectives of this work unit are to: (1) maintain awareness of state-of-the-art cabling technology for unmanned spacecraft including applicable documentation, (2) demonstrate advanced cabling and interconnection approaches which provide substantial improvements in weight and noise reduction, ease of fabrication, maintainability, and reliability of spacecraft subsystems, and (3) develop format and employ machine data processing techniques for generation of wire and connector tabulation, and routing.

The short range objectives of the work unit during FY 69 are to: (1) determine the present status of cabling technology being used in unmanned spacecraft by various agencies and contractors; (2) develop advanced interconnection technologies for interconnection between microelectric modules, discrete component modules, subassemblies and assemblies and combinations of these; and (3) demonstrate a punched card documentation system for a cable harness and compare with presently used combinations.

PROGRESS

Punched Card Cabling Documentation

No further work as an advanced development effort was done using punched cards for cabling documentations. Based on the previously published report JPL TR-32-1326 "Documentation of Wiring Harnesses by Use of Punched Card Techniques," the documentation of the Mariner '71 Operational Support Equipment (OSE) cabling is being done by means of punched card techniques in a simplified form i.e. the voltage level, noise index numbers, impedances, etc. are not included. The system is being used only to keep track of the wire and cable connectors. If this OSE application proves suitable, it may be used on Mariner '71 spacecraft cabling documentation. Plans are also in progress for use of this cabling documentation system on a Nimbus flight experiment. Unless some problem arises in its application, no further work is anticipated.

Flexible Cable Harness

From the bids submitted, a vendor was selected to fabricate the etched flat cable substitution for the main CSAD Lander cable harness. To date, the final art work is in preparation for checking and approval by JPL, whereupon the final harness configuration will be fabricated. A wire by wire checking of the preliminary art work showed several discrepancies and errors which are being corrected in the final art work. Three cable harnesses were ordered. Upon receipt of these, the connectors will be installed and checked against the functional operation of the lander.

A contact was made with the Astrionics Laboratory of the George C. Marshall Space Flight Center in Huntsville, Alabama, to ascertain if their flat cabling group would be interested in fabricating an equivalent cable to compare with the etched cable being obtained for the flexible harness. Because of their work commitments, they stated that they were unable to support this project other than possibly giving JPL some pieces of flat cable.

PUBLICATIONS

None

MICROELECTRONIC PACKAGING ADVANCED DEVELOPMENT

NASA Work Unit 125-25-03-02

JPL 325-50201-0-3570

E. R. Bunker, Jr.

OBJECTIVE

The long range objective of this work unit is to develop better techniques for packaging cased integrated circuits and miniature discrete components. A further long range objective is to develop better wire routing and joining techniques and to evolve a process for effecting all shielded and subsequently all coaxial interconnections with a batch system for the integrated circuit module developed at JPL. This module is a packaging technique developed under this work unit during FY 65 and FY 66.

The FY 69 objectives include the further development of the folded stick module and the development of hybrid component interconnecting techniques.

PROGRESS

Folded Stick Interconnection

The properties of several plastic materials which would be candidates for replacement of the polyethylene were reviewed, but no decision was made. Further work was suspended on the folding stick due to manufacturing problems being encountered with the original green stick. Further work on the folding stick will be performed in FY 70.

Green Stick

Delays were being encountered in the procurement of the green sticks for flight applications which were blamed at first on the manufacturing problems being encountered by the vendor. A careful study of the stick configuration, review of drawings and tolerances, and associated data, including breakage of the mold resulted in the conclusion that vendor incompetence was the main difficulty. To provide a backup for procurement of the green sticks, the decision was made to send out bids for an additional mold to prospective vendors who have no connections with the original procurement. The purchase order for this additional mold and an initial stick procurement was let. The vendor who was awarded the contract, designed and fabricated his mold on a somewhat different principle which would probably eliminate most of the problems previously encountered.

This new mold has been completed and the first stick submitted for first article inspection. The original mold which had been broken in the molding press by the vendor has just been obtained and will be reworked or repaired so as to give two possible sources of stick modules.

Composite Stick Module

With the problems being encountered in obtaining a molded stick module mentioned above, an independent approach was initiated for a simple stick configuration which would be built-up essentially by off-the-shelf items bonded together by suitable adhesives into the stick configuration. The hand built prototype is shown in an exploded view in Figure 1 and assembled in Figure 2. A metallic frame is used as a carrier and also functions as a heat sink for the flatpacks. The mounting screws are also a part of this frame. The terminals for the flatpacks are inserted through appropriate holes in the plastic mount and wiring guide, similar to the green stick. There are no metallic inserts molded into this plastic making it very simple to make.

The external connections are achieved by a subminiature flat connector, obtainable in strip form as shown. The connector is cut to the proper length, the terminating wires bent to a right angle and inserted through holes in the plastic carrier, then bonded to it. Connections to the flatpack terminals are achieved in the same manner as before with #32 wire welded or soldered and routed around the wiring guides.

As can be seen from Figures 1 and 2, 78 connections are available instead of 39 of the green stick. Terminations of the mating connector on the chassis can either be integral stranded wire as shown in Figure 1, or solid bus wire in Figure 2. The plug-in feature, which does not require a separate

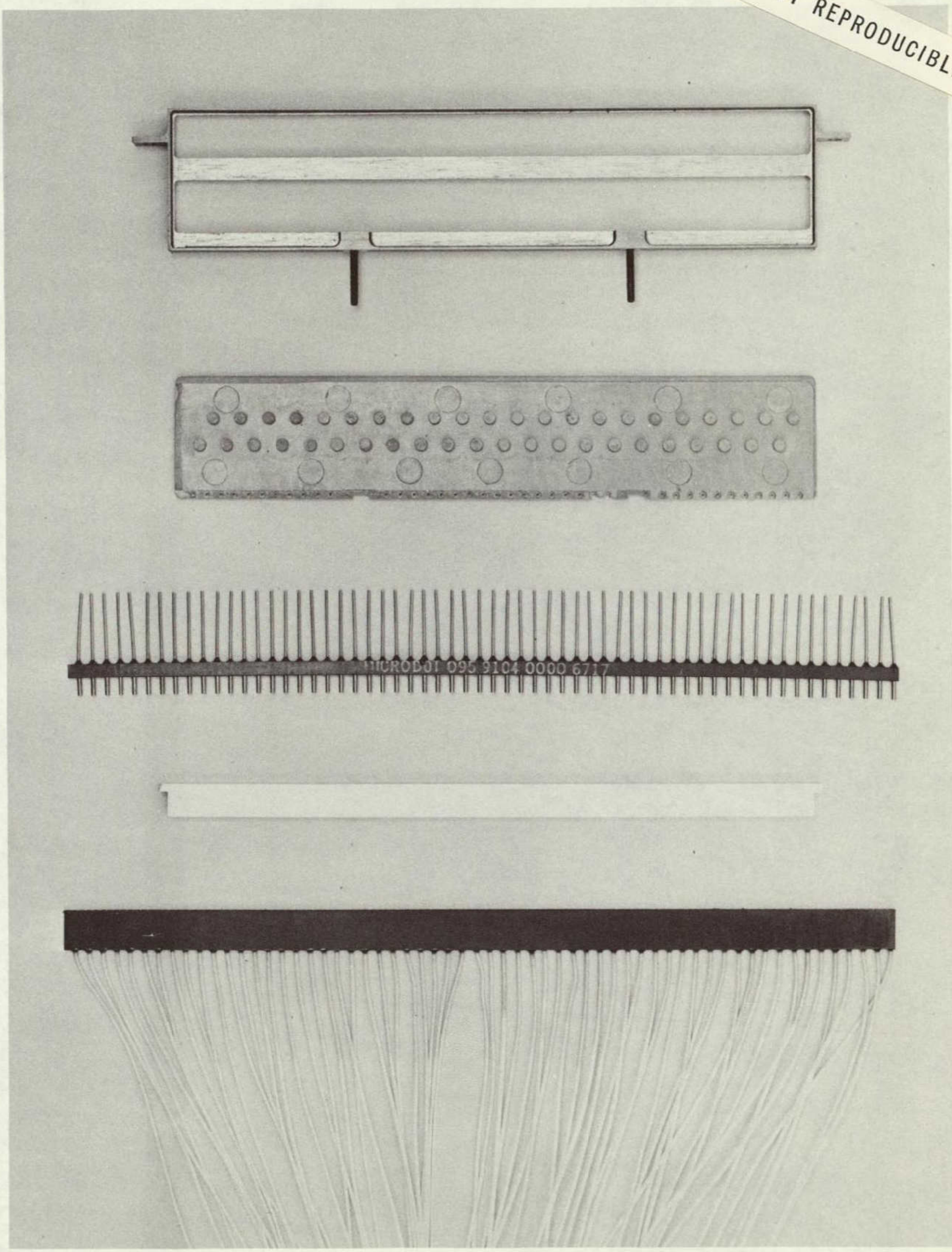

Figure 1. Prototype Stick Module Exploded

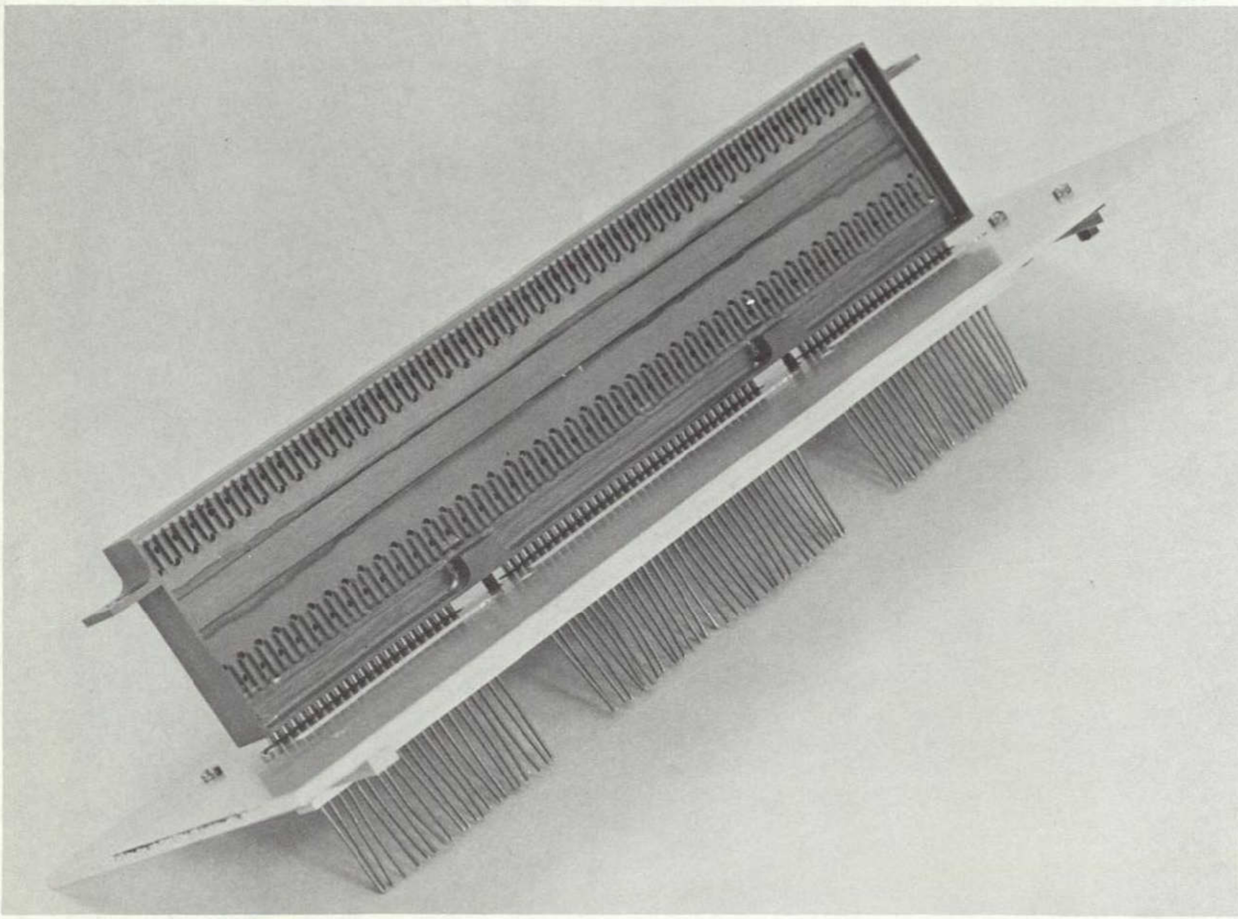

Figure 2. Prototype Stick Module Assembled

connector, would be of advantage in spacecraft applications. Composite sticks of various lengths could be made by merely obtaining a metal carrier of the desired length and trimming the rest of the parts to fit.

Further work will be done with this approach in FY 70 to determine its desirability and feasibility in flatpack mounting and interconnection.

PUBLICATIONS

None

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IN-FLIGHT FAILURE RATES OF SPACECRAFT ELECTRONIC PARTS

NASA Work Unit 125-25-04-03

JPL 325-50601-0-3540

W. R. Scott

OBJECTIVE

The long range objective of this effort was to investigate the preflight treatment of the electronic and electromechanical parts employed in Mariner IV and Mariner V spacecraft and the effect of such treatment on the in-flight failure rates displayed by the parts. The objective was to be pursued in three phases: (1) survey of Mariner IV and Mariner V data; (2) analysis of the data; and (3) extension of the first two phases to cover the Mariner '69 data, the design of experiments to yield and update actuarial data on parts life expectancies, and the correlation of real life observations with analytically derived prediction criteria.

PROGRESS

The efforts of this report period dealt with the first two phases. In pursuit of the first phase, the parts control activities contributing most to success were identified; some improved parts control techniques were delineated, and cost burdens which might have been reduced or obviated by suitable planning and funding schedules were indicated.

The second phase efforts included the verification of the validity of premises and criteria from experimental and failure report analyses and the determination of what experimental data and observations were lacking which could most enhance reliability techniques and associated cost-effectiveness.

The original plan to extend the effort objectives to cover the Mariner '69 data was not pursued due to the gross unavailability of Mariner '69 information in reduced form at this time. It is recommended that phase III be pursued when the data becomes available. The study effort has been concluded and a final report prepared. Further effort on phase III will not be conducted due to task termination as a result of fund limitations.

PUBLICATIONS

None

HYBRID PACKAGING ADVANCED DEVELOPMENT

NASA Work Unit 125-25-04-04

JPL 325-50901-0-3570

E. R. Bunker, Jr.

OBJECTIVE

The long range objectives of this unit are to: (1) maintain awareness of hybrid packaging technology by studying requirements of unmanned spacecraft subsystems along with present techniques being employed by industry and NASA centers so that problem areas can be determined and recommendations made, and (2) develop knowledge of process of hybrid packaging so that preparations of specifications, monitoring of procurements, and participation in design reviews will be effective. The FY 69 objective is to become familiar with the work of others in new thick film technology, active device attachment, and environmental protection for hybrid circuits and hybrid circuits inter- and intra- connecting. This task was to cover all aspects of developing thick film circuits, including mask preparation, firing, resistor and capacitor trimming, registration, termination, and protection.

PROGRESS

Hybrid Microelectronics Facility

After the various pieces of equipment were installed in the new facility, and operation commenced, various shortcomings and a freak accident to the furnace caused a delay in fabrication of thick film circuits and test patterns. Recommended practice is that when the furnace is up to temperature and the profile determined, it is to be operated continuously without interruption, night and day. Sometime during the weekend, with the furnace running at full power, the water supplied to the cooling jacket was interrupted. The over-temperature trips, designed to protect the furnace in such a situation, shut down the furnace as the temperature limits were exceeded. When the water came back on, the jacket was still at a sufficient temperature so that when struck by the cold water it ruptured. Valves were installed so that in the future if the water supply is interrupted, not only will the over-temperature trips shut down the furnace, but the water will be shut off.

In order to regain some of the time lost, it was decided to fabricate a limited number of circuits along with the test patterns previously prepared to evaluate the equipment and the techniques being employed. Although the industry recommends that from six months to a year be used to evaluate equipment test patterns and technology before actual circuit fabrication is attempted, the requirements of JPL would seem to indicate that this may not be necessary. In industry, several hundred circuits are considered as prototypes preparatory to the production run. It is this step between prototype and production where a lot of problems occur. Since spacecraft requirements would hardly ever require more than the prototype number because of the limited number of subsystems, this problem area would be avoided. Consequently, circuits are being fabricated to representative schematics of spacecraft subsystems with a close control of the various steps being employed.

To data, a limiter-amplifier employing an operational amplifier and a flatpack configuration together with screened on resistors, abrasively trimmed, and a chip capacitor were interconnected on a substrate. The hybrid equivalent of the wirecon utility test module which uses 6 transistors in a J-K flip-flop configuration, described in JPL Space Programs Summary No. 37-40, Vol. IV, Pg, 38, has been designed and laid out in a hybrid configuration which will employ leadless inverted device (LID) transistors.

Difficulties encountered with certain steps in the design and layout of hybrid circuits pointed out the need for additional or better equipment. For example, it was found that the precision obtainable on a drafting board was not suitable for layout of complex hybrid circuits; consequently, a coordinatograph was ordered. Employing this device for accurate layout of the hybrid patterns will facilitate the investigation into the smallest possible sizes for conductors, spacings, and component attachment pads. An automatic resistance trimming bridge was found necessary to obtain a repeatable matching of resistors in the resistor test patterns. Other minor pieces of equipment were ordered to allow the speeding up of various phases of the hybrid process and result in saving of personnel time.

PLANS

During the next interval, test patterns will be run for various parameters encountered in the hybrid processes. Representative circuitry for the STAR computer has been obtained so that functioning circuits may be fabricated.

PUBLICATIONS

None

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HIGH VOLTAGE ELECTRONIC PACKAGING ADVANCED DEVELOPMENT

NASA Work Unit 125-25-04-05

JPL 325-51001-0-3570

E. R. Bunker, Jr.

OBJECTIVE

The long range objective of this work unit is to develop the technology of high voltage packaging by means of optimum procedures, materials uses and hardware geometries so that breakdown will not occur in high voltage circuits.

The FY 69 objective is to demonstrate the effectiveness of the packaging technology for representative high voltage power subsystems that are applicable to present and future spacecraft systems.

PROGRESS

Corona Detection Network

The problems encountered with the first prototype were analyzed to modify the design of a second model, but based on the same basic principles. Some of the features of the second model include shielding all of the high impedance signal components by a metallic box which is insulated from the chassis. This would eliminate the stray ac fields causing cross-talk and noise in the signal circuits which were encountered in the first model. An additional source of hum pickup was eliminated by operation of the mode indication lights on low voltage dc rather than 120v ac.

A new approach to the method of bucking out the voltage induced into the system by stray capacitance was being investigated. The original circuit, which used a conventional resistance-capacitance phase shifter to match the capacitance voltage with the bucking voltage, both in amplitude and phase, did not perform properly in the presence of harmonics. The proposed approach employs the use of rectified dc to be applied to the microammeter circuit, which will be proportional to the stray capacitance voltage and thus give a bucking action. This approach eliminates any problems from harmonics or the phasing of the two ac wave forms.

Further work will be performed on Model #2 to determine its capabilities and limitations, and it will have a sensitivity calibration to enable a comparison with more conventional corona detection and measuring equipment.

Variable Frequency Power Supply

Initial tests with the 60 Hz to 2. 5 kHz step-up transformer driven by a 75w power amplifier with a pure sign wave input were made. The output is sinusoidal with apparently no harmonics until about 4 kv is reached, whereupon a large spike appears at the peak of the output wave. Whether this is due to instability in the power amplifier or an interaction between the transformer and amplifier needs to be determined. Further work on the high voltage power supply has been suspended pending the procurement of a direct reading high voltage volt meter of better accuracy than is now available.

High Voltage Transformer Embedment

The samples of various encapsulating materials with high voltage wire embedded in them as described in the previous progress report were exposed to high voltage. Upon application of voltages in excess of 500 volts, one of the exposed ends of the test sample would breakdown with what appeared to be an internal arcing through the insulation. A careful analysis of the wire showed the presence of a conductive coating next to the shield which was causing the conductive path and burning of insulation. Very careful cleaning of the insulation surface with a solvent would remove this coating, whereupon the wire would withstand the rated voltage without breakdown. Since the specification called out the conductive powder only for the central conductor, its presence under the shield was not realized and therefore was not cleaned off the insulation surfaces embedded in the embedment material undergoing tests. Because of this problem the ability of the various materials to bond to insulation with the presence of this powder and the possibility of a conductive path existing between the shield and the center wire makes the long term high voltage tests of questionable value. Fabrication of the test samples will be repeated with the surface of the insulation being cleaned before encapsulation. Further tests will then be run on these new samples.

Voltage Breakdown Workshop

The second workshop on Voltage Breakdown in Electronic Equipment at Low Air Pressures was held on March 5, 6, and 7, 1969. Attendance averaged about 90 people per day, with a total of 107 attendees. Twenty-three papers were presented, followed by a round table discussion on the last afternoon. Attendance was considered good, in view of the travel restrictions now being encountered. It was recommended by those present that a third voltage breakdown workshop should be held within one to two years rather than the last 3 1/2 year interval. Another interesting observation was that very few were in attendance at both workshops, indicating an extensive turnover in personnel.

The next step in the preparation of the proceedings is to compare the court stenographer's record with the tapes, so that technical editing of the various papers may be achieved. Following this step, the corrected manuscripts will be submitted to Publications for further editing and submittal to the authors for their approval.

ANTICIPATED PUBLICATIONS

1. "Voltage Breakdown in Electronic Equipment at Low Air Pressures — Second Workshop" (Tentative Title)

PUBLICATIONS

None.

HUMAN FACTORS SYSTEMS SRT (127)

MAN-SYSTEM INTEGRATION (127-51)

MAN-MACHINE FUNCTIONS IN CONTROL OF AN UNMANNED ROVING VEHICLE

NASA Work Unit 127-51-01-02

JPL 327-10201-2-3430

V. F. Anthony
R. A. Lewis
J. W. Moore

OBJECTIVE

The objectives of this unit are to develop an understanding of man-machine concepts pertinent to the remote control of unmanned planetary and lunar roving vehicles, to investigate and establish requirements and techniques for integrating man-machine functions into the control system, and to apply this knowledge to laboratory studies and projects.

APPROACH

The feasibility of using unmanned roving vehicles for lunar and planetary exploration is directly dependent upon the capability for effectively and safely controlling vehicle motion over long distances and for extended periods of time. The control function must include human participation in the system control loop to provide judgement, reasoning, diagnosis, perception, and reaction to unexpected circumstances while operating the vehicle in unfamiliar and severe environments. Because these human functions are intimately interrelated with other elements of the complete control-mobility system, this work unit is being carried out in mutually beneficial association with OSSA developmental task "The Remote Operation of a Roving Vehicle" NASA Work Unit 186-68-02-25-55.

PROGRESS

During FY 69, a series of field experiments were run to test the ability of various operators to correlate aerial photographic maps with television images transmitted from the Control Test Model (CTM) Vehicle, to identify land marks, and to derive vehicle position and heading. Each operator was given an aerial photo map of the test site, a separate transparent plotting board, a TV monitor view of the scene as viewed from the vehicle, and a vehicle camera-pan remote control. The vehicle was placed within the area covered by the photo map, but at a location and heading unknown to the operator. The operator was expected to scan the scene and pick out landmarks identifiable on the photo map. The azimuth direction and estimated range from the vehicle to the landmark were plotted on the plotting board. By overlaying the plotting board on the photo and matching landmarks and azimuth lines the operator determined vehicle location and heading. A total of 23 operators completed the tests.

Analysis of the test results has been completed and a generalized computer simulation of the landmark navigation process has been initiated. The simulation will generate data similar to that used in the tests, and will process it as the human operator-computer might. By perturbing the parameters of the tests and their density functions, the sensitivity of the results to these perturbation can be studied. The sequence of landmarks generated by the simulation will reflect the type of landmark, and the frequency and accuracy of identification indicated by the actual tests.

Of the 23 operators completing the test, 65% located the vehicle to within 20 feet; all but one of the other 35% were at least 80 feet in error. Range estimates were generally quite poor, with the range to landmarks closer than 40 feet overestimated and the range to more distant landmarks underestimated. The average total time each operator spent in completing the test was 91.3 minutes. The preliminary conclusions reached were: (a) navigation by landmarks is feasible and (b) the human operator, unaided, cannot make accurate or reliable range measurements; this degrades his ability to confidently position himself relative to landmarks. With a range-finding sensor, the feasibility of roving vehicle navigation by landmark identification and map-matching would be greatly enhanced.

Installation and checkout of the surplus Surveyor flight and operational control equipment is continuing. Most of the equipment intercabling has been completed and several subsystem elements have been turned-on and checked-out. The installation and checkout process will be completed upon receipt of the outstanding equipment.

PLANS

In addition to completing the simulation of actual tests, and studying the effects of perturbations on the simulation, work will continue on vehicle motion control tests.

Data from the motion control tests will be used to measure the operator's ability to control the vehicle motion over both specified and unspecified traverses. Of particular interest will be the time of execution, the number of commands transmitted, traverse deviation, and methodology employed by each operator. Operators selected for these tests will be from both trained and untrained classes.

The vehicle will be shared with Division 35 (Engineering Mechanics Division) for a series of wheel-soil interaction tests on a selection of soils at various slopes. These tests will continue for about one month.

Support of the JPL Advanced Lunar Studies and the MSFC Dual-mode Lunar Roving Vehicle efforts will continue.

PUBLICATIONS

None

CHEMICAL PROPULSION (128)

LIQUID ROCKET TECHNOLOGY PROGRAM (128-31)

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ADVANCED TECHNOLOGY CONTRACT MANAGEMENT FOR RPL

NASA Work Unit 128-31-20-01

JPL 328-10401-2-3840

C. R. Foster

OBJECTIVE

The objective of advanced technology contracts is to advance the technology of all phases of liquid propulsion through contracts to industrial aero-space firms.

APPROACH

Under the above work unit, JPL engineers, experienced in the liquid propulsion field, provide the technical management of some of these advanced technology contracts. These advanced technology contract management tasks are supplementary to the normal in-house assignments of these engineers on research, advanced development, or flight projects.

In general, the work consists of visits to the contractor's plant for technical information and direction, review of monthly progress reports, and quarterly reviews of progress at the contractor's plant. In addition, the engineer participates in planning and recommending new work, prepares the statement of work for proposed new (or continuing) advanced technology contracts, provides technical evaluation of proposals received, and gives technical review and approval to the final reports which are submitted by the contractor. On a semi-annual basis, the engineer submits an informal report to the NASA Headquarters Project Manager to give his technical judgment on the status of the contractor's effort and results.

PROGRESS

Thirty-two Advanced Technology contracts in liquid propulsion have been in effect during the second half of FY 69 that were technically managed by engineers in the Propulsion Division (38) of JPL. It is expected that technical management of advanced technology contracts will continue at approximately the same level of effort during the first half of FY 70.

PUBLICATIONS

None

APPLICABILITY OF LASER DIAGNOSTICS TO ROCKET ENGINES

NASA Work Unit 128-31-21-01

JPL 328-10701-3840

J. H. Rupe

OBJECTIVE

The objective of this experimental program is to demonstrate the feasibility of producing useful laser holograms of the reacting environment in liquid propellant rocket engines. The JPL effort also provides support of other work units in the form of studies of nonreactive sprays.

Laser Holograms

As stated in the previous report, a joint effort using JPL propulsion personnel and equipment and TRW's expertise in laser technology has been completed. The results have been documented in a final report (TRW No. 68.4712.2-024, dated July 31, 1969) which, in summary, concluded that it was feasible to obtain such holograms. Although a number of holograms of good quality and covering a range of operating conditions were obtained during FY 68, there was little or no effort expended in analysis and/or interpretation of these results. (This task was purposely omitted from the original work statement in order to concentrate on feasibility.)

However, a cursory evaluation of the records revealed certain anomalies that required explanation prior to attempts to apply the technique for quantitative analysis. In particular, under certain operation conditions there was no evidence of the anticipated droplet cloud that has historically been utilized to characterize the reacting environment. Therefore, a small supplemental effort was initiated in order to (1) "estimate" the probable resolution of the holocamera system as it was finally developed, and (2) provide a comprehensive study of the existing holograms for purposes of identifying the information that can be obtained from such records. To this end, a new contract (JPL 952357) was negotiated with TRW for a 14-week effort to be initiated 30 January 1969 (8 plus months from completion of procurement plan).

At the contractor's request a no-cost time extension of 3 months was granted prior to starting this work, which is now scheduled for completion on 8 August 1969.

In conformance with Article 1. (b)(1) of that contract, the holograms to be analyzed were selected on 8 May 1969 and this work is now in process.

Non-Reactive Studies

Investigations into the hydrodynamic instability of the common stagnation pressure impingement process are continuing. In view of the apparent significance of this new model to rocket injector design criteria, and in particular to combustion instability, it seems pertinent to review some of the implications (still to be verified) of the postulate.

If one presupposes (as was first done by Dr. Dipprey in private communication to J. Rupe) that two or more impinging jets are, in general, non-identical, then it becomes immediately obvious that, at least in the 2-dimensional case, the interfacial streamline contains a stagnation point for only one jet — in other words the high dynamic head jet cannot stagnate and will pass through the impingement region without bifurcation. Once this fact is accepted, then it becomes obvious that the common stagnation point model — the so-called classical version — is unconditionally unstable since an infinitesimal change in stagnation-pressure-ratio precipitates an instantaneous change in topology with one, and only one, stream being divided. If the stagnation pressure ratio oscillates about unity (as might be imagined for identical "turbulent" jets) then first one jet and then the other is divided.

The changes in topology that are incurred (by a 2-dimensional system) are illustrated in Figure 1 and are intended to represent typical results (albeit schematically) of a 2-dimensional analysis. It can be seen that the "return" flow is alternately comprised of fluid entirely from stream A or B — not a mixture. In injectors utilizing unlike doublet elements this means that fluid directed toward the injector face is either all oxidizer or all fuel — depending on which jet has the lower stagnation pressure. Obviously this effort (assuming it is indeed carried over into a 3-dimensional spray) has important implications for heat transfer and chemical compatibility of the injector face.

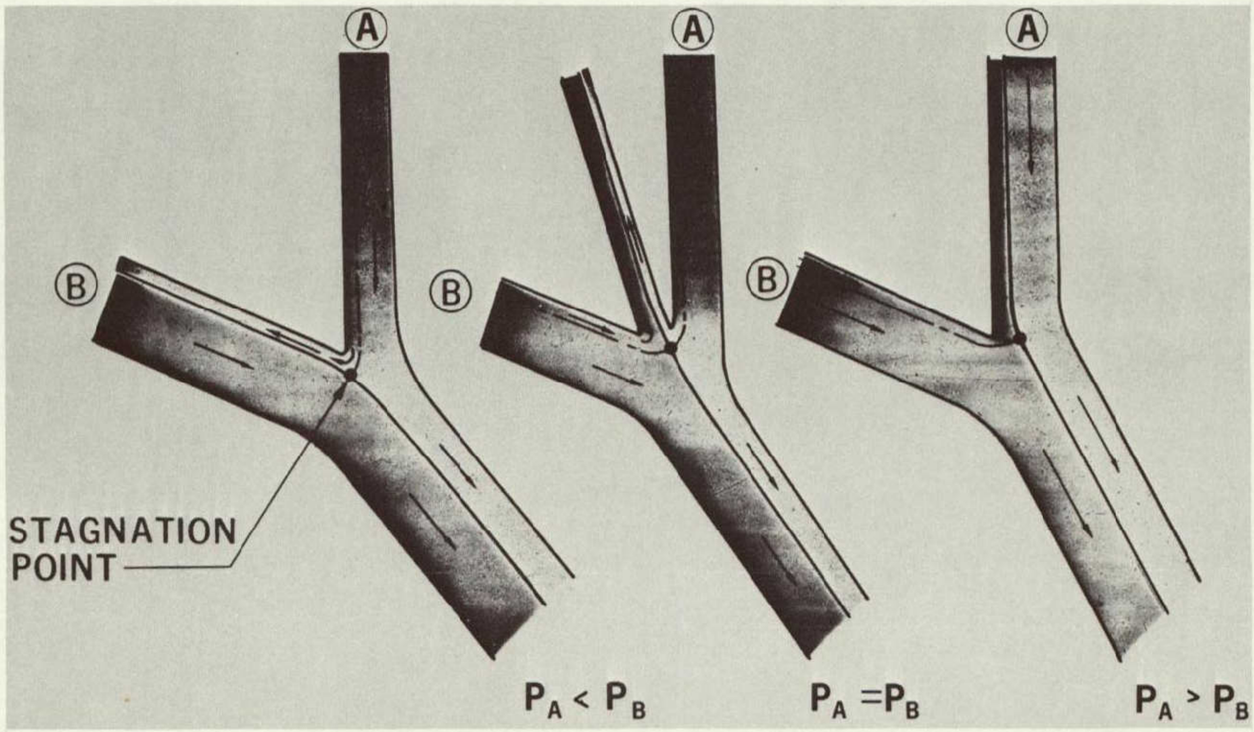

Figure 1. Schematic Representation of the Impingement Region for 2-Dimensional FREE Liquid Jets

Further, the resultant direction of the combined flow effluent is changed, discontinuously, as first one stream and then the other is divided. Thus, in a rocket engine, the initial mass flux distribution can be considerably different for slightly different operating conditions. Hence, given an appropriate starting point, a small change in mixture ratio for an unlike doublet (for example) can produce sudden changes in compatibility and/or performance.

Finally, the "mixture-ratio" of the bulk of the effluent flow also changes discontinuously as the "flip" from one topology to the other takes place. Thus, marked changes in mixture ratio occur simultaneously with the changes in mass flux distribution.

At first look, it might appear that the problems associated with this instability are unique to the "unlike" impinging jets but this is indeed not so. Although it is true that a single pair of jets forming a like-on-like element do not exhibit mixture ratio variations, the consequences to combustion are the same since secondary mixing (which is an essential property of this type of injection scheme) does change discontinuously (and probably at random) as individual pairs attempt to operate at the unstable condition. The fact that the conventional design is intended to produce identical jets for each like-on-like pair precludes a stable impingement region. In addition these schemes should in general produce a "return" flow comprised of both propellant (from different impinging pairs) and should therefore tend to produce a reactive mixture near the injector face. In the unlike-doublet configuration the environment can be controlled to be either fuel rich or oxidizer rich depending on the operating condition specified by the designer.

The significance of this hydrodynamic instability to combustion instability cannot be over emphasized. It is now patently obvious that most injection schemes incorporate a fundamental mechansim — not dependent on flukes or malfunctions — that will initiate the transition to a resonant mode.

Thus, any element that by design is intended to operate at equal stagnation pressures is a potential source of distrubance — which then can very rapidly couple with a reactive environment and lead to a high-amplitude destructive oscillation.

The initial results of this study will be published in a forthcoming SPS and will be presented to the 6th ICRPG Combustion Instability Conference in September.

This work unit is being terminated at the end of FY 69. The follow-on work will be conducted as part of JPL Work Unit 328-12401-0-3840.

PUBLICATIONS

None

TRANSPORTABLE SUPPLY MODULE FOR OF_2/B_2H_6

NASA Work Unit 128-31-21-02

JPL 328-14601-1-3840

J. H. Rupe

OBJECTIVE

The objective of this work unit is to provide for the design, fabrication, and testing (under contract) of a transportable supply module intended for use at any one of several JPL test facilities where the $OF_2 + B_2H_2$ propellant combination is required. It also provides for training of the JPL personnel required to operate that facility.

PROGRESS

The procurement action required to implement this work unit was consumated in an approved contract (JPL Contract 952393) with Aerojet General, Sacramento, California, on 22 May 1969. Authorization to proceed was transmitted to Aerojet by a TWX of 5/29/69 (one year and twelve weeks after initiation of procurement action).

In accordance with Article 1., (a), (2), (E), (i) of that contract, a conceptual design meeting was held at the contractor's plant on 3 June 1969. The preliminary design is underway.

This work unit is being terminated at the end of this fiscal year with the required support activity and funding being incorporated into JPL Job No. 328-10901-0-3840.

PUBLICATIONS

<u>Contractor Reports</u>

1. Minutes of Conceptual Design Meeting, June 3, 1969, Portable Cryogenic Facility, JPL Contract 952393.

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ADVANCED EXPULSION DEVICES TECHNOLOGY

NASA Work Unit 128-31-33-04

JPL 328-11901-2-3840

H. B. Stanford

OBJECTIVE

The objective of this work unit is to advance the technology of phase separators for liquid propellant control in spacecraft applications. This is to be accomplished through investigation of the problems associated with various materials and types of devices suitable for use with both Earth- and space-storable propellants for missions of up to ten years duration. The work is concerned with: (1) mechanisms to control propellant sloshing, (2) development of materials of construction for expulsion bladders (such as laminates and composite structures), and (3) the fabrication techniques required to produce these devices. The goal is to furnish information for engineering application that will result in designs with more reliable performance.

PROGRESS

I. In-house Activity

In house activity consisted of technical management of the contracted expulsion devices tasks.

II. Off-lab Activity

A. Expulsion Bladder Material Development for Earth and Space Storable Propellants.

Stanford Research Institute Contract No. 951484

1. The objectives of this program are:

   a. To develop control parameters for the production of liquid-propellant expulsion bladder materials, such as Teflon films.

   b. To improve techniques of cladding or laminating these materials.

c. To provide improved test methods and apparatus for detection of long-term permeation of nitrogen tetroxide and hydrazine through materials.

d. To investigate the compatibility of materials with oxygen difluoride and diborane.

2. Status

This contract was supplementally funded and ran until its close out date of March 30, 1969. Neither the funds nor the contracted man hours were completely expended because of internal organizational difficulties at SRI. Settlement of the resulting contractual anomalies is currently in process. The following technical accomplishments were made:

a. Comparison studies of polytetrafluorethylene films made from aqueous dispersions from Imperial Chemical Industries Ltd. (Fluon GP-1) and Dupont (TFE-30) were conducted. Identical processing was used in both cases, and it was proven that dispersions from different sources respond similarly in film fabrication. The film made from the ICI material had smaller particle size, was lower in molecular weight, and exhibited a longer flex life in subsequent testing.

b. The micro crease tester, a device for testing small sections of bladder material in small amounts of propellant for safety's sake, was rebuilt with metals compatible with N_2O_4 and OF_2. The loading system was redesigned to provide smoother and more accurate performance at a constant tension.

c. The feasibility of cladding titanium alloys with an electroless nickel plate to protect them from impact sensitivity in OF_2 was indicated as the result of a literature survey. It also appears likely that hydrogen embrittlement of titanium resulting from contact with B_2H_6 can be prevented by this technique.

PUBLICATIONS

Contractor Reports

1. Stanford Research Institute Addendum to Final Report "Development of Techniques to Improve Bladder Materials and Test Methods," March 30, 1969, JPL Contract 951484 under NAS7-100.

CHEMICAL ROCKET EXPERIMENTAL ENGINEERING (731)

CHEMICAL ROCKET EXPERIMENTAL ENGINEERING (731)

CHEMICAL ROCKET EXPERIMENTAL ENGINEERING (731)

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SPACE STORABLE PROPELLANTS COMBUSTION DEVICE TECHNOLOGY

NASA Work Unit 128-31-34-04

JPL 328-11501-2-3840

R. Y. Oshiro

OBJECTIVE

The primary objective of this program is to design, develop, and demonstrate the feasibility of advanced low-thrust rocket engine concepts as applied to liquid bipropellant systems using the space-storable propellant combination of oxygen difluoride (OF_2) and diborane (B_2H_6). The optimized engine configuration will be scalable to higher thrust ranges and allow operations in the throttling mode. The immediate goals are to acquire firsthand experience in propellant handling and safety procedures, to determine operational characteristics and components selection for a cryogenic feed system, and to develop high-performing injectors and compatible chambers capable of extended-duration operation.

APPROACH

The updated propellant feed systems will be completely checked out with a known injector prior to the initiation of hardware evaluation testing. Injector and chamber compatibility along with performance and heat transfer characteristics will be determined for each engine configuration. Copper heat sink chambers and other chamber materials coupled with several types of injectors having different injection schemes such as impinging sheets, impinging jets, self impinging doublets, triplets, etc., will be evaluated. Such parameters as chamber characteristic lengths (L^*), contraction area ratios (ϵ_c), and cooling techniques such as barrier and film cooling will also be investigated.

PROGRESS

The propellant system major modifications started during the last period were completed in third quarter of FY 69. The independent feed systems were subjected to several thermal cycling tests to demonstrate adequate preconditioning capability to desired run temperatures. Subsequently, a thorough system leak check at 500 psig with helium was successfully conducted under chilled conditions prior to propellant (B_2H_6) transfer into the run tank. A system checkout firing of short duration was conducted, and all systems appeared to function as planned. The second checkout attempt resulted in a diborane fire in the test cell caused by a leak at the main fire valve. The resulting fire caused extensive damage to instrumentation wiring; however, system damage was minimal and the fire valve was rebuilt and reinstalled for service in the fuel system. There was no damage to the oxidizer (OF_2) system, and the test hardware experienced no harmful effects. The system rebuilding effort is approximately 90% complete and system checkout is expected to start before the end of the fiscal year. Component hardware testing is expected to begin at the start of next fiscal year.

PUBLICATIONS

None

LIQUID PROPELLANT MATERIAL COMPATIBILITY

NASA Work Unit 128-31-37-01

JPL 328-11801-0-3840

L. R. Toth
O. F. Keller

OBJECTIVE

The broad objectives of this work unit are: to advance the technology of materials of construction for liquid propulsion systems for future space missions; to determine acceptably inert materials having high reliability after periods of up to two years storage in the mission environments while in contact with hydrazine (N_2H_4), monomethylhydrazine (MMH), or nitrogen tetroxide (N_2O_4); to understand the implications of extended storage periods of two, five, and ten years such as those associated with an advanced mission to the outer planets; and to generate data upon which to base flight commitments.

PROGRESS

Phase II (Earth Storables)

Incremental funding in the amount $40, 000 was added to the contract for the continuation of fabrication and preparation of the material compatibility Test-Specimen/Capsules. Distribution of the total number of Test-Samples is indicated in Table 1. Test-Specimen/Capsules delivered to JPL/ETS for long-term storage tests as of June 30, 1969, include: 218 N_2H_4, 112 MMH, and 120 N_2O_4.

The electrical wiring of the fuel-side lazy susan at JPL/ETS was completed during this report period. The wiring of the oxidizer-side lazy susan remains about 50% complete.

Table 1. Phase II - Sample Distribution

MATERIALS	PROPELLANTS			
	N_2H_4	MMH	N_2O_4	TOTALS
Stainless Steels	160	58	186	404
Aluminums	135	13	134	282
Titaniums	126	21	122	269
Plastics	87	8	54	149
Others	233	0	218	451
Totals	741	100	714	1555

The nitrogen calibration system, capable of calibration test-capsules at nine different pressure levels simultaneously, was also completed during this report period. Figure 1 illustrates several nitrogen test-capsules mounted in the fuel-side lazy susan which will function as part of the nitrogen calibration system. The purpose of the nitrogen calibration system is to provide a series of base-line pressure readings for correlating fuel-test-capsule pressure rise data.

Phase III (Space Storables)

The objective of the Space-Storable material compatibility program is similar to the broad objective as outlined above for Earth-Storables except that the primary emphasis will be placed on the space-storable propellants oxygen difluoride (OF_2) and diborane (B_2H_6). Preliminary planning in connection with test facilities, test-specimen/capsule configuration, and test data acquisition systems continued at a relatively low level of effort.

PUBLICATIONS

Contractor Reports

1. "Monthly Reports of Work in Process," Pressure Systems, Inc. Report Numbers: 6720-18, 6720-19, 6720-20, 6720-21, 6720-22, and 6720-23; December, 1968 through June, 1969, JPL Contract No. 952004.

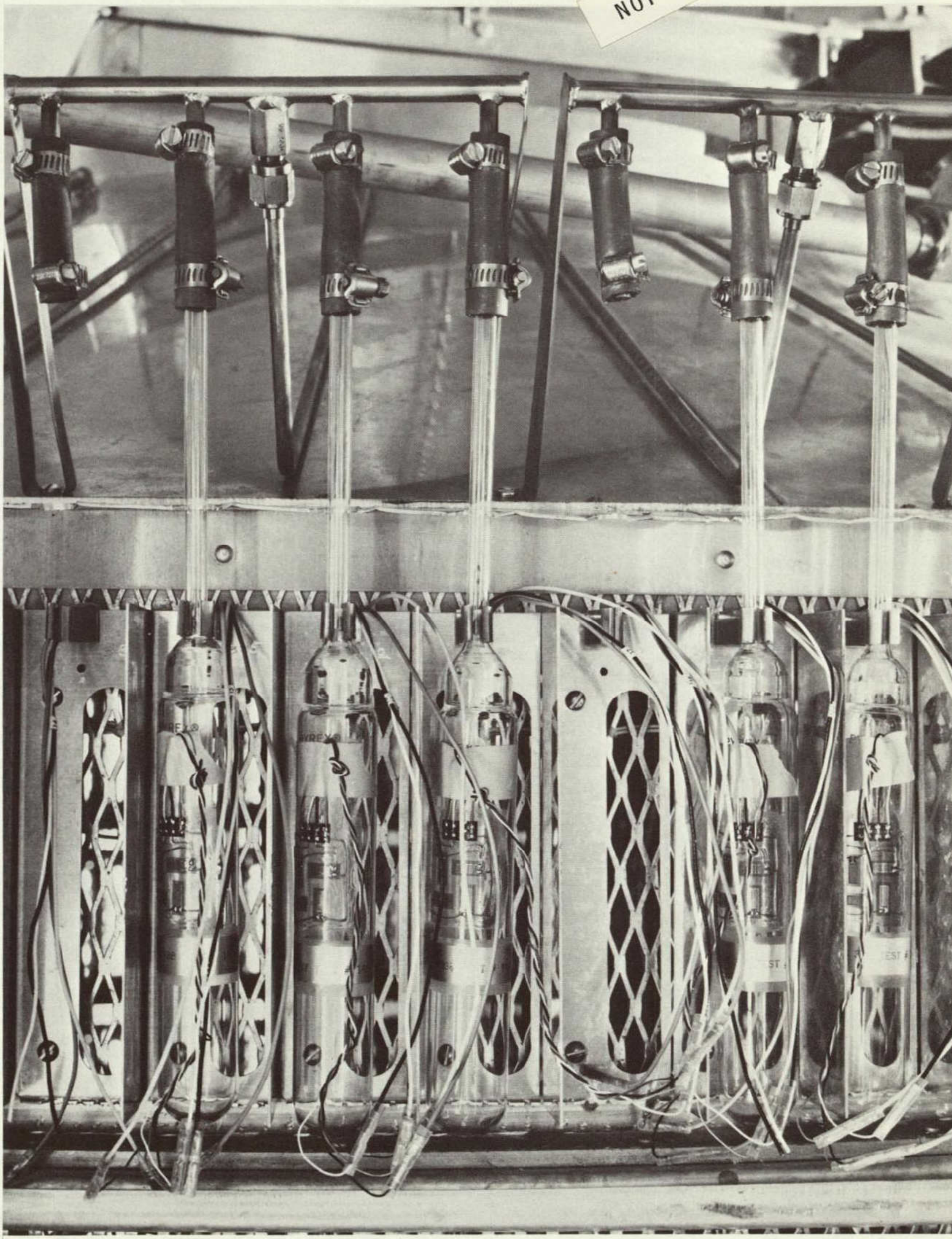

Figure 1. Test Capsules Mounted on the Fuel-Side Lazy Susan as Part of the Nitrogen Calibration System

COMBUSTION EFFECTS IN SPRAYS

NASA Work Unit 128-31-50-01
JPL 328-10901-1-3840
J. Houseman

OBJECTIVE

Experiments conducted at JPL with highly reactive propellants have shown that rapid chemical reactions occurring at the interface formed by a pair of unlike impinging jets play a key role in the establishment of the mass, mixture ratio, and drop size distributions achieved in an actual rocket engine. Thus it is essential that a quantitative evaluation of these effects be obtained so that the range of applicability of the non-reactive data can be established and the reaction effects correlated with the design parameters.

To this end, the experimental verification of several theoretical models for predicting the presence (or absence) of stream separation, i.e., the separation of the fuel and oxidizer jets due to gas evolution at the impingement point, is being pursued. A procedure has been developed to measure the mixture ratio distribution produced by a single unlike impinging doublet injector element using reactive fluids in a combustion chamber. The combustion gas in the chamber is sampled continuously by means of a scanning probe. On-line chemical analysis of the gases is carried out by a fast-scanning quadrupole mass spectrometer. The end result is a mixture ratio distribution across the chamber for a combusting spray.

PROGRESS

A great deal of progress has been made during the last six months. A total of 484 test firings were made on a virtually routine basis. The test results show some interesting new phenomena that can be applied directly in optimizing injector designs.

From measurements of the gas composition of the combusting spray, it was found that there are two main modes of operation, namely penetration and separation. In the former mode the hydraulic parameters are dominant, while in the separation mode the liquid-phase chemical reactions are controlling. Both modes are characterized by rather poor mixing. An optimum mixing point has now been found at the crossover point between these two modes. Operation of an unlike doublet at this optimum mixing point results in improved performance.

In the last report only data on jet separation were presented. By using smaller orifices jet penetration has now been observed, in which the side of the spray opposite to the fuel orifice is high in fuel content, while the side of the spray opposite the oxidizer orifice has a high oxidizer content. This is very similar to the results obtained with cold flow tests. Jet separation shows exactly the opposite effect. It was found that there is a gradual transistion from the penetrated mode to the separated mode as the orifice jet velocity is increased, resulting in a simultaneous increase in chamber pressure. This phenomenon is shown on Figure 1 as a plot of local mixture ratio versus chamber pressure for the side of the chamber on the oxidizer orifice side and for the fuel orifice side. It is apparent that there is a crossover point at which the local mixture is constant across the chamber. This presents an optimum performance point. Since all the runs of Figure 1 meet the Rupe optimum mixing criteria, there is obviously a second optimum superimposed upon the Rupe criteria, and this second design criterion has to be applied to reactive propellant systems where jet separation can occur.

Orifice size appears to be the main variable, since all the tests with 0.020-inch-diameter orifices gave penetration, and all the tests with 0.040-inch-diameter orifices gave separation. With a 0.029-inch-diameter set of orifices, both penetration and separation can be obtained, depending upon the run conditions. Correlation of the data is continuing, including modifications to the theoretical model.

In addition to the expected chemical species of hydrogen, water, and nitrogen, the chemical analysis showed the presence of nitric oxide (NO), free oxygen (O_2), and some nitrous oxide (N_2O). The presence of these species in the combustion gas corresponds to less than ideal performance, and the variation in concentration of these species with the impingement parameters is being studied.

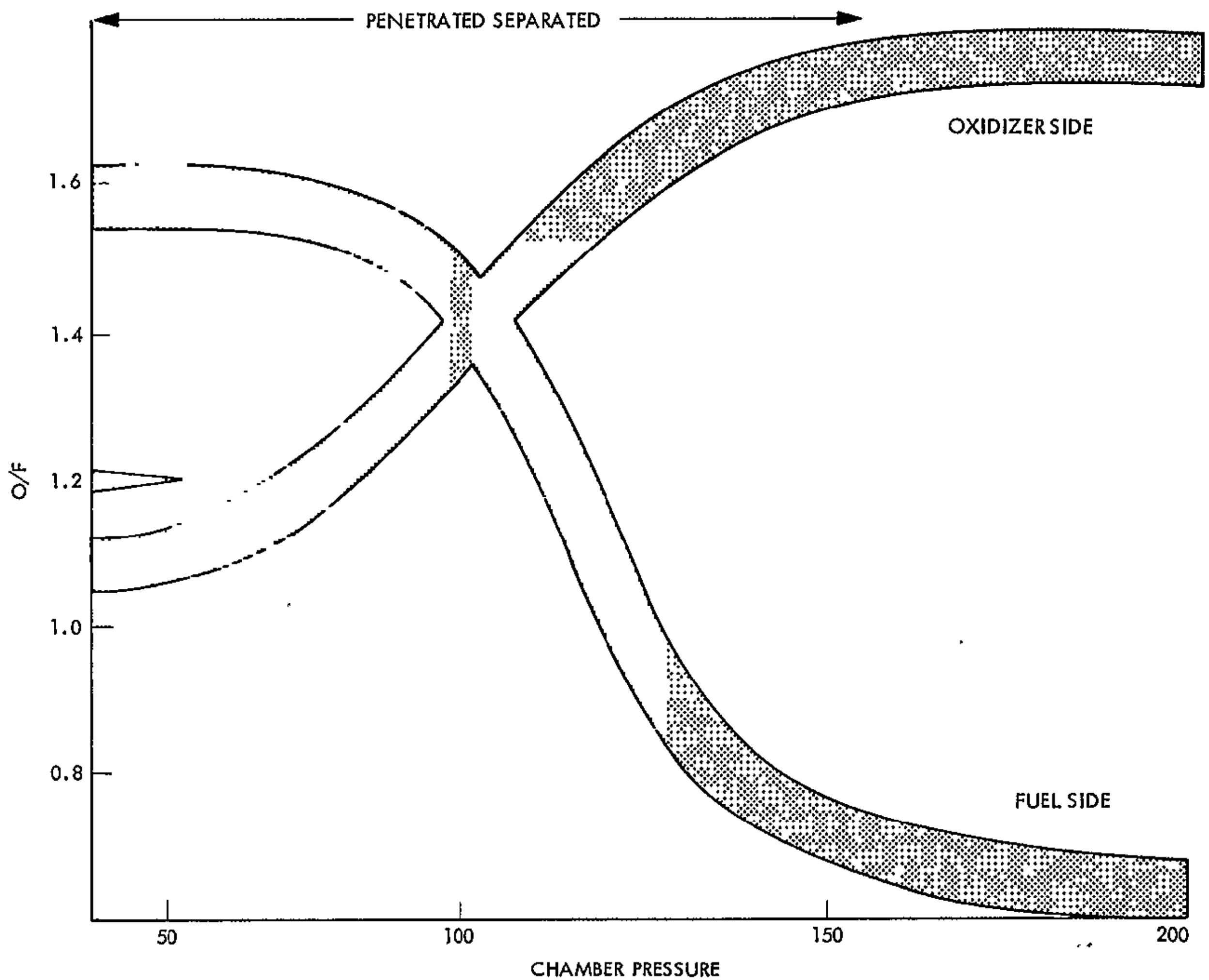

Figure 1. Combustion Effects

PLANS

(1) Complete mapping of data over complete range of operating variables and formulate corresponding theoretical model for jet separation.

(2) Convert sampling probe to molecular-beam type.

(3) Plan modification of equipment and procedure for the OF_2/B_2H_6 system.

(4) Check out possible correlation between combustion roughness and jet separation.

The principal investigator received a Director's Award under the Cost Reduction Program for a "New Method of Mass Spectrometer Operation and Data Acquisition," which resulted in a savings of $20, 280. 00.

PUBLICATIONS

Meetings and Symposia Papers

1. Houseman, J., a Space Programs Summary on "Combustion Effects in Sprays", SPS 37-54, Vol. III.

ANTICIPATED PUBLICATIONS

An abstract of a paper on "Jet Separation and Optimum Mixing for an Unlike Doublet" has been submitted for presentation at the Sixth ICRPG Combustion Conference.

RESONANT COMBUSTION

NASA Work Unit 128-31-51-01

JPL 328-10601-1-3840

R. M. Clayton
R. Kushida

OBJECTIVE

This is the final progress report of this work unit. The over-all objective has been to evolve liquid rocket injector/combustor design criteria which will yield high-performance steady-combustion with a high margin of stability against transitions to destructive resonant combustion.

PROGRESS

In pursuit of the objective, it has been shown that when the interaction of the local combustion chamber pressure with the injected flow rate is small, then high-amplitude, steep-fronted (detonation-like) waves are formed and propagate continuously around the chamber. The spatial properties of these waves have been characterized experimentally for two cylindrical engines (11- and 18-inch diameters) and the external 3.5-inch annulus of that 18-inch geometry. Analysis (to be discussed) has verified the existence of these waves and infers that a combustion process must be directly coupled with the wave if it is to be sustained.

It has been experimentally demonstrated, however, that the development of sustained waves of this nature can be relatively easily prevented by utilizing baffles placed across the face of the injector and extended axially through a substantial fraction of the early reaction zone of the combustion process. This implies that there must be a critical relationship between baffle effectiveness and the boundaries of that early reaction region, and hence, for maximum baffle effectiveness, this zone must be spatially steady and reproducible for a given baffle installation. These properties of the early reaction environment are controlled mainly by the injection scheme, and achieving this control has been emphasized in the present investigation.

On the other hand, the rocket engine industry invariably compromises injector design and has had poor experience in achieving combustion stability without costly development programs. This observation and the opposing experience of the JPL investigation have led to the major conclusion of the present work unit, that engine stability can be reliably achieved by utilizing a relatively high-impedance injection scheme with well-controlled hydraulics in conjunction with baffles. The efficacy of this conclusion and the specification of quantitative design criteria will be investigated under a new work unit (JPL 328-12201-0-3840) proposed for the FY 70 program.

Because of the importance of spontaneously-generated combustion disturbances to combustion stability and because both the annular and cylindrical 18-inch engines exhibit these disturbances (called pops), the experimental work for this concluding report period emphasized an investigation of popping. As a consequence of that emphasis and of a temporary reassignment of supporting engineering personnel, both the baffled engine bomb experiments and the development of other pulsing techniques planned for this period were delayed and are now planned for the FY 70 program.

However, besides the popping investigation, progress was made on in-house analysis of the role of detonation processes in sustained resonant combustion, and on the design of the variable-orifice-geometry injector (designated RC-2) to be used in the new work unit.

Investigation of Popping

Popping is manifested as spontaneous, aperiodic, large-amplitude pressure waves which propagate throughout the combustion volume during otherwise steady combustion. If the engine is unstable to such disturbances (not equipped with baffles, for example), the initial pop invariably precipitates sustained combustion resonance immediately. An analysis (reported in the last semiannual report) has shown that a pop generally is the product of a relatively small initial disturbance which has become a large-strength wave through combustion enchancement as the disturbance transits the chamber in its first pass. In essence, the pop is a spherically expanding detonation wave, and both a source disturbance and a surrounding reactive environment are required to produce it.

An analytical technique (to be reported in a future SPS) for deducing the location of the pop sources from the simultaneous outputs of an array of transducers located on the chamber boundaries has shown that popping for the 18-inch diameter engines originates in the boundary region of the chamber. This is consistent with previous indications that the boundary injection system utilized by the RC-1 injector exhibits a controlling influence on the production of pops. Because this influence is manifested by particular operating conditions (mixture ratio and propellant temperature) of that flow system, a concerted effort was made to correlate these conditions with a rational mechanism of pop sources.

Ultimately, a correlation was achieved relating popping to the dynamic pressure ratio of the streams of the doublet boundary injector elements and to the boundary propellant temperature. This correlation and its rationalization is summarized in SPS 35-37, Vol. III., pp 204-212, and is to be further documented in a Technical Report which is in preparation.

Briefly, the proposed mechanism is based on a concept coupling rapid hypergolic reactions (a function of temperature) occurring in the impingement region to certain fluid stagnation conditions in this region that are dictated by the relative stream dynamic pressures. In particular, one of three stagnation configurations are postulated (cf semiannual report of work unit 128-31-21-01-55) for a given doublet element flow condition; for equal dynamic pressures both streams stagnate, while for unequal pressures only the stream with the smaller dynamic pressure stagnates. Thus, a small kernel of reactant(s) conceptually is stagnated at the impingement point, but the composition of this kernel may be either all one reactant, or both, depending on the relative stream dynamic pressures. When the dynamic pressures are nearly equal, the flow field in the vicinity of the stagnation point is comprised of a small quantity of stagnant fluid from one stream and a low-velocity region of the second stream. Hence, the reactants experience a relatively long contact time along the interface. It is envisioned that this situation could produce a small "explosion" that would serve as the initial disturbance for a pop.

Furthermore, it can be shown that the condition of equal dynamic pressures is, in itself, inherently unsteady (without consideration of chemical reactions). This unsteadiness is evidently sufficient, under the proper conditions of reactivity of the surrounding environment, to act as a pop source, since pops have been produced in the 18-inch engines even with a like-on-like boundary element configuration.

Experimentally, popping rate (pops/sec) was maximized when the boundary elements were operated with unity dynamic pressure ratio. At this flow condition, a temperature range of 60 to 70°F formed a threshold where popping occurred sporadically. A maximum pop rate (~45 pops/sec) was reproducibly exhibited at about 80°F with decreasing rates for temperatures to about 105°F, the highest utilized in the experiments.

For off-unity pressure ratios, popping rate decreased approximately symetrically on either side of unity until the production of pops ceased, regardless of temperature, for values of dynamic pressure ratio outside the range of 0.43 to 2.3. This broad range reflects, in part, the fact that the boundary system is composed of 24 elements and the pressure ratio was computed from total boundary flow rates assuming a uniform flow distribution from the manifolds to all elements. Obviously, the distribution cannot be uniform and a spread of flows around the mean value must be present.

Because of a close correspondence of the threshold temperature to the temperature for stream separation for these elements, it has been concluded that for hypergolic impingement, pop sources are a product of the inception of stream separation, and as gross separation develops, the generation of pop sources will be minimized. This is believed to explain the reduction of popping rate for the higher temperatures and also to explain the fact that popping is not produced by the main elements of the RC-1 injector, these elements being about twice the size of the boundary elements and having shown evidence of gross stream separation.

In summary these results show that pop sources are:

(1) a major cause of combustion instability

(2) a function of the stream separation parameters of element size scale, propellant temperature, chamber pressure, and impingement stagnation dynamics

(3) maximized by the condition of unity dynamic pressure ratio of the impinging streams

Detonation Wave Analysis

The similarity of the characteristics of the pressure wave-form found in a resonantly-unstable engine to the wave-form one would expect for a detonation wave has led to the use of the descriptive term "detonation-like". Typically the waves are steep-fronted, high-amplitude, steeply spiked, and supersonic. A theory of Adamson on the rotating detonation wave engine has been adapted to the present analysis of liquid rocket engine stability.

The combustion chamber is assumed to be a thin annulus in which liquid propellant is injected as a spray at a constant rate. Vaporization-controlled combustion of the spray droplets occurs. The mixture of burned gas and residual spray exhausts through an annulus-slot nozzle. A detonation wave is assumed to propagate around the annulus, sustained by the instantaneous combusion of spray droplets which pass through the wave. There are therefore two modes of combustion in the combustor — evaporative and detonative. By neglecting the variation of properties in the longitudinal direction and by assuming a steady periodic passage of the wave, the equations are reduced to a set of ordinary differential equations. These were solved numerically.

The pressure wave-forms obtained in the analysis are detonation-like by the same criteria as those applied to the experimental observation.

The analysis indicates that a periodic steep-fronted wave cannot be sustained by purely evaporative combustion; there must be some heat release by a very rapid process inside the detonation wave. In this limiting case of a steady periodic wave, the wave must be of the Chapman Jouguet type, i.e., the gas velocity behind the wave is sonic with respect to the wave.

The analysis for the steady periodic wave is being documented. Work is being pursued on the analysis of the transient phenomena, for which the steady-state process is the limit at infinite time.

RC-2 Design

Detailed design has commenced via the JPL Contract (952400) with Lockheed Aircraft Service Company. Preliminary evaluations of manifolding concepts have been conducted using a full-scale mock-up of one segment of the injector. Further hydraulic tests are in progress to ascertain the stream velocity profiles and their symmetry, and the flow distribution from the proposed manifolds.

One requirement is to provide a means of degrading the entry flow to the orifices to simulate gross turbulence and cross velocity in the manifold. Hydraulic testing is planned for developing devices for this purpose that can be installed at the entry of each main orifice.

PUBLICATIONS

Journal Articles

1. Sotter, J. G., Woodware, J. W., and Clayton, R. M., "Injector Response to Strong, High-Frequency Pressure Oscillations," Journal of Spacecraft and Rockets, Vol. 6, No. 4, pp 504-506, April 1969.

JPL Publications

1. Clayton, R. M., "Resonant Combustion," SPS 37-55, Vol. III, pp 245-257, February 28, 1969.
2. Clayton, R. M., "Resonant Combustion," SPS 37-56, Vol. III, pp 204-212, April 30, 1969.
3. Rupe, J. H., "An Experimental Correlation of the Nonreactive Properties of Injection Schemes and Combustion Effects in a Liquid-Propellant Rocket Engine: Part V. On the Influence of Vanes on Combustion and Combustion Stability," TR 32-255, September 15, 1967 (distributed this report period).

COMBUSTION LIMITS IN MIXING STREAMS

NASA Work Unit 128-31-51-02

JPL 328-11601-1-3840

R. Kushida

OBJECTIVE

A new type of laminar flame burner is being utilized to measure rates of chemical reactions in combustion reactions. An objective of this program is to perfect the theory of this burner to the point where predictions of quenching, blowoff, ignition, and steady combustion can be made for systems with known rates. A second objective is to use the experimental data on these phenomena to obtain overall rates of chemical reaction, and to obtain, if possible, detailed mechanism of reaction. Studies on the rates of reaction of space storable propellants are being carried out.

PROGRESS

This is the last progress report for this research project. Further studies will be continued as a part of another work unit.

The experimental flame using ethylene and oxygen was shown to conform quite well to the requirements of the theory. Both diffusion flames and premixed flames could be obtained on the same geometric configuration of the burner. The flames proved to be flat as predicted. Limits of flammability were measured by slowly changing the reactant flow rates or by changing the pressure. The extinction of a flame by flowoff at high Reynolds number could be distinguished from quenching, which is a low Reynolds number phenomena. The relation between the limits for a premixed flame and a diffusion flame of the same constituents were determined. The experimental work with ethylene-oxygen were concluded since the main tenets of the theory were verified.

The relation of the blowout limits to chemistry were tested using the well-stirred reactor theory. A single bimolecular reaction proved too simple to fit the flammability limits over a wide range of mixture ratios. Extension to the case of two consecutive reactions introduced an unexpected anomoly. There proved to be more than one extinction point. This is believed to be a theoretical explanation of cool flames sometimes obtained with hydrocarbon mixtures. However, the introduction of a second reaction permitted so many new parameters that no conclusions could be drawn at this time as to the validity of the fit to experimental data. A much more discerning examination of possible reaction mechanisms will be needed to match the data to theory.

Solutions to the differential equations for the flow field were obtained for a single reaction using the Runge-Kutta method. Since there are boundary conditions to be fitted at both ends of the integration interval, it was necessary to adopt an iterative technique, in which initial values were varied until a fit to the known conditions at the far boundary was obtained. The technique proved cumbersome and hard to extend to a more complex chemical system.

Extensive modification of the opposed-flow flame extinction apparatus were made to accommodate the space storable propellants, OF_2 and diborane, safely. Flame extinction is obtained by varying the gap spacing between the opposed parallel porous flame holders. Due to the reactivity of the propellants, the opposed-flow extinction can only be obtained with these propellants in the diffusion flame mode. Chamber pressures will be varied from 50 to 2000 torr.

In summary the opposed-flow flame configuration has proved suitable for measurement of flame properties such as extinction and quenching which are directly dependent on reaction rate. In principle, the rates of combustion reactions can be obtained but this has proved to be more difficult than expected.

PLANS

Future work will consider methods of solving the boundary value problem for arbitrary chemistry. Experimental flammability limits for OF_2 and diborane will be obtained.

PUBLICATIONS

None

NUMERICAL ANALYSES OF HETEROGENEOUS COMBUSTION

NASA Work Unit 128-31-51-03

JPL 328-11071-1-3840

J. H. Rupe

OBJECTIVE

The current effort of this work unit is directed toward the development of a solution of the non-steady, fluid dynamic equations of motion with arbitrary sources and sinks and is being conducted under JPL Contract No. 951546 with Mathematical Applications Group, Inc. This contract is nearing completion of the second year of work and the contractor has, in essence, completed the required tasks.

This work unit encompasses three separate tasks of which only one has been funded due to budget limitations.

PROGRESS

The final report covering the results of this contract will be received during the month of June. This document incorporates the fluid dynamic model, the development of the nonlinear differential and difference equations for both pancake and annular models, and the droplet evaporation and combustion analyses. Together with the "Description of Programs," the computer decks, and a description of the verification experiments, this will complete the effort under this contract.

The supplemental effort to bolster the verification of the analyses by direct comparison with experiment that was mentioned in the previous report was finally consummated as a separate contract (JPL Contract 952505). That contract was dated 18 February 1969 and is scheduled for completion (delivery of final report) on 30 June 1969. A "Preliminary Summary of Results ---" covering three of the nine experiments required by the contract was received on 17 June 1969.

This work unit is being terminated as of the end of FY 69. Subsequent effort of this nature will be accomplished via NaPO contracts and JPL work unit 328-12201-0-3840.

PUBLICATIONS

Contractor Reports

Preliminary Summary of Results for the Computer Experiments Conducted under Jet Propulsion Laboratory Contract 952505, Mathematical Applications Group, Inc., White Plains, New York, 10 June 1969.

NOZZLE FLOW AND VACUUM EXHAUST TECHNOLOGY

NASA Work Unit 128-31-53-01

JPL 328-12101-X-3840

W. Simon

OBJECTIVE

The objective of this work unit is to collect and formalize the analytical techniques necessary for the design of nozzles and the determination of nozzle plume characteristics in a space vacuum environment. Particular emphasis is on small nozzles with large boundary layers, which are typical of many used for spacecraft applications and for which insufficient design information is presently available. A further objective is to evaluate plume/spacecraft interaction effects caused by plume impingement, heat transfer, and condensation. This effort is to augment and consolidate the existing analytical tools into a useful form for spacecraft applications.

PROGRESS

Pressure calibrations vs nitrogen flow rate of the JPL 25-ft Space Simulator and the JPL MOLSINK facility have been completed. The minimum chamber pressure in the Space Simulator after one minute with 0.8 gm/sec of nitrogen flowing was 10^{-2} torr or an equivalent altitude of approximately 260,000 feet. The MOLSINK facility pressure remained at 10^{-5} torr (420,000 feet) with flowrates as high as 3.3 gm/sec.

A complete set of test nozzles were designed and fabricated. Area ratio variations from 15:1 to 240:1, throat size variations from 0.050 to 0.283 inches in diameter, wall half-angles from 15° to 40°, and both favorable and adverse wall pressure gradient nozzles are included in the set of 24 nozzles.

Hardware to mount the test nozzles in the 25-ft simulator for thrust and boundary layer measurements has been designed and fabricated. The thrust measuring device is a 6-component wind tunnel type strain gage thrust balance.

Hardware to mount the test nozzles, electric beam apparatus and quartz crystal micro-balance system in the MOLSINK has been designed and is being fabricated. The electric beam measures the gas density in various parts of the plume, while the quartz crystals measure the force per unit area due to molecular impingement.

Visits to inspect vacuum plume test facilities and exchange technical information were made to the Naval Research Laboratories in Washington, D. C., and to ARO at AEDC in Tullahoma, Tenn.

A computer program to design and evaluate the performance of contoured nozzles of the Rao type was received from Rocketdyne Division of North American Rockwell.

A study contract is being negotiated with the University of Southern California to provide information on boundary layer phenomena and condensation effects as they affect nozzles and plume flow. The data from this study will be correlated with the planned JPL nozzle tests.

PLANS

After thrust measurements and boundary layer surveys of the test nozzles are completed in the 25-ft Simulator, the nozzles will be installed in the MOLSINK. Plume characteristics will be evaluated over a range of flow conditions. The data will be correlated with existing analytical prediction techniques, and improvements will be made in the prediction methods.

PUBLICATIONS

None

REDUCTION OF TURBULENT HEAT TRANSFER IN NOZZLES

NASA Work Unit 128-31-54-02

JPL 328-11001-0-3830

P. F. Massier

OBJECTIVES

The primary objectives of this task were (1) to determine the parameters that govern the reduction in turbulent heat transfer that has been found to occur in supersonic nozzle investigations, including rocket engine tests, and (2) to establish the limiting conditions for which this phenomenon takes place so that it may be used advantageously for the design of rocket nozzles that may be either cooled, uncooled, or ablative. This phenomenon is more commonly referred to as laminarization of a turbulent boundary layer which occurs as a consequence of the acceleration of the flow. The observed reduction in heat transfer in the convergent section of a nozzle may be as much as 50% of that expected for turbulent flow.

An additional objective was to acquire longitudinal heat transfer distributions along a supersonic second-throat diffuser. Exhaust diffusers of this type are commonly used in rocket test facilities to simulate altitude conditions at the nozzle exit. The heat transfer in such a diffuser is difficult to predict because of the complex shock-wave boundary-layer interactions that occur.

PROGRESS

During FY 69, an experimental investigation was made of the effects of wall cooling on the boundary-layer structure in the convergent section of a nozzle where laminarization is indicated by the heat transfer measurements. The heat transfer measurements in the supersonic diffuser were made concurrently. The abstract of a paper (Ref. 1) describing the over-all heat transfer in the nozzle-diffuser system has been submitted for presentation at the 4th International Heat Transfer Conference to be held in Paris, France, in 1970.

The boundary layer data were acquired in a nozzle which has convergent and divergent half angles of 10°. Measurements with wall cooling were made for a stagnation temperature of 1,500°R and for nearly adiabatic flow at approximately room temperature. Tests were conducted over a range of stagnation pressures including conditions for which laminarization occurred. Acquisition of the boundary layer data has been completed at four locations in the subsonic region of the nozzle where transition from a turbulent to a partially laminar boundary layer takes place, as well as at the nozzle inlet and exit. Hence, a good description of the history of the boundary layer in the nozzle has been obtained.

Measurements were also made at Reynolds numbers that were large enough for the boundary layer to remain turbulent along the entire nozzle. For a boundary layer that remains turbulent, the effect of acceleration in the convergent section is to make the velocity gradient steeper at the wall and flatter in the outer part of the layer. In the divergent section the effect of acceleration is less than in the convergent section, and the normalized velocity distribution near the nozzle exit was somewhat closer to a 1/7 power distribution typical of unaccelerated turbulent boundary layers. Significantly, however, the normalized temperature distribution retained a nearly 1/7 power shape throughout the entire nozzle. This accounts for the reasonable correlation between the local Stanton number and energy thickness Reynolds numbers for nozzle flows when the boundary layer remains turbulent throughout the nozzle.

When a significant reduction in heat transfer occurred even though the boundary layer was turbulent at the nozzle inlet, the results clearly show that both the velocity and thermal boundary layers become laminar-like near the wall. Futhermore, the velocity boundary layer becomes partially laminarized at higher Reynolds numbers than did the thermal boundary layer. Thus it appears that as a consequence of acceleration a reduction in the turbulence occurs as the Reynolds number decreases which first influences the velocity distribution. Then the effect is transmitted to the thermal layer which is closely coupled with the heat transfer. Laminarization of the thermal layer became apparent when the local value of K exceeded about 2×10^{-6}. The mechanism by which turbulence is produced in the wall vicinity is apparently suppressed in accelerating flows, and this view is consistent with observations on the important role of the wall in the production of turbulence. A paper pertaining to laminarization (Ref. 2) will be presented at the ASME-AIChE 11th National Heat Transfer Conference this summer.

PLANS

The investigation under this work unit has been completed except for the preparation of papers describing the results. A category of nozzles with very steep convergent angles (as large as 90°) will be studied beginning in FY 70 under work unit 128-31-95-01-55 which has been designated as "Investigation of Nozzles of Radical Configuration." These nozzles have application to the Inter-regen Engine concept in which laminarization and a short heat conduction path between the throat and the nozzle inlet are important.

In addition, the nozzle boundary layer data obtained for turbulent and laminarized flow will be valuable as a guide for the proposed theoretical work in this direction to begin in FY 70 under work unit 128-31-95-03-56.

REFERENCES

(1) Back, L. H., Cuffel, R. F., and Massier, P. F., "Experimental Convective Heat Transfer and Pressure and Boundary Layer Distributions in Turbulent Flow Through a Variable Cross-Sectional Area Channel," submitted for presentation at the Fourth International Heat Transfer Conference in Paris, France, August 31 - September 5, 1970.

(2) Back, L. H., Cuffel, R. F., and Massier, P. F., "Laminarization of a Turbulent Boundary Layer in Nozzle Flow - Boundary Layer and Heat Transfer Measurements with Wall Cooling," accepted for presentation at the ASME-AIChE Eleventh National Heat Transfer Conference, Minneapolis, Minnesota, August 3-6, 1969.

PUBLICATIONS

Journal Articles

(1) Back L. H., Cuffel, R. F., and Massier, P. F., "Laminarization of a Turbulent Boundary Layer in Nozzle Flow," AIAA Jornal, Vol, 7, No. 4, April 1, 1969, pp. 730-733.

JPL Publications

(1) Cuffel, R. F., Back, L. H., and Massier, P. F., "Laminarization of a Turbulent Boundary Layer in a Nozzle with Wall Cooling," SPS 37-57, Vol. III, June 30, 1969.

SOLID PROPULSION TECHNOLOGY PROGRAM (128-32)

ADVANCED TECHNOLOGY CONTRACT MANAGEMENT

NASA Work Unit 128-32-20-01

JPL 328-20101-2-3810

W. Gin

OBJECTIVE

The objective of this work unit is to provide technical management of contracts and grants which are under the program management of NASA Office of Advance Research and Technology, Solid Propulsion Supporting Research and Technology, Code RPS.

PROGRESS

Under this task, the following contracts and grant were technically managed during this report period:

"Metal Combustion," W06032, Naval Weapons Center

"Binder Model System," NAS7-689, Stanford Research Institute

"Advanced Binder Synthesis," NAS7-669, Thiokol-Elkton

"Advanced Fuel Synthesis," NAS7-551, Unified Sciences Associates

"NP Stability Evaluation," NAS7-561, Midwest Research Institute

"Fuel Oxidizer Formulation," NAS7-655, Rocketdyne

"Chemistry of Solid Propellant Combustion," NGL-45-003-019, University of Utah

"Laser Pyrotechnic Ignition," NAS7-670, Space Ordnance Systems

"High Energy, High Slope Propellant," NAS7-661, Rocketdyne

"Heterogeneous Combustion Kinetics," NAS7-481, United Aircraft CRL

"Nozzle Transition Arc Ratio," NAS7-706, Thiokol-Wasatch

PLANS

In process at NaPO procurement are contracts for the following:

Burning rate modification of Saturethane propellants

Solid state laser rod beam homogeneity

High performance controllable rocket motor

Composite double base propellants for space

Also, the semi-annual oral report on all contracts and grants being managed by JPL will be made to NASA headquarters RP personnel and Center representatives on July 10, 1969, at JPL.

PUBLICATIONS

None

Reports and other publications being done as part of the contracts and grants being managed are identified in the separate progress reports of the respective work units.

ROCKET MATERIALS AND COMPONENT DEVELOPMENT

NASA Work Unit 128-32-36-01

JPL 328-20201-2-3810

R. L. Bailey
R. A. Grippi, Jr.

OBJECTIVE

The long-range objective of this work is to evaluate new and promising materials for possible solid-propellant motor component applications, such as nozzles, chamber insulation, TVC systems, and low-acceleration, long-burning-time motor systems. Fabrication techniques and component design using the more promising materials will be evaluated.

PROGRESS

LMH_2 Nozzle Performance

Nozzle performance analysis of the LMH_2 propellant systems test results has been completed. Eight runs were made; four of the VIY formulation (Hercules) and four of the 332A formulation (Atlantic Research). The following table summarizes the erosion rate analysis:

Run No.	Prop.	P_c-Ave. psia	Erosion Rate-Mils/Sec.
1	332A	775	1.00
2	332A	576	.25
3	332A	540	.25
4	332A	799	.81
5	VIY	653	1.00
6	VIY	487	.33
7	VIY	629	1.00
8	VIY	470	.33

The highest erosion rate occurred during the high-pressure runs as expected, although the erosion rate was reduced by a factor of 3 to 4 with only a 200 psia drop in chamber pressure. The 332A propellant system exhibited the lowest nozzle erosion rate. However, this may be due to the excessive coating (up to 27 mils) that occurred with this propellant. The VIY propellant system exhibited negligible nozzle coating. Based on the erosion rate analysis it is concluded that the LMH_2 propellant systems are comparable or less erosive than aluminized propellant systems. This completes the work on the nozzle test results with LMH_2 propellant systems.

Multicomponent Test Stand

The multicomponent test stand's calibration acceptance tests were completed and found to be acceptable. In order to perform a final acceptance test on the stand, it was subjected to a motor firing. The motor selected for the test was an SR-12-1 flight motor. This choice was made since the performance history on this type of motor has been well documented. The particular motor utilized was a back-up flight motor for the Syncom Flight Program, and was cast in March, 1964. The motor fired successfully with the resulting performance agreeing very closely to previous test data. Of significant importance is the fact that this motor had a storage history of almost five years (59 months) prior to firing it on February 19, 1969.

The test stand performance indicated extremely noisy channels with respect to the side load forces measured, which were yaw, pitch, vertical, lateral, and roll. Axial thrust was also noisy, but this probably was due to the fact that the motor was not fired at altitude. Investigation of the noise problem indicated that both the motor and test stand contributed to the noise. It was decided that the noise problem could be handled, and that the test stand was acceptable for use.

Long-Burning-Time Nozzle Materials

A purchase order was awarded to Reflective Laminates (subsidiary of Fansteel Corp.) for two nozzles fabricated from Fibergraph. This material is similar to Carborundrum's Carbitex. The main nozzle body, including the exit cone will be filament wound, and then subjected to the required heat treatment phases. The transition piece, structural member from nozzle body to nozzle attachment ring, will be tape wrapped, and also heat treated. The first nozzle was due the end of May, but during the heat treatment cycling, the exit cone delaminated. The heat treatment parameters were recalculated, and the second nozzle was started through the cycling process. It is due the first part of July.

Two 60-lb. end-burning motors were cast, cured, and static test fired. The nozzles utilized for these tests were of submerged configuration. They consisted of tape-wrapped carbon cloth/phenolic material with a high-density graphite throat insert. The burning times for the two motors were approximately 39 and 49 seconds at average chamber pressures of 178 and 101 psia respectively. The nozzles exhibited low or negligible erosion and charring. The change in throat areas were 1.5% (t_b = 39 sec.) and 2.0% (t_b = 49 sec.). The nozzles appear satisfactory for refiring with only the submerged outside diameter needing refurbishing.

A purchase order was awarded to Edler Industries for fabrication of ablative-type nozzles for use on the end-burning motor. These nozzles are being fabricated as an ablative back-up design to the radiation-cooled nozzle design (Fibergraph). Light-weight and low-cost materials will be evaluated on these nozzles.

Long-Burning-Time Motor

In order to demonstrate the end-burning concept in a more meaningful motor size, a salvaged ATS flight motor was loaded with 800 lbs. of JPL 540 propellant. The motor was insulated with GTR V-52 rubber (standard ATS material). The nozzle utilized was a modified flightweight ablative nozzle with a high-density graphite throat insert. To accommodate the longer burning time, 110 sec. compared to a standard 42 sec., the submerged outside diameter portion of the nozzle was insulated with GTR 4010. The motor was successfully tested, demonstrating that fully case-bonded 800 lb. end-burning motors are feasible. The motor burned for 110 sec. at an average chamber pressure of 110 psia. The nozzle performed very satisfactorily with a negligible change in throat area of 0.3% compared to a standard

1.5% change for the ATS flight motor. The nozzle throat exhibited no coating, which is of significant importance. Apparently as the throat size is increased the coating problem disappears even though the motor operated at a low chamber pressure. Post-fire inspection of the GTR 4010 and V-52 interface, nozzle to chamber, revealed that the 4010 material significantly outperformed the V-52.

Ethylene-Propylene Insulation

The ethylene-propylene terpolymer rubber (EPR) series GTR 4010 and 4030 has been evaluated with respect to case-bonding techniques and propellant bonding techniques as reported previously. Additional evaluation has demonstrated the EPR material's superior capability to the V-52 or NBR type material. Eight 60-lb. flightweight chambers have been insulated with GTR 4010 for use in the long-burning-time motor program.

PLANS

Multicomponent Test Stand

The test stand will be used to evaluate radiation-cooled nozzles and ablative nozzles for long-burning, end-burning motor applications at altitude.

Long-Burning-Time Nozzle Materials

Testing of the radiation-cooled nozzles (Fibergraph) will be accomplished. The nozzles will be instrumented with strain gages and thermocouples to obtain mechanical and heat transfer properties during testing. They will be tested on the 60-lb. motors loaded with the Saturethane propellant system. These motors will be tested on the multicomponent test stand at altitude.

Since radiation-cooled nozzles may prove unsatisfactory for long-burning-time applications, evaluation of ablative materials for these applications will be conducted. The types of materials that will be evaluated are the lightweight silica and carbon systems, the low-cost materials, as well as the standard ablative materials.

Ethylene-Propylene Insulation

Further evaluation of the EPR materials will be conducted to determine the best propellant bonding technique and ablation rates at much lower chamber pressures (50-150 psia).

Long-Burning-Time Motor

It is planned to insulate an ATS-size chamber with GTR 4030 and load it with 800 lbs. of Saturethane propellant. The motor will be designed to burn for 160 sec. at 150 psia. A flightweight nozzle will be designed and fabricated for this application.

PUBLICATIONS

Meeting and Symposia Papers

1. Anderson, F. A., and Bailey, R. L., JPL, "Ballistic Evaluation of High Energy LM_2 Propellants", presented at Fourth ICRPG/AIAA Solid Propulsion Conference at Chicago, May 20-23.

JPL Publications

1. Anderson, F. A., and Bailey, R. L., "Ballistic Evaluation of High Energy, LMH_2 Propellants", TR-32-1418.

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PROPELLANT FUELS

NASA Work Unit 128-32-40-01

JPL 328-23301-2-3810

F. A. Anderson
R. A. McKay

OBJECTIVE

The long-range objective of this work unit is to develop a propellant family based on beryllium and on LMH-2 for use in spacecraft midcourse and terminal maneuver motors. Included in this objective is the performance evaluation of these propellant systems as they become available. An intermediate objective is to provide a self-contained in-house facility at JPL for small-scale development and testing of non-detonable beryllium propellants. A facility design goal is to provide for complete containment of all accidental emission from deflagrating propellant.

PROGRESS

The construction contract for the in-house beryllium facility was completed in June except for assorted minor deficiencies noted during the final inspection. These deficiencies are to be corrected without delaying JPL occupancy of the building.

The next phase of the work will be to outfit the building for propellant work. The motor test tank, now modified, was placed in its test cell. The mixer enclosure and the preparation bench were also put into place. The laboratory fume hoods and the glove box were fabricated; installation is imminent. Construction of the propellant curing and conditioning chambers and the control panel is nearing completion. The design and procurement of other components are in various stages of progress.

PUBLICATIONS

Meetings and Symposia Papers

1. F. A. Anderson and R. L. Bailey, a paper entitled "Ballistic Evaluation of High Energy LMH-2 Propellant," 4th ICRPG Solid Propulsion meeting, Chicago, Illinois, May 20-22, 1969.

PROPELLANT BINDER
NASA Work Unit 128-32-40-02
JPL 328-21501-2-3810
H. E. Marsh, Jr.

OBJECTIVES

The primary objective of this program is to develop a new propellant binder suitable for advanced solid propellants for space application. Additional objectives are evaluation of new binder curing reactions and investigations of model polymerization systems leading to the determination of the functionality or reactive group-terminated prepolymers.

PROGRESS

Union Carbide Contractual Research

Having achieved most of the objectives of the program, the contractor concentrated on the major remaining problem with the otherwise best candidate prepolymer, the ethylene-propylene copolymer. That problem, improvement of functionality, was found to be intractable partly for fundamental reasons and was put aside for later study. In the meantime, the Carbide researchers were directed to change their emphasis from terminal difunctionality to random intrachain functionality. This shift was desired for two reasons; (1) to capitalize on this easier approach in order to evaluate more easily the predicted advantages of the ethylene-propylene chain backbone, and (2) to provide a potential back-up prepolymer for a current JPL propellant development project, under Work Unit 128-32-42-03.

Whereas the application of telomerization to the free-radical synthesis of ethylene-neohexene prepolymers raised the apparent functionality from near one to values approaching two, it was found that not all potential functional sites were readily converted by the planned treatment. Partial improvement was achieved by different approaches. However, at best, functionalities of around 1.5 were obtained. This undesirable result was compounded in the ethylene-propylene system because of its tendency for hydrogen transfer during synthesis, resulting in average functionalities again of near one. In either case, the striving for higher molecular weights (which will be necessary) will further aggravate the problem. Approaches that will be tried when this problem is taken up later will include new comonomers, new initiators and telogens, and better methods of conversion. And of course, if reasonably good functionalities can be achieved in synthesis, the products can be beneficiated by separation methods discussed previously.

Although random intrachain functionality is less desirable than terminal difunctionality, it is not unacceptable to the propellant industry, as is evidenced by the wide usage of at least two such prepolymers. The Carbide researchers showed that this is easy to achieve in their synthesis by the introduction of termonomers such as vinyl alcohol. This demonstration was made at a time when a back-up prepolymer was desired for a current propellant development program — for a low-thrust planetary orbit motor demonstration program. The first prepolymer sample selected from this approach for propellant formulation study immediately showed the processing advantage of low fluidity. With the propellant cured however, mechanical properties were poor. Subsequent tests will be made with different termonomers and in different proportions.

JPL Research

Very little time was available for in-house study of polymer network theory. It was demonstrated that the approach to network description based on extension of Flory's theory is applicable to systems containing mixed-functional cross-linking agents. A relation for mixed tri- and tetra-functional agents was derived. Experimental work to verify theory is continuing under Work Unit 128-32-40-03, and is beginning again at JPL.

PUBLICATIONS

None

HIGH ENERGY PROPELLANT

NASA Work Unit 128-32-41-01

JPL 328-20801-2-3810

F. A. Anderson

OBJECTIVE

The objective of this program is to develop a high-energy propellant system, based on hydroxylammonium perchlorate as the oxidizer, which will offer a higher performance potential than the conventional ammonium perchlorate propellant systems.

PROGRESS

In the previous semi-annual report it was stated that compatibility studies between HAP (hydroxylammonium perchlorate) and potential binder ingredients were continuing, and that a candidate propellant formulation containing 80% total solids was under development. A specific impulse goal had also been set which required a solids loading of 84% in the candidate propellant system if the I_{sp} goal were to be reached. The continuing compatibility studies and processing development of the candidate propellant formulation have resulted in the selection of two different candidate formulations. Both of these newer formulations do contain 84% total solids and do meet the theoretical I_{sp} target. The theoretical vacuum I_{sp} at a nozzle expansion ratio of 50 is 323 seconds. The predicted value for a delivered vacuum I_{sp} at an $\epsilon = 50$ is 300+ seconds. The selected target had been a delivered I_{sp} vac. of 300 seconds. Development studies involving the two current candidate formulations are being conducted. Twenty-gram samples are being routinely prepared in a dry-box facility. Samples have been cured and satisfactorily stored up to several weeks at 140°F.

A laboratory technique for grinding the HAP oxidizer has also been developed. This technique involves the use of a mechanical mortar and pestle, operated remotely. Other grinding techniques are being investigated which would better lend themselves to scale-up.

PLANS

Future plans call for continued development and scale-up to one-lb batches of the candidate propellants. The larger batch sizes will permit initiating physical property studies. It is also planned to begin ballistic property studies during this next period.

PUBLICATIONS

None

PROPELLANT IMPROVEMENT AND CHARACTERIZATION

NASA Work Unit 128-32-42-03

JPL 328-21701-2-3810

D. E. Udlock

OBJECTIVE

The objective of this work unit is to improve and characterize the performance, ballistics, mechanical properties, processing, and ingredient quality control of newly-developed propellants or of existing propellants for new applications.

PROGRESS

Low-Modulus Propellant

In order to meet the requirements for a low-acceleration motor, a low-modulus, high-elongation, low-burning-rate propellant is being developed for use in a fully-case-bonded, end-burning motor. For feasibility demonstration purposes a low-modulus, high-elongation modification of JPL-540 propellant was formulated.

Motors using Syncom and ATS flight-weight chambers, which had been reclaimed from previous static firing tests, were loaded with JPL 540 propellant in a fully-case-bonded, end-burner configuration. They were tested for retention of integrity under severe temperature cycling and were subsequently static fired successfully. The mechanical properties of the JPL-540 propellant were as follows:

Motor Type	Approximate Propellant Weight lbs	Sm psi	m %
Syncom	50	145	82
ATS	800	126	129

To provide even lower thrust than that available with JPL-540 by capitalizing on the low-burning-rate characteristics of the Saturethane propellant, a development program was undertaken to improve the mechanical properties of the Saturethane sufficiently to adapt it to the case-bonded, end-burner configuration.

Initial attempts to achieve higher elongation from the normally higher-modulus Saturethane propellant yielded propellants with up to 85% elongation at maximum tensile strengths of from 150 to 250 psi. Attempts to duplicate these results with subsequent lots of prepolymer have been unsuccessful. With current lots the highest elongation achieved has been 67% at 145 psi.

To lower further the burning rate, a tri-modal distribution of oxidizer was employed. This successfully lowered the burning rates of both Saturethane and JPL-540 propellants by approximately 15% at 100 psia. However the use of the larger (400 micron) oxidizer caused the Saturethane propellant to develop voids during cure, and its use has been discontinued at present.

Heat-Sterilizable Propellant

The conclusions reached previously were further verified. These are that there is apparently no correlation between ammonium perchlorate (AP) stability, in terms of exotherms (measured on a DSC) or high-temperature (275 to 350°F) weight loss, and propellant stability.

The major effort was devoted to writing a comprehensive technical report (TR-32-1406) which discusses all the aspects of our sterilization efforts.

PLANS

There are several problems which must be solved before the maximum potential of Saturethane propellant can be realized. Among these are: (1) Lot-to-lot variations in the prepolymer (saturated secondary-hydroxy-terminated polybutadiene) must be eliminated. This will require a coordinated effort between ourselves and the supplier (General Tire and Rubber Company). (2) The problem of larger particle AP stability is one that has been observed before. Study of it is being carried out under another program. (3) An optimum liner preparation procedure for obtaining the best possible bond strengths between liner and propellants is needed. (4) The present cure temperature (190°F for 13 days) should be lowered in order to decrease the stresses created within the grain during cooldown from cure. The use of slower-reacting isocyanates, possibly with catalysts, will be studied. However the useful pot life of the propellant must be extended so that larger (150 gallon) batches can be routinely processed. These combined problems will be examined.

There are several other saturated hydrocarbon prepolymers now under development which will be examined as potential improvements over the one presently being used.

PUBLICATIONS

JPL Publications

1. Robillard, C., Udlock, D., "Burning Rates of Saturethane Solid Propellants." SPS 37-55, Volume III, p. 179.

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RHEOLOGICAL PROPERTIES OF PROPELLANTS

NASA Work Unit 128-32-43-01

JPL 328-20301-1-3820

R. F. Landel
R. F. Fedors

OBJECTIVE

The long-range objective of this work unit is to evolve and substantiate a theory of viscoelastic behavior that will permit the prediction of the response of a solid propellant to a generalized stress-time-temperature field. This requires studies of:

(1) Finite deformation under (at least) unequal biaxial loads.

(2) The origin of rupture and its dependence on factors such as time, temperature, crosslink density, and type of polymer.

(3) Effects of the type and concentration of filler particle on the rheology of filled systems over this same range of small deformation, finite deformation, and ultimate behavior.

Once a general understanding of these areas is obtained, attention will be turned to more complex systems.

PROGRESS

The new parallel plate apparatus has been completed. Measurements on standard oils continue to give erratic results, though our recently-ordered set of new standardized oils with corresponding temperature dependence calibrations has been received and is now being used to check the apparatus. A series of slurries of glass beads in mineral oil has been made up to check the new apparatus against the old.

As for studies on elastomers, the failure data on the natural rubber specimens have been analyzed and shown to be consistent with the over-all behavior previously reported by Smith. Further data reduction (of the stress-strain curves themselves) is now under way with the object of determining the stress-relaxation modulus as a function of time for comparison with direct measurements carried out by Thirion in France.

Our theory for the mechanical properties of the filled system has been extended in two areas. On the one hand, considering inert fillers as has been done in the past, the theory of the dewetting behavior as a function of the strain has been extended to the region of uniaxial compression, which is equivalent to biaxial extension. In this case, the void cavity is that of a doughnut around the hard spherical particle. The doughnut in cross-section can be treated as either triangular or parabolic. For both cases, equations for the modulus-strain and the volume strain dependence have been derived. As might be expected, the modulus drops off much more rapidly with compressive strain than it does with tensile and the volume change increases much more rapidly.

Measurements on the filled systems have been extended to two additional filler types, calcium carbonate as an example of a non-reinforcing filler and HAF as an example of a highly-reinforcing filler. The results of these studies when combined with the existing results on glass-bead-filled and Thermax-filled (a non-reinforcing black) rubber should give a reasonably complete picture of the effect of particle-filler interaction on the mechanical properties and the ease of dewetting.

In addition to the uniaxial tensile experiments, which we have been carrying out in the past, studies in these materials have been extended to tear by Professor Joseph Glucklich, a Resident Research Associate from the Technion in Jerusalem. Experiments on the glass-bead-filled systems have been completed and those on Thermax are under way.

To date, nearly all of our studies have been concerned with solid fillers although some work has been done on analyzing literature data for foams. In this case the filler is highly compressible. As a preliminary to extending our work on filler effects to liquid fillers, Professor Glucklich has derived equations for the relative modulus of systems with liquid (Newtonian) and viscoelastic (Maxwellian) fillers in elastic and viscoelastic (standard-solid) matrices. For simplicity, this first treatment has been limited to considering cases in which the distribution of filler particles within the mass is of cubic rather than random order.

As part of this task, a contract had been let to Thiokol Chemical Corporation to conduct a study of the characteristics and standard variability of composite propellants as a function of degree of crosslinking and test temperature for three binder types including polybutadiene (carboxy terminated), polybutadiene-acrylonitrile, and polyurethane. The results of this study will be used to determine how the variables of degrees of crosslinking, test temperature and binder type affect the ultimate properties of a propellant. The experimental study has been completed, but the final report has not yet been released.

PUBLICATIONS

Meeting and Symposia Papers

1. R. F. Landel, "Mechanical Behavior of Propellants", 65th National Meeting of American Institute of Chemical Engineers, May 7, 1969.

JPL Publications

1. R. F. Fedors and R. F. Landel, "Dewetting of Composites in Uniaxial Compression", SPS 37-55, Vol. III, February 28, 1969, p. 193.

2. Joseph Glucklich, "Hookean, Newtonian, and Maxwellian Fillers in Hookean and Standard Solid Matrices", SPS 37-57, Vol. III, May 30, 1969.

DEGRADATION MECHANISMS

NASA Work Unit 128-32-43-02

JPL 328-20401-1-3820

J. D. Ingham
D. D. Lawson

OBJECTIVE

The objectives of this work unit include:

(1) Studies of the mechanisms of thermal degradation of polymers.

(2) Investigation of the synthesis of new polymers as potential binders.

(3) Determination of the molecular structure of polymers by nuclear magnetic resonance (NMR) spectrometry and other methods.

PROGRESS

Polymer Degradation

Work has been started on the AT contract (Rocketdyne) to investigate the interactions of saturated hydrocarbon polymers with oxidizer. Although some experimental difficulty was encountered in the preparation of the polymers, most of them have been prepared, subjected to thermal treatment, and separated for analysis and characterization.

A new thermoanalytical apparatus has been constructed. This instrument is used to measure low-level visible radiation evolved when a previously-irradiated solid material is heated at a constant heating rate to temperatures below incandescence. It can also be used to record the light evolved on oxidation of organic materials. It is planned that measurements of light emission of X-irradiated oxidizer and/or propellants will be made to attempt to correlate the results with stability characteristics, and to study oxidizer interactions with binder materials.

Polymer Synthesis

Although extensive efforts have been made to prepare difunctional poly (isobutylene) by polymerization of monomer in the presence of allyl chloride and titanium tetrachloride, none of the polymers were low enough in molecular weight to be useful as prepolymers or to accurately determine their endgroup functionality. When conditions were adjusted to decrease the molecular weight, measureable polymerization did not occur. However, difunctionally-unsaturated poly (isobutylene) was prepared by direct polymerization by molecular sieves. The endgroup functionality was determined by NMR (by Dr. S. L. Manatt) to be 1.8 to 2.1, for number average molecular weights of 1150 to 3600.

Polymer Molecular Structure

Molecular structure and polymer characterization studies have been carried out on the isobutylene polymers by NMR, intrinsic viscosity measurements, ozonolysis, and gel permeation chromatography (GPC). Ozonolysis showed that most, if not all, of the double bonds were terminal, since no molecular weight reduction was observed. GPC was used to determine molecular weight distributions and number average molecular weights.

FUTURE ACTIVITY

When results are available from the AT contract, they will be assessed to determine and implement modifications for propellant stability improvements. As mentioned above, thermal analysis methods will be used to investigate propellant ingredient stability. Isobutylene prepolymers prepared by molecular sieve catalysis will be investigated for utility as prepolymers for binders. Possible methods of chain extension and/or crosslinking involving the terminal double bonds will be examined, as well as conversion to hydroxyl groups, to be followed by chain extension (or crosslinking) by urethane or ester formation.

PUBLICATIONS

Journal Articles

1. J. A. Miller, "Binder Polymers Provided by Molecular Sieve Polymerization," New Technology Report, Case No. 1809, May, 1969.

JPL Publications

1. D. D. Lawson, C. Pazaree, and J. D. Ingham, "The Use of a Torsion Pendulum," 37-55, Vol. III, p. 201, December-January 1969.

2. S. Fogler, W. Dowler and D. D. Lawson, "Low Temperature Decomposition of Ammonium Perchlorate," 37-55, Vol. III, p. 177, December-January 1969.

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PROPELLANT STRESS ANALYSIS

NASA Work Unit 128-32-43-03

JPL 328-20501-1-3820

G. W. Lewis
E. Duran
E. Heer

OBJECTIVE

The long-range objective of this work unit is to integrate material characterization studies, experimental and analytical stress analysis techniques, and to evolve satisfactory failure criteria into a rational designer-usable stress analysis. The short-range objectives are the improvement of the tools and techniques of experimental stress analysis, the adaptation of the JPL in-house Structural Analysis and Matrix Interpretive System (SAMIS) Program to propellant grain analysis, the continuing study of finite deformation theory, and the development of satisfactory failure criteria for elastomeric materials.

PROGRESS

The motor modeling tests using the stress-freezing epoxy in a spherical motor have been delayed due to difficulties uncovered in case bonding epoxy to metal in the motor configuration because of the differences in the coefficients of thermal expansion. The feasibility of using a fiber glass case which will minimize this difference is being explored.

The contract let to Whittaker Corporation in Pasadena to improve the thermal properties of the JPL-developed miniature stress transducer has not been successfully completed due to technical difficulties encountered by the contractor. It is believed that either the contractor underestimated the complexity of the task or the state-of-the-art has not progressed as rapidly as was anticipated.

A finite-element formulation for linear thermoviscoelastic materials has been accomplished. The finite-difference, finite-element (finite differences in time, and finite elements in space) matrix equations have been developed ready for computer programming. Attention has been given to the experimental determination of material properties and their utilization in analysis. The material property data enter the finite-element analysis as time-dependent "stiffness" data, so that material properties that have been measured as compliances or Poisson's ratio must first be converted to the corresponding stiffnesses. The material properties can be entered into the computations directly for each time step or they can be approximated by exponential time series. In the first case the data must be computed and entered as input at each time step, requiring the recomputation and summing of the response contributions at all previous time steps, thus frequently increasing computational labor. In the second case, if one assumes a uniform temperature field in each finite element, it is shown that this leads to recurrence of matrix equations eliminating the problem of calculating at each time step the history of material response.

Concurrent with the analytical formulation, the development of a computer program called VISCEL (viscoelastic) was initiated and is presently being debugged. This version of VISCEL uses material stiffness properties as input at each time step. The time step increments are variable so that efficient use of computer time can be accomplished.

A joint JPL-Caltech program was initiated with Professor Knauss of Caltech to test the applicability of crack propagation theories developed under NASA Grant NGL05-002-005 to operational solid propellants. Heretofore, they have worked solely with gum rubbers such as Solithane 113, and the universality of the theories is unknown. The joint test program will serve to fill in that gap. To implement the program, a batch of JPL-540, a polyurethane-based propellant used in the ATS, Syncom, and end-burner motors, was cast at Edwards Test Station. Minor modifications are being made to Professor Knauss' equipment to insure compatibility with the propellant specimens. The testing will start in July and should be finished by the end of summer.

PLANS

As indicated, work will continue on completing the VISCEL computer program, and on applying it to solid propellant motor designs now under study. Work will also progress on the JPL-Caltech joint test program and the completion of equipment development on the biaxial tester and photoelastic material calibrator. Any further work on the miniature stress transducer will be brought in-house, with emphasis on packaging improvement. It is anticipated that a program will be initiated to determine the distribution of the thermal stress field in a motor as a function of time.

PUBLICATIONS

Journal Articles

1. Akyuz, F. A., "Natural Coordinate Systems — An Automatic Input Data Generation Scheme for a Finite-Element Method," to appear in Nuclear Engineering and Design, July, 1969.

JPL Publications

1. Akyuz, F. A., "FEDGE — A General Purpose Computer Program for Finite Element Data Generation: Vol. I User's Manual, Vol. II Program Manual," JPL TM 33-431, 1969.

2. Heer, E., and Chen, J. C., "Finite Element Formulation for Linear Thermoviscoelastic Materials," JPL TR 32-1381, March 15, 1969.

SOLID ROCKET COMBUSTION STUDIES

NASA Work Unit 128-32-50-01

JPL 328-22701-2-3810

Combustion Modeling

R. Klaus

OBJECTIVE

The objective of this work unit is to develop a sound theoretical understanding of the mechanisms of solid propellant combustion under both steady and transient conditions and the application of this understanding to the various phenomena of interest in solid rocket combustion such as steady burning rates, ignition, extinction, oscillatory combustion, erosive burning, etc.

PROGRESS

Work in this period was directed toward surveying existing combustion models and in formulating a general model which includes all the known important effects. Within the solid the most important consideration is heat transfer away from the surface into the interior. The heat conduction equation has been formulated and solved in such a way as to make numberical solution easiest and with boundary conditions which apply to propellant combustion. The effects of radiation penetration into the solid are also included. Future work will include generalization of these results to include an oscillating burning surface, a burning surface with arbitrary motion and phase changes within the solid. Since radiation penetration can be an important consideration, a statistical model has been developed for radiation penetration into composite propellants.

In order to model properly the bulk of the gas phase, the one-dimensional unsteady gas dynamic equations have been formulated in such a way as to be applicable to the combustion model and their properties thoroughly investigated. Future extensions will include effects due to condensed species and burning condensed species. The equations have been put into a form which is convenient for numerical solution, and a computer program is being developed to solve them for very general boundary conditions.

The most difficult and controversial part of the model is in the region of the flame, which is very close to the pyrolyzing surface. Two models have been formulated, one of which is relatively simple and one of which is more complex but describes the basic burning mechanism more realistically. Computer programs are under development to perform the necessary calculations. The first application of these models will be to ignition and extinction. Following that there will be a treatment of their application to oscillatory combustion.

STUDIES IN IGNITION AND FLAME SPREADING — R. Klaus

Objective

The objective is to develop a mathematical model and computer program to describe flame spreading in solid propellant motors.

Progress

During this period the basic mathematical model has been formulated. It is a transient model and includes the effect of spatial variation of temperature and pressure throughout the rocket chamber and nozzle. The equations have been formulated and numerical methods for their solution developed. Work has begun on a computer program to solve the equations and thus to simulate flame spreading. Future work will include the completion of the computer program and then its further refinement to include a more accurate treatment of heat transfer to the propellant surface including the effect of impinging hot particles, the substitution of a more valid criterion of ignition, and a more detailed analysis of plume impingement with particular application to aft-end ignition.

T-BURNER STATUS REPORT — E. Perry

Objective

This program seeks to provide a better understanding of the T-Burner and an examination of its role in combustion instability studies.

Progress

Tests were recently conducted in transparent plastic T-Burners in order to obtain high-speed motion pictures of T-Burner test firings. These tests demonstrated very clearly that the T-Burner is essentially a one-dimensional device with three-dimensional effects confined to the vicinity of the vent. In addition some rather useful information related to ignition techniques was obtained.

A series of tests using JPL T-17-E2 propellant provided a comparison of results obtained in T-Burners to those obtained several years ago in actual rocket motors. The favorable comparison was very encouraging and indicated that the T-Burner might well indeed supply vital information relevant to combustion instability in full-scale motors.

An experimental examination of the variable-area method of conducting T-Burner tests is presently being carried out. From tests completed thus far it appears that this method is rather questionable since one of its basic assumptions does not seem to be borne out in practice.

An SPS article is planned which will detail the work reported above.

Future studies include a continuation of the effort to determine the nature of the acoustic losses in the T-Burner and an attempt to relate the steady-state amplitude of the T-Burner pressure oscillations to other instability parameters.

MEASUREMENT OF SOLID PROPELLANT BURNING RATES DURING RAPID PRESSURE TRANSIENTS — D. Norton .

Objective

This program is to develop a technique for determination of burning rates under transient conditions and to obtain transient burning rate data.

Progress

Preliminary measurements of depressurization burning rates indicated that the burning rates were not a function of pressure alone. Subsequent examination of these records also indicated a small oscillation in the burning rate during the transient. In order to make accurate determinations of the burning rate over small time periods, the fixed reflections in the microwave system were reduced by employing an improved transition and calibration device. In addition an analysis of the returning amplitude and phase signals was made so that the raw data could be operated upon mathematically to eliminate any remaining undesirable reflections.

In October, a new digital data acquisition system will be installed so that accurate measurements of amplitude, phase, and pressure can be made with a 2-μsec sampling window; then, this raw data will be operated upon to eliminate fixed reflections by simultaneous use of the amplitude and phase signals. The final result will then be the burning rate in engineering units over depressurization conditions.

PUBLICATIONS

JPL Publications

1. Klaus, R. L., "The General Behavior of the Equations for One-Dimensional Unsteady Compressible Flow," SPS 37-56, Vol. III, April 30, 1969.
2. Klaus, R. L., "Heat Transfer in a Solid Propellant Grain During Ignition with Radiation Penetration and Convection Boundary Conditions," SPS 37-57, Vol. III, June 30, 1969.
3. Klaus, R. L., "Flame Spreading in Solid Propellant Rocket Motors," SPS 37-57, Vol. III, June 30, 1969.
4. Perry, E. H., "T-Burner Studies," SPS 37-54, Vol. III, December 31, 1968.

SOLID PROPELLANT DETONATION RESEARCH

NASA Work Unit 128-32-50-02

JPL 328-23201-2-3810

O. K. Heiney

OBJECTIVE

The goals of this task are to investigate analytically and experimentally high-rate energy release phenomena occurring in solid propellants. This effort is currently being channeled into two main areas. The first is an analysis of the mechanism of the coupling between the chemical energy and pressure release waves occurring in solid propellants. The processes considered will be detonation and deflagration wave onset and propagation as well as conventional ignition. The second area of research is that of applied unconventional interior ballistics for space application to propellant-actuated devices.

PROGRESS

Equipment has been fabricated and instrumentation acquired to investigate the ignition and flame spread transients occurring in a solid propellant grain. Measured quantities will include ignition induction time, flame spread rate, pressure gradient formation, solid phase propellant temperature histories, and high-speed photographic coverage of the event. These experimental data will be correlated with several extant analytic approaches as well as JPL-generated analyses.

In the field of unconventional interior ballistic development, the high-low propellant-actuated device formulation has been applied to a flight-weight aerodynamic deceleration system suitable for planetary entry application. The mechanism has been fabricated and successfully tested in a free-fall environment.

PUBLICATIONS

JPL Publications

1. Heiney, O. K., "Ballistic Design & Experimental Test of High-Low Parachute Mortar," JPL SPS 37-55, Vol. III, February 28, 1969.

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SOLID ROCKET GASDYNAMIC STUDIES

NASA Work Unit 128-32-52-01

JPL 328-21101-2-3810

D. Norton

OBJECTIVE

This program is to determine the gasdynamic effects of varying the throat radius of curvature ratio, r_c/r_t, and the nozzle inlet angle on mass flow, thrust, and specific impulse compared to one-dimensional results.

PROGRESS

The computer program describing the flow for two-dimensional, rotational gasdynamics is currently being employed to investigate systematically effects of radius of curvature ratio and nozzle inlet angle on the performance of certain classes of nozzles. The theory employed for these studies is quite general in that the effects of varying total temperatures may be included.

It is expected that the two-dimensional effects experienced in small-radius-of-curvature nozzles with large inlet angles can be investigated. In this way, decisions may be made regarding best trade-offs between reduction in heat transfer and reduced mass flow coefficient. The program is also useful for obtaining the sonic line for a more accurate starting point for Method of Characteristics Solutions for the supersonic flowfield.

PUBLICATIONS

1. Norton, D. J., Shelton, S., "Performance of Rocket Nozzles with Low Radius of Curvature Ratios," SPS 37-55, Vol. III.

CHEMICAL ROCKET EXPERIMENTAL ENGINEERING (731)

LIQUID SPACE PROPULSION SYSTEMS (731-12)

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LIQUID PROPULSION COMPONENTS

NASA Work Unit 731-12-03-03

JPL 331-10201-0-3840

W. F. MacGlashan

OBJECTIVE

The broad objective of this work unit is to advance the technology of liquid propulsion components for future space missions. Emphasis is placed on space-storable components, although earth-storable components are still considered for specific requirements. Current objectives are to develop solutions to problems identified in the space-storable module work unit, 731-12-04-01, and the combustion devices development work unit, 731-12-04-04.

PROGRESS

Component investigations oriented toward the earth-storable propellants have been deemphasized while redirection of effort toward space-storable investigations has received the major emphasis.

Component Testing with Space-Storable Propellants

The space-storable propellant test console at the JPL-Edwards Test Station has been completed. Leakage, storage, and nominal flow-type testing of components with oxygen difluoride diborane can now be conducted.

The components immediately available for test are the bobbin-type-seal connectors; the one-quarter-inch fill valves in aluminum, titanium, and stainless steel, and a single laminated valve-seat.

Belleville Spring Redesign

As a continuation of the hysteresis investigations, 100 Belleville springs were fabricated from 0.0225-inch-thick Elgiloy strip stock.

The springs were dished with varying degrees of conical height so that, by selection, a multiple-spring package could be assembled to give any desired load-versus-deflection characteristic. Twenty springs were made with a height-over-thickness ratio of 1.20, 60 with a 1.27 ratio, and 20 with a 1.38 ratio.

A typical 35-pound-force spring was mounted in a dry-lubed solid aluminum holder and deflected 1/4 million times at ambient temperature. The total excursion was 0.025 inches within a 0.020 through 0.045 inch deflection from the free position. A load-versus-deflection curve was obtained after each 15,000 cycles.

The initial hysteresis was approximately 1/2 pound and increased to a maximum of 2-1/2 pounds before leveling-off about 250,000 cycles.

The increase in hysteresis is believed to be caused by an increase in friction at the support annuli; possibly as a result of breakdown of the dry-lube.

No damage or wear to the Belleville spring was evident.

This work will be continued for the space-storable applications at a temperature of -230°F.

PUBLICATIONS

None

SPACECRAFT PROPULSION MODULE USING SPACE STORABLE PROPELLANTS

. NASA Work Unit 731-12-04-01

JPL 331-10701-0-3840

D. L. Young

OBJECTIVE

The objectives of this unit are to establish the requirements for and coordinate the development of a prototype propulsion module using space-storable propellants and to contribute to the over-all technology base required for the use of this class of propellants.

PROGRESS

During this reporting period, the propulsion module requirements were refined and schematics were established for the four-tank system configuration. Contact was made and plans were started with AFRPL personnel for use of the TAPR facility for module testing. Work continued on the thermal control and structure, and their interrelationship with the module and a Mariner-derivative spacecraft.

The various system studies performed indicated that in order to realize the full potential of these propellants, a more advanced design philosophy had to be taken to reduce the inert mass of the propulsion system. Therefore, two new tasks were undertaken with the Engineering Mechanics Division. These were (1) analyze and design composite tanks for use with the pressurant gas and propellants, and (2) use of composite integrated tanks and structure (making use of common bulkheads). This effort is being coordinated with LeRC in order to eliminate duplication of effort. The system studies performed also indicated that, because of packaging considerations, the four-propellant-tank configuration will be the baseline concept. However, the two-tank concept will still be under study wherever possible. A potential inert mass reduction for the four-tank configuration is the removal of the explosive valves from the propellant lines. Positive propellant shutoff will be obtained by the use of a dual inlet antimigration valve in series with the bi-propellant valve. The dual pressurization system has been deleted as the baseline on the gas side. It has been replaced by the more conventional single pressurization system. This system will incorporate a zero-leakage solenoid valve downstream of the regulator to preclude, with certainty, the mixing of propellant vapors during cruise. In order to determine the severity of the vapor mixing problem, a task has been let to Stanford Research Institute to investigate the flammability limits of OF_2/B_2H_6 vapors under the anticipated module operating conditions.

Two procurement actions were initiated during this report period. One was for an OF_2 transport and storage trailer. The other was for fabrication of zero blow-by explosive valves. The successful demonstration of these valves will permit a fall-back position if the baseline concept does not meet expectations.

PLANS

During the next reporting period, work will continue on all phases of the composite tank program. It is anticipated that the thermal control support will increase significantly, Evaluation of the explosive valves will begin. System studies will continue. The module requirements will continue to be refined and formalized into a reportable document. This unit will continue to serve as the coordination point of JPL's committment to develop a propulsion module using OF_2 and B_2H_6.

PUBLICATIONS

None

ADVANCED COMBUSTION DEVICE DEVELOPMENT

NASA Work Unit 731-12-04-04

JPL 331-10301-2-3840

R. W. Riebling

OBJECTIVES

The objective of this work unit is the utilization of recent advances in injector and thrust-chamber technology in the development of advanced, high-performance rocket engines to near-flight-prototype status. Problem areas associated with the application of this recently-developed technology will be exposed, and problems will either be solved as they arise or made the subject of further technology studies. The program is sufficiently flexible that new technology may be incorporated as it becomes available or that promising concepts exposed during development may be pursued further. This integrated approach is intended to produce basic engineering information concerning and demonstrating the performance and reliability of advanced rocket engine concepts so that new high-energy, space-storable propulsion systems will be ready for inclusion in forthcoming space flight project planning. Primary emphasis is being placed on the propellants oxygen difluoride (OF_2) and diborane (B_2H_6).

APPROACH

A number of injectors and chambers, all based on concepts already evaluated in OF_2/B_2H_6 service, have been fabricated. To conserve costs, and also because of the possibility that a spacecraft engine of this scale may be required, these components have been designed to produce a vacuum thrust of approximately 200 lb_f. All elements of this hardware are interchangeable so that various injector-chamber combinations can be made up and tested. Thousand-second-duration firings will be attempted for each combination, and based on measured combustion efficiency and durability, the most promising concept will be selected for further development. This future development will take place at the 1000-lb_f-thrust level because of potential application to a 1000-lb_f-thrust, space-storable propellant propulsion module being studied concurrently. It will incorporate refinements as necessary, based on the results of the 200 lb_f program.

STATUS

Fabrication of two 200-lb_f-thrust injectors is complete. Their designs are based on criteria developed for OF_2/B_2H_6 propellants under contract NAS7-304, "Chamber Technology for Space-Storable Propellants." Both are self-impinging doublet-type injectors made of nickel, and contain multiple injection elements arranged in such a way that the spray consists of a high-mixture-ratio, high-performance core region containing the bulk of the propellant mass flux, surrounded by a low-mixture-ratio barrier zone adjacent to the chamber walls. The purpose of this barrier zone is to minimize wall and throat erosion by reducing the temperature, heat flux, and concentrations of corrosive species adjacent to the wall. The two injectors are nearly identical; differing only slightly with regard to their specific pattern arrangements.

One 200 lb_f-thrust chamber is being fabricated in-house, while six others have been designed and fabricated by outside contractors. All these chamber designs incorporate liners made of carbonaceous or graphitic materials to withstand the high combustion temperature of the OF_2/B_2H_6 propellants. The use of such materials for chamber liners with these propellants has been demonstrated on the above-cited NASA contract. Chamber cooling is completely passive, relying primarily on the barrier zone and the superior high-temperature properties of the carbonaceous materials. In the event that such engines must eventually be used in a "buried" configuration, the thrust chambers are all insulated so as to reduce the outside wall temperature to a nominal value of 600°F.

One of the chambers made by a contractor (Figure 1) is basically a free-standing Carb-I-Tex chamber with its inner surface impregnated with a layer of pyrolytic graphite (Carb-I-Tex is a fiber-reinforced, graphite composite material). This is surrounded by a standoff shield of lighweight, multilayer tantalum foil insulation. A second contracted chamber (Figure 2) consists of a graphite liner, and pyrolytic graphite heat conduction wedges which conduct a portion of the heat from the throat area to a region of the chamber near the injector, where it is rejected. The wedges are surrounded by two layers of insulation material in series. The third chamber fabricated under contract (Figure 3) consists of a liner made of a material similar to Carb-I-Tex, the

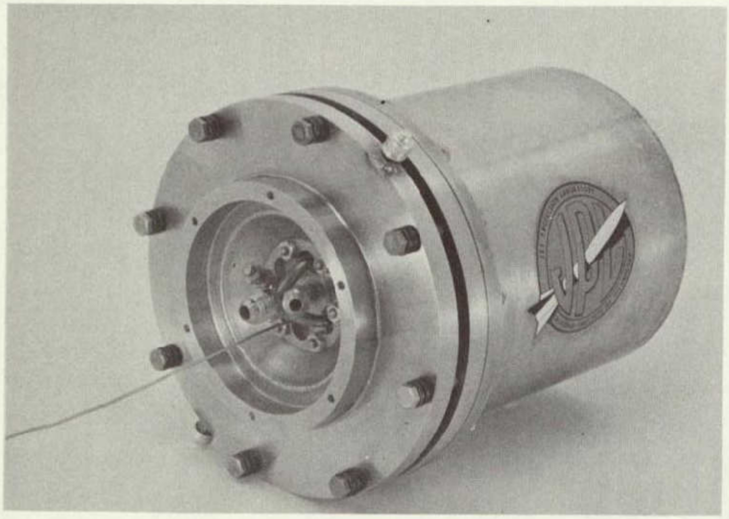

Figure 1. 200 lb_f OF_2/B_2H_6 Thrust Chamber Designed and Built by the Marquardt Corp., Van Nuys, California

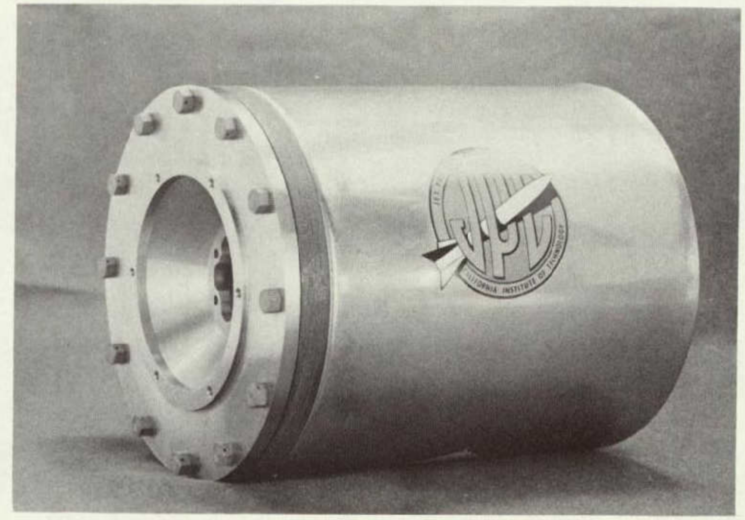

Figure 2. 200 lb_f OF_2/B_2H_6 Thrust Chamber Designed and Built by Thiokol Chemical Corp., Reaction Motors Division, Denville, N. J.

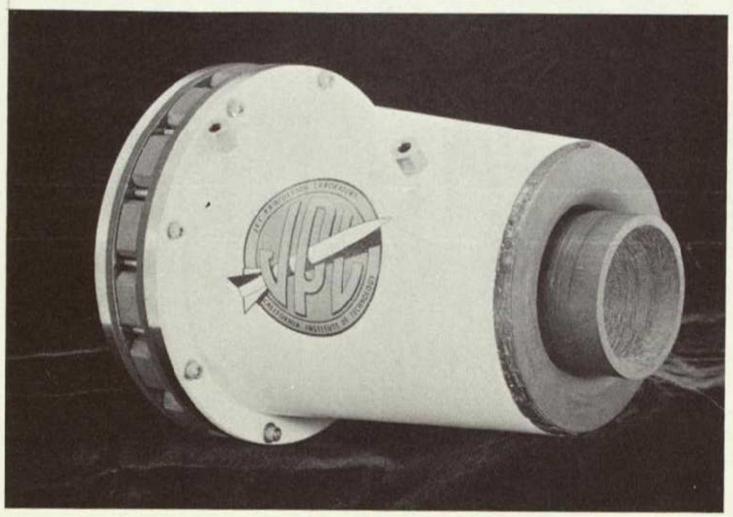

Figure 3. 200 lb_f OF_2/B_2H_6 Thrust Chamber Designed and Built by Aerojet-General Corp., Sacramento, California

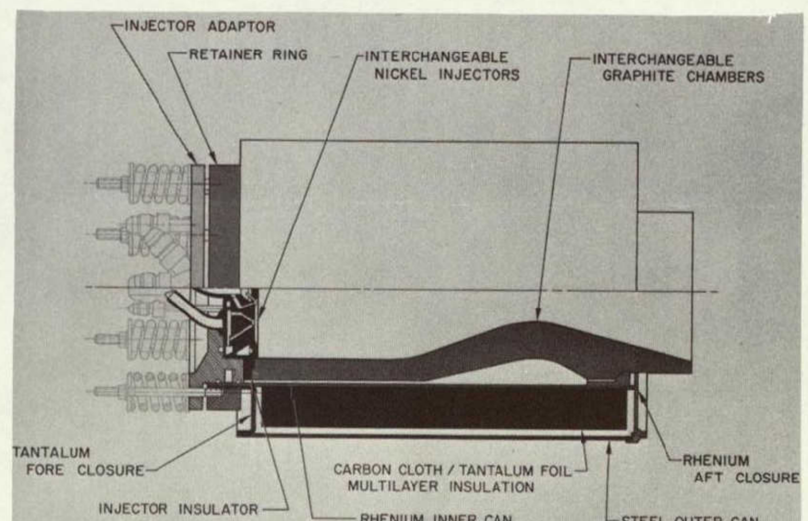

Figure 4. 200 lb_f OF_2/B_2H_6 Thrust Chamber Designed and Built by the Jet Propulsion Laboratory.

inner surface of which is impregnated with pyrolytic graphite. This is surrounded by an ablative Teflon insulator. A fourth, being made (Figure 4), incorporates a free-standing graphite liner surrounded by a carbon cloth/tantalum foil multilayer insulation system of the type developed under NASA contract NAS7-474, "Spacecraft Rocket Engine Chamber Insulation Materials." Liners for the in-house chamber have been made of ATJ graphite, several grades of POCO graphite, boron carbide, and vitreous carbon. Six complete thrust chamber assemblies have been delivered by the contractors. Components of the in-house chamber are nearing completion, with final assembly scheduled for the first quarter of FY 70. Test-firings at the Edwards Station will begin as soon as facility modifications (to permit operations with OF_2/B_2H_6 propellants) have been completed. These are being accomplished under a separate NASA work unit, Space-Storable Propellant Engine Testing, 731-12-04-05.

PUBLICATIONS

JPL Articles

(1) Riebling, R. W., "Injector Development - Impinging-Sheet Mixing," SPS 37-55, Vol. 3, pp 240-245, Feb. 28, 1969.

(2) Riebling, R. W., "Injector Development - Impinging-Sheet Backspray," SPS 37-55, Vol. 3, pp 235-240, Feb. 28, 1969.

(3) Riebling, R. W., "Advanced Combustion Device Development," SPS 37-57, Vol. 3, June 30, 1969.

Meeting and Symposia Papers

(1) Riebling, R. W., "Application of Space-Storable Injector and Chamber Design Criteria to Spacecraft Engine Development," AIAA Paper No. 69-508, presented at AIAA 5th Propulsion Joint Specialist Conference, Colorado Springs, Colorado, June 11, 1969.

SPACE STORABLE PROPELLANT ENGINE TESTING

NASA Work Unit 731-12-04-05

JPL 331-10601-2-3840

W. B. Powell

OBJECTIVES

The objective of this work unit is to provide a facility for development testing of rocket engines and components for significant durations using the high-performance space-storable propellant combination of oxygen difluoride (OF_2) and diborane (B_2H_6) at thrust levels up to 10,000 lb_f. Testing development-type engines of this scale for long duration will expose problems that should be made the subject of separate technology studies, and will contribute to the development of integrated propulsion systems matched as far as possible to potential spacecraft applications, having high performance, reliability, and long life.

APPROACH

An existing test stand at the JPL Edwards Test Station is being modified to accommodate the OF_2/B_2H_6 propellant system. Temperature-controlled and insulated propellant tankage is being procured. Propellant run tank capacity corresponds to total altitude impulse of 1.35×10^6 lb_f-sec. Initial operation will be at thrust levels of up to 2000 lb_f. Straight-tube diffusers will be coupled to the motor exhaust nozzles; enabling operation at an expansion ratio of up to 5 and closely duplicating high area ratio nozzle heat flow conditions in the throat region. The diffusers will discharge into a scrubber designed to remove as much as possible of the fluorine and boron from the exhaust products.

PROGRESS

The majority of the equipment needed for the test stand conversion has been procured and is on hand at the site. The propellant tanks have been installed and the jacketed propellant piping is being fitted into place. Bellows sealed valves have been received and are being used throughout the propellant system.

A new thrust stand designed to accommodate a range of test motors having 200 lb_f to 2000 lb_f vacuum thrust has been fabricated and installed, and a calibration system and calibrating weights are being fabricated.

A contract has been let to supply all of the necessary components for a propellant exhaust gas scrubbing system and to provide the drawings and specifications for the site work needed to mount this equipment.

Auxilliary cooling systems for the propellant lines, valves, and tanks are being assembled.

The system will be leak checked, cooled down near the end of the fiscal year, and readied for shakedown tests. Intital short-duration testing will be conducted without the scrubber, which will not be completed until October 1969.

PUBLICATIONS

None

LIQUID AUXILIARY PROPULSION SYSTEMS (731-13)

EXTENDED MISSION GAS ACTUATOR SYSTEM DEVELOPMENT

NASA Work Unit 731-13-01-03

JPL 331-30301-X-3440

J. D. Ferrera
F. G. Roselli-Lorenzini

OBJECTIVE

The long-term objective of this task is to provide improved alternatives to cold gas such as higher specific impulse, lower weight, and longer life in order to meet A/C thruster requirements for future planetary missions.

The immediate objective of this work unit is to integrate and evaluate the warm gas distribution subsystem, developed under contract with the General Electric Company in FY 68, with two types of warm gas supply subsystems being developed by the Propulsion Division (38). A second distribution system was developed in-house during this reporting period utilizing spare parts from the main system. The two gas supply systems being developed for test are an evaporating ammonia subsystem and a hydrazine-catalytic decomposition subsystem. A secondary objective for FY 69 was the measurement of thrust due to gas valve leakage.

PROGRESS

Distribution System

The main distribution subsystem has been functionally tested with nitrogen. Satisfactory results were obtained. The second distribution subsystem was built and functionally tested and then underwent a short-term compatibility test with liquid hydrazine. No significant compatibility problems were uncovered. Both subsystems are ready for the integration test. There has been about a three-month slippage in the combined test program due to problems with the delivery of the two gas supplies. However, it is anticipated that this time can be recovered due to the availability of the second distribution system enabling the testing of both gas supplies simultaneously. Testing will be completed during the next reporting period. Also, during FY 70 work will be initiated by both Divisions involved to develop a flight prototype of a single system which more exactly meets anticipated mission requirements.

Pressure Regulators

As a result of functional tests performed by GE under the distribution system contract, that contract was extended in the last reporting period to supply two improved pressure regulators (one soft and one hard seat design for comparison) with response, particularly at the thermal extremes, being a significant improvement over the breadboard system.

There has been a two-month slip in the contract effort due to difficulties at the vendor with long-lead item procurements. However, the detail design of the two procured regulators has been established. Testing of these two regulators, both at GE and JPL, will be accomplished in the next reporting period.

Thrust Versus Leakage

In an effort to understand some of the torque unbalances observed on Mariner spacecrafts in flight, a testing effort was conducted in the last reporting period which indicated rough correlation of thrust ($<0.3 \times 10^{-6}$ lb) vs. leakage with theoretical results. During this reporting period, the testing technique was further refined and additional testing performed. This additional testing established good correlation (within a few percent) with theory. A detailed description of the test and results can be found in the SPS article listed at the end of this report. This information will be useful in formulating more accurate trajectory programs for future deep space missions.

PUBLICATIONS

JPL Publications

1. Roselli-Lorenzini, F. G., "Warm Gas Distribution System (WGDS) Breadboard for Compatibility Tests," SPS 37-55, Vol. III, February, 1969.

2. Roselli-Lorenzini, F. G., "Nozzle Thrust at Leakage Flow Rates," SPS 37-57, Vol. III, June, 1969.

3. Ferrera, J. D., McKown, P. M., "A Method for Calculating Steady-State Thrust and Flow-Rate Levels for Mariner IV Type Attitude Control Nitrogen Gas Jets," JPL Technical Report No. 32-1353, December 1, 1969.

TOROIDAL TANK BELLOWS MONOPROPELLANT UNIT

NASA Work Unit 731-13-01-04

JPL 331-30601-2-3840

E. Romvary

OBJECTIVE

To demonstrate an experimental monopropellant (hydrazine) propulsion system incorporating a toroidal tank, bellows expulsion unit, and outer container having length/diameter ratio of approximately 1.0. This unit is to be capable of sterilization, multicycle operation and long-term space storage for periods of up to ten years.

PROGRESS

In-house Activity

In-house activity has consisted of technical management of contracted tasks to design, fabricate, and test toroidal tank bellows propulsion assemblies for purposes of demonstrating the feasibility of this type of integrated expulsion device for a spacecraft propulsion package.

Contracted tasks have been completed. In view of the complex nature of the toroidal unit which involves the combination of pressure vessels, a detail development test specification has been generated. Expulsion testing and long-term storage were initiated during the latter part of June.

Off-lab Activity

Toroidal Tank Expulsion Device for Spacecraft Propulsion Package
Solar Division International Harvester
Contract No. 951940

The off-lab activity has been completed with delivery of two assembled toroidal tank bellows units as stipulated in Contract No. 951940.

Projected Activity

Continuation of testing and long-term storage will continue under work unit number 731-12-42-03-55 (331-10801-0-3840).

PUBLICATIONS

None

REACTION CONTROL GAS SUPPLY SYSTEM

NASA Work Unit 731-13-01-07

JPL 331-30101-0-3840

A. Karbin

OBJECTIVE

The goal of this work unit is to advance technology in attitude control propulsion gas supply systems which will support advanced spacecraft designs. Three types of gas supply systems have been pursued. One is a passive vaporizing liquid ammonia system which does not require an external energy source other than thermal radiation and conduction from the surrounding spacecraft. The ammonia is stored and vaporized on demand for use by the attitude control reaction jets. The second type uses liquid hydrazine which is decomposed by an in-plenum hydrazine (Shell 405) gas generator. The gaseous products are stored in the plenum and used on demand by attitude control reaction jets. The third system requires about 1 watt of electrical power to electrolyze hydrazine into nitrogen and hydrogen gas, which is stored and used on demand by attitude control reaction thrusters.

All three methods of generating attitude control gases offer significant system mass reductions as compared to high-pressure gas storage systems because the propellants are stored as liquids, and low-pressure gases are generated as required.

VAPORIZING AMMONIA SYSTEM

General Electric has concluded their contract (JPL 951895) except for the final report, which they have promised to deliver before the end of this fiscal year. Demonstration of the system, which embodied conversion of liquid ammonia to a superheated state, has been successfully concluded. Briefly the system consists of a single-pass tubular heat exchanger brazed to the exterior surface of an 18-inch ammonia propellant storage tank, with associated valves and fittings. At the conclusion of the testing, the hardware was delivered to JPL for further testing, supplying vapor to a JPL (Division 34) Warm Gas Attitude Control Distribution System. Upon receipt of the ammonia system it was determined that complete replumbing and cleaning was necessary before the system could be used as a source of attitude control gas for the Warm Gas Distribution System. The system has been reworked and preliminary testing is underway. Operation of the system should start before the end of FY 69. (In addition, a flight system based on the subject contract has been fabricated by General Electric and has been sent to GSFC under their contract for testing.)

HYDRAZINE ELECTROLYSIS FOR SPACECRAFT PROPULSION

JPL contract 951720 with Hughes was concluded in the first quarter of FY 69. The electrolysis system successfully generated and stored gases (H_2 and N_2) by the electrolysis of hydrazine. The hardware was developed (and tested) to produce and expel gas in various storage tank attitudes; simulating (to some degree) zero 'g' conditions. The zero 'g' capability will be determined during flight tests of a system developed by Hughes Aircraft for GSFC, based on the results of this contract.

An addendum to the JPL contract 951720 provided for a brief test program to determine if a controllability problem exists. The test program was to demonstrate that the electrolysis cell could operate under conditions off nominal, somewhat behond expected spacecraft temperatures, pressures, current and voltages. It was felt that success at these limits would remove all doubt of the controllability of the hydrazine electrolysis system. The same hardware that was used in the prototype testing was used in the controllability testing. The severe testing at high voltages, current and temperature using the prototype hardware resulted in severe fracturing of the hardwared in the first phase of testing. The causes have not been conclusively ascertained, but engineering opinion has been that a local area within the hydrazine cell became very hot and that arcing may have occurred. It is the author's opinion that if another model were constructed including the newer component designs of the Goddard model, and tested to more reasonable off-nominal conditions, the unit would probably survive.

PLANS

The ammonia vaporizing system will be tested and operated at JPL to supply superheated ammonia gas to the Warm Gas Distribution System. The latter system will be operated in a compressed time mode of approximately 6-1/2 days to simulate a 200-day interplanetary mission.

The in-house hydrazine plenum system at JPL will also be operated and the plenum gases generated and supplied, in a similar compressed time cycle, to the Warm Gas Distribution System.

The General Electric ammonia system final report has been promised, again, for delivery in June 1969 and distribution during the first quarter of FY 70.

The hydrazine electrolysis controllability experiment report has been written, and a rough draft is expected before FY 70.

No plans have been made to continue development of the latter system.

PUBLICATIONS

None

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LIQUID PROPELLANT EXPULSION

NASA Work Unit 731-13-04-02

JPL 331-30401-0-3840

G. A. Yankura

OBJECTIVES

To advance the technology of liquid propellant orientation and management in spacecraft propulsion systems. To understand the problems associated with (1) phase separation in a gas-liquid propellant medium, either earth- or space-storable; and (2) making end use application of metallic and non-matallic phase separators to stablize the separation of two-phase media (gas-liquid) for planetary missions of up to ten years duration.

PROGRESS

1. In-house Activity

a. Storage Testing (Material Compatibility)

The storage test results of ethylene propylene terpolymer (EPT)-8, EPT-10, and butyl in hydrazine (N_2H_4) were as follows. The EPT-8 and EPT-10 test was interrupted after 135 days at 125°F when the retort pressure reached 40 psig. The hydrazine was not discolored, and the surfaces of both specimens were unchanged. The percent weight gain of the EPT-8 was 4. 91 and that of the EPT-10 was 0. 46. The same specimens were given another 328 days exposure before the pressure again reached 40 psig. The hydrazine was not discolored, and the surface of both specimens was unchanged. The percent weight gain of the EPT-8 was now 13. 16 and that of the EPT-10 was 3. 01. The butyl test lasted 547 days at 125°F before the 40 psig condition was attained. The specimen was badly blistered on one surface (apparently a result of salt core mold contamination on that surface), and its shape was greatly distorted due to swelling on the blistered surface.

2. Off-lab Activity (Contractural)

a. Reinforced Stainless Steel Expulsion Diaphragm, Arde, Inc., Contract No. 951898

This contract is for the purposes of demonstrating the propellant compatibility, impermeability, sterilization tolerance, and recycling ability of stainless steel expulsion tank hardware of flight weight configuration.

Status. Two 18-inch-diameter ARDEFORM tanks and wire reinforced, constrained-to-rolling, reversing metal diaphragm assemblies have been received. Each assembly weighs 16.6 lb. The tanks will be subjected at ETS to the storage of N_2O_4 and MMH at 300 psig. The storage facility will be capable of sampling the propellant and pressurant without interrupting the storage test.

The purchase of two additional tank and diaphragm assemblies from Arde, Inc. has been negotiated. These will differ slightly from the former tank in the girth ring design in order to eliminate CRES 301 material from the final girth ring to diaphragm weld, which cannot be solution annealed. These tanks will be subjected to the storage of OF_2 and B_2H_6 propellants at -230°F.

b. Development and Approval of Ethylene Propylene Rubber Compounds for Flight Acceptability, Accessory Products, Contract No. 951939

The purposes of this contract are to (1) evolve an ethylene propylene rubber compound acceptable for long-term space storage with hydrazine (the compounding formula is to be available to the Government so that proper quality controls can be identified), and (2) prove the fabricability of this compound for one-piece molded bladders of Mariner '69 design.

Status. Although several bladders have been molded from the EPT-8 and EPT-10 materials, some problems still exist. The difficulties are encountered in removing the baldders from the molding die. No satisfactory mold release has yet been found to permit consistently removal of the molded bladder from the die without tearing. Two reasons are apparent: (1) the non-carbon-bearing EP rubbers have low hot strength, and (2) they seem to have a greater tendency to adhere or vulcanize to the metal surface. A search for an adequate mold release continues. Also, attempts to etch out the mandrel have been unsuccessful. The etchant attacks the EPT severely when on the mandrel. Samples of EPT separated from the mandrel are only mildly affected.

Two EPT-10 bladders with the mandrels etched out and two with the bladders still in place have been delivered. The suitability of these four items relative to continuing evaluation tests with hydrazine will be determined during July, 1969.

PUBLICATIONS

Contractor Reports

(1) Arde, Inc., Interim and Final Report, "Development of Gold Brazing Technique and Design and Supply of 18" Diameter Positive Expulsion Tank Assembly," Report No. 56001-2, February 1969.

LIQUID PROPULSION TEST METHODS, EQUIPMENT, SAFETY, AND SUPPORT (731-14)

ADVANCED TECHNOLOGY CONTRACT MANAGEMENT FOR RPX

NASA Work Unit 731-14-01-03

JPL 331-40201-2-3840

C. R. Foster

OBJECTIVE

The purpose of advanced technology contracts is to advance the engineering development of liquid propulsion systems through contracts to industrial aerospace firms.

APPROACH

Under the above work unit, JPL engineers, experienced in the liquid propulsion field, provide the technical management of some of these advanced technology contracts. These advanced technology contract management tasks are supplementary to the normal in-house assignments of these engineers on research, advanced development, or flight projects.

In general, the work consists of visits to the contractor's plant for technical information and direction, review of monthly progress reports, and quarterly reviews of progress at the contractor's plant. In addition, the engineer participates in planning and recommending new work, prepares the statement of work for proposed new (or continuing) advanced technology contracts, provides technical evaluation of proposals received, and gives technical review and approval to the final reports which are submitted by the contractor. On a semi-annual basis, the engineer submits an informal report to the NASA Headquarters Project Manager to give his technical judgement on the status of the contractor's effort and results.

PROGRESS

Four Advanced Technology contracts in liquid propulsion engineering development have been in effect during the second half of FY '69 that were technically managed by engineers in the Liquid Propulsion Section (384) of JPL.

It is expected that technical management of advanced technology contracts will continue at approximately the same level of effort during the first half of FY '70.

PUBLICATIONS

None

OPTIMIZATION CRITERIA FOR SPACECRAFT PROPULSION

NASA Work Unit 731-14-01-05

JPL 331-40102-2-3850

J. R. Wrobel

OBJECTIVE

The objective of this work unit is to consolidate the propulsion subsystem optimization analyses conducted under Contract NAS 7-519. These analytical techniques are to be directed to rapid planning use for planetary spacecraft studies.

STATUS

No effort was expended on this work unit in the past period because of lack of manpower.

PUBLICATIONS

None

SOLID SPACE PROPULSION SYSTEMS (731-26)

MOTOR CONTROL TECHNOLOGY

NASA Work Unit 731-26-02-02

JPL 331-60101-2-3810

L. Strand

OBJECTIVE

The objectives of this study are to: (1) determine the optimum method of water injection to obtain extinguishment, (2) better understand the quench mechanism so that it may be optimized, (3) establish means for predicting water requirements of any given motor, and (4) determine feasibility and performance of water extinguishment of flight motors.

PROGRESS

The window motor quench tests with high-speed motion picture coverage were completed. Nine motor firings were carried out during the report period with successful quench occurring in five of the tests. The five successful tests consisted of the following:

(1) Two tests using the overhead water injector system with motor pressure and water injection rates of approximately 95 psia and 1 lb/sec respectively. The ratio of water injection rate to the calculated propellant gasification rate was approximately 5.5. Solid stream and flat spray water injections were used.

(2) Two tests using the overhead injector system with motor pressure and water injection rates of approximately 260 psia and 2 lb/sec respectively. The ratio of water injection and calculated propellant gasification rates was approximately 6. Flat spray and solid cone water injectors were used.

(3) One sheet injector motor fired at a motor pressure of 150 psia and an injection rate of approximately 2-1/2 lbs/sec.

A camera field of view of approximately 2 inches square yielded some details of the quench process.

Briefly summarizing the results:

(1) In general, the injector spray pattern used in the overhead injector system did not produce a detectable effect on either the quantity of water injected up to complete quench or the rapidity of the quench.

(2) At a constant chamber pressure, increasing the rate of water injection decreased the quantity of water required to produce a quench and increased the rapidity of the quench.

(3) With approximately equal injection to propellant gasification rate ratios, roughly equal quantities of water were injected up to complete quench at the two motor chamber pressures tested, i. e., the ratio correlated the data for these few tests.

(4) The success of the sheet injector demonstrated that, at least for this motor, the chamber gases do not have to be cooled to attain extinguishment.

(5) The motion picture data showed quenching of combustion (darkening of combustion zone above propellant surface) to be coincident with the advancing of the water interface over the propellant surface. Simple thermal quenching of the propellant combustion zone and continued cooling of the surface until the hot chamber gases have been exhausted seems to be a reasonable model for describing the extinguishment characteristics.

During the report period, it became obvious that one of the program objectives, a determination of the optimum method of water injection to obtain extinguishment, could not be determined from the tests. It was decided that, in order to determine any possible differences between the different injector systems, a series of go, no-go type tests was required using more carefully controlled injected water quantities and injection rates than were possible with the existing test system. The test plan has been amended to include such a series. The test system has been modified and is in the process of being checked out. The AC solenoid valve has been replaced with two DC Annin valves, one normally closed and one normally open. Actuation of the valves is controlled by two digital counters. To reduce the water pressure drop during injection, the 5-gal accumulator has been re-installed. The quantity of water injected is controlled by the water pressure and the time interval between actuation of the valves. The results of initial checkout tests have been encouraging.

The laboratory motor phase of the test program will be completed during the next report period, and equipment buildup for the Phase 2 motor tests should be initiated.

PUBLICATIONS

JPL Publications

Strand, L. D., "Solid Propellant Rocket Motor Command Termination by Water Injection," SPS 37-55, Vol. III, February 28, 1969.

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SPACECRAFT MOTOR TECHNOLOGY

NASA Work Unit 731-26-05-09

JPL 331-60401-2-3810

J. I. Shafer

OBJECTIVE

The objective of this work unit is to demonstrate feasibility and assess approximate performance level of long-burning-time, low-thrust retro rockets and propulsion systems.

PROGRESS

The effort was reoriented so that test results would be more applicable to the VIKING '73 orbit insertion propulsion requirements. Work on the case-bonded end-burning motor now includes development efforts using 60-lb sub-scale flight-weight motors salvaged from the successful Syncom program and a demonstration phase using 780-lb scaled-up motors salvaged from the successful ATS program. All work in this period used the well-established polyurethane propellant, JPL540, but future efforts will use the new lower burning rate Saturethane propellant.

During the previous reporting period (Ref. 1) 60-lb case-bonded end-burning motors, without mechanical stress relief, had been pressure tested in simulated static firings over the temperature range of 165° to -65° F without producing propellant failure or motor flaws as revealed by x-ray or visual inspection. After storage at ambient temperature for eight months to allow propellant stress relaxation of the induced compression stresses, one of those motors has now been subjected to the same pressurization program over the same temperature range. It is reassuring that x-ray and visual inspection again revealed no motor flaws.

Two static test firings with sub-scale 60-pound motors and one firing with the large 780-pound case-bonded end-burning motor were made. See Table 1 for some motor characteristics, Table 2 for static firing results, and Figure 1 for a cross section of the 780-lb Long Burning Time Motor Assembly.

Table 1 - Characteristics of Cast-In Fully Case-Bonded End-Burning Motors

	60 lb. (P-78)	60 lb. (P-45)	60 lb. (T-10)
MOTOR PROPELLANT			
Cure temperature (°F)	140	140	140
Cure type zone cure	Zone cure	Zone cure	Zone cure
Cure pressure (psi)	175	175	175
Maximum tensile strength (psi)	75	147	126
Elongation at maximum stress (%)	139	85	129
Propellant weight (lbs)	56.82	56.58	778
CHAMBER			
Type	410 chrome steel	410 chrome steel	6Al 4Va Titanium
Proof Pressure (psi)	290	290	225
Length (in)	12.8	12.8	28.8
Diameter (in)	12.06	12.06	28.1
Weight	3.84	3.92	24.4
INSULATION (NBR GEN-GARD V-52)			
Thickness (in)	0.40 to 0.20	0.40 to 0.20	0.40 to 0.10
Weight (lb)	7.23	7.03	37.4
NOZZLE (SUBMERGED; CARBON AND SILICA CLOTHS)			
Expansion ratio	15.5	14.1	11.0
Throat diameter (in)	1.303	1.484	3.546
Weight (lbs)	4.73	5.08	23.0

Table 2 - Static Firing Results
Of Cast-In Case-Bonded End-Burning Motors

	60 lb. SYNCOM[a] (REFERENCE)	60 lb. (P-78)	60 lb. (P-45)	760 lb. ATS[a] (REFERENCE)	789 lb. (EB-1) (END BURNER)
Motor Temperature (°F)	60	60	60	60	60
Type of Test	Horizontal	Horizontal	Horizontal	Horizontal Spin	Vertical
Action Time (sec.)	19.55	39.4	48.2	42.5	110.0
Mean Effective Pressure (psia)	197	178	101	205	110
Maximum Pressure (psia)	258	197	118	260	136
Propellant C* (ft/sec) [b]	4918	4915	4827	4969	4958
Average $\dot{m}$ (lb/sec)	3.1	1.44	1.2	18.1	7.1
Change in Throat Area (%)	0.5 to 1.5	1.5	2.0	1.5	0.3
Inert Weight Exhausted (lb)	0.5	0.72	0.79	9.0	12.5
Weight of Al_2O_3 SLAG (lb)	Trace	0.043	0.29	Trace	Trace

(a) From motor qualification data.

(b) Based on loaded propellant weight and average throat area.

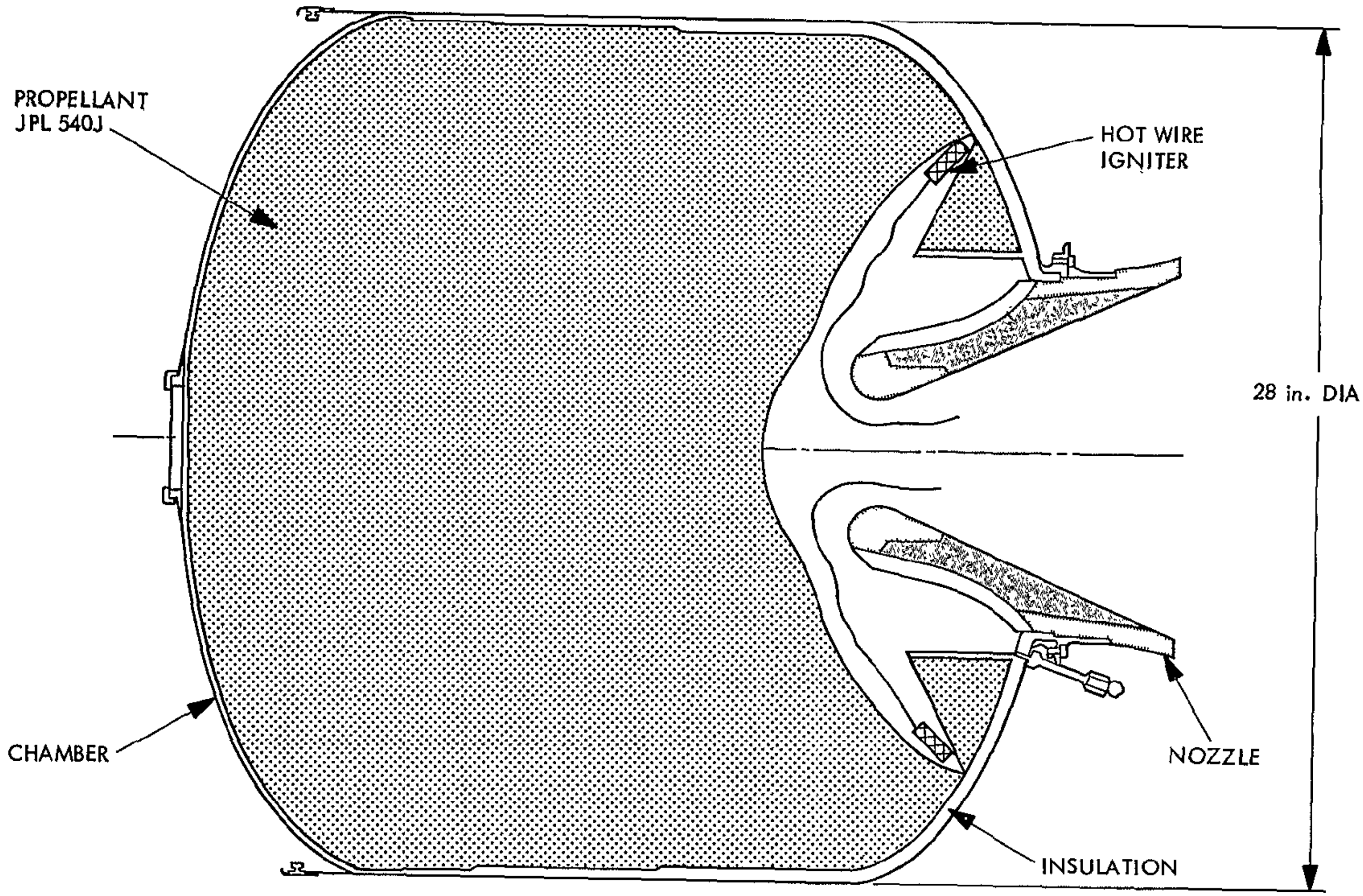

Figure 1. Long Burning Time 780-lb Motor Assembly

These test results were very gratifying; with the firing of these units, it is believed that fully case-bonded end-burning motors in both the 60- and 800-pound class have been demonstrated as feasible.

The presence of a significant amount of the aluminum oxide slag after the firing of the 60-pound motor P45, the precurser for the large 780-pound demonstration motor firing, prompted the change from a horizontal to a vertical firing in the large motor test in order to minimize the likelihood of a chamber burn-through. If subsequent testing reveals the slag is a serious problem, it may prove desirable to change from a submerged to an external nozzle design.

The fact that the propellant characteristic velocity, c*, changed only slightly with creasing pressure is particularly gratifying and warrants further investigation for future spacecraft motor applications requiring high performance through high mass fraction.

Efforts to incorporate the new lower-burning Saturethane propellant into motors for test were slowed when the new lot of Telagen prepolymer produced poorer propellant mechanical properties. Receipt of a new lot of prepolymer has relieved the situation somewhat so that three 60-lb case-bonded end-burning motors with Saturethane have now been cast. If they pass through the critical cool-down-from-cure successfully, the first will be fired at ambient temperature and pressure as a qualification round. The second and third would then be fired at simulated altitude in the TAPR facility at the Air Force Rocket Propulsion Laboratory in order to obtain a measured vacuum specific impulse at about 140 to 85 psia pressure respectively.

Preparations for the testing of 3 fibrous graphite (Carbitex) nozzles being fabricated by the Carborundum Co. under contract NAS7-695 have been started. The bonding of strain gages to Carbitex, the design and fabrication of spring loaded thermocouples, procurement and familiarization with the use of a recording optical pyrometer, and the development of a satisfactory hot seal for the nozzle's threaded joint have all been initiated in preparation for firing in late August or September.

REFERENCES

Semiannual Review of Research and Advanced Development. Document 701-23, Vol. II, Feb. 15, 1969. Jet Propulsion Laboratory, Pasadena, California.

PUBLICATIONS

Meeting and Symposia Papers

Shafer, J. I., "Long-Burning-Time Motors for High Incremental-Velocity Maneuvers at Low Acceleration" 4th ICRPG Solid Propulsion Conference held May 20-22, 1969 at Chicago.

JPL Publications

Shafer, J. I., "Solid Propellant Spacecraft Motors," SPS 37-55, Vol. III pp. 185-92, Feb. 28, 1969.

SOLID AUXILIARY PROPULSION SYSTEMS (731-27)

ELECTRO-EXPLOSIVES TECHNOLOGY ADVANCEMENT

NASA Work Unit 731-27-02-01

JPL 331-70101-2-3810

V. J. Menichelli

OBJECTIVE

The objective of this program is to ensure that technologies are available to allow design, fabrication and test of any reliable explosively-actuated device which might reasonably be needed for a spacecraft application.

PROGRESS

During this report period there has been a change in personnel actively engaged on this work unit. The change resulted in a fall-off of effort. However, activity was applied to utilizing technologies fostered earlier under this work unit. Specifically, efforts have been expended in the procurement of squibs for Mariner '71. The squib design is basically an outgrowth of the development carried out by Atlas Chemical Industries for JPL on contract 951912. Because of the technologies advanced during the performance of the above contract, a non-proprietary squib, incorporating features such as non-magnetic, dual bridge, insensitive to static spark discharge and RF, non-conductive ignition mixtures, and capable of containing pressures greater than 40K psi is being procured for Mariner '71. Complete disclosure of the squib (which is fabricated in three different thread sizes) is now on JPL documentation.

This work unit is being phased out as of the end of this report period.

PUBLICATIONS

Contractor Reports

J. A. Barrett, "Design and Fabrication of Four Pin High Pressure Squib, Final Report," Atlas Chemical Industries, November 22, 1968, Contract #951912.

SOLID PROPULSION, TEST METHODS, EQUIPMENT, SAFETY, AND SUPPORT (731-28)

RESEARCH PROGRAM SRT (129)

FLUID PHYSICS RESEARCH (129-01)

BOUNDARY LAYER TRANSITION STUDIES

NASA Work Unit 129-01-04-03

JPL 329-10901-0-3280

J. M. Kendall, Jr.
L. M. Mack

OBJECTIVE

The objective of this work unit is to explore the relationship between stability and transition in order to identify the source of boundary layer disturbances present in supersonic tunnels.

PROGRESS

Supersonic Tunnel Experiments - J. M. Kendall, Jr.

Experimental work during the report period was principally concerned with a supersonic tunnel test program. Excellent progress was made. No tunnel operational problems were encountered, and tunnel costs were somewhat lower than anticipated.

All testing was conducted at Mach 4.5 in the unit Reynolds number range 50,000 to 200,000/inch. The measurements consisted of one-dimensional spectra of fluctuations in the boundary layer and free stream, two-anemometer correlations as a function of lateral spacing (the Fourier transform of which will yield the wave spectrum in the lateral direction and hence the two-dimensional spectrum), the x-growth of fluctuation energy for various frequency waves, and included were some studies of the effect of leading edge bluntness on fluctuation growth.

Although data analysis is incomplete (much of the data being on tape recordings), the following have been determined: (1) Fluctuations in the boundary layer of all wave lengths exhibit monotonic, streamwise growth in amplitude from a small value near the leading edge to a large value preceding transition. Apparently, the forcing of the boundary layer by the tunnel sound waves overcomes any damping expected from stability considerations. (2) The one-dimensional spectrum of fluctuations in the layer closely resembles that in the free stream.

(3) Although no transforms have yet been computed, the waves in the boundary layer are mostly oblique. The fluctuation correlation falls to zero for a lateral separation distance on the order of 2 or 3 boundary layer thicknesses.
(4) Small amounts of leading edge blunting (0.010 inch) produce vast changes in the fluctuation x-growth rate for all but the lowest frequency waves.

In continuation, we will: (1) attempt to clarify the mechanism of energy transfer from sound waves to boundary layers by studying the susceptibility of the layer to polarized sound waves of various orientations; (2) repeat the one- and two-dimensional spectral measurements at a lower Mach number where sound probably plays a less decisive role; (3) measure mean boundary layer profiles and the changes resulting from leading-edge blunting in order to understand the astonishing effectiveness of that parameter in controlling fluctuation growth; and (4) extend the relevant measurements into the transition zone.

Theoretical - L. M. Mack

A new class of neutral solutions of the inviscid stability equations has been discovered. Previously know neutral solutions with a phase velocity c_r that is subsonic with respect to the free stream velocity were (1) those connected with the point η_s where $(U'/T)' = 0$, and (2) those with $c_r = 1$. The latter solutions were poorly understood, but did serve as "end points" for the higher mode amplified solutions. It has now been determined that there is a whole class of neutral solutions with $1 \leq c_r \leq 1 + 1/M_1$, and the $c_r = 1$ solutions belong to this class. The upper limit of c_r is a second neutral sonic solution (M_1 is free-stream Mach number). These solutions have no critical point ($U = c_r$) and so are regular. Provided there is a region in the boundary layer of supersonic flow relative to the phase velocity, which is the case for almost all supersonic Mach numbers, these solutions are multiple; i.e., there is an infinite sequence of wave numbers for each c_r. The neutral sonic solution $c_r = 1 + 1/M_1$ also has multiple wave numbers, including $\alpha = 0$, in contrast to the previously known neutral sonic solution with $c_r = 1 - 1/M_1$ which has only the single wave number $\alpha = 0$. There are no amplified or damped solutions with $1 \leq c_r \leq 1 + 1/M_1$, and there appear to be no solutions of any type with $c_r > 1 + 1/M_1$.

There are viscous counterparts of the regular neutral solutions which are damped, but for the same phase velocities have nearly the same wave numbers as the corresponding inviscid solutions. Such solutions have been computed at $M_1 = 3.8$. These solutions are important in the viscous theory because they permit the unstable second-mode disturbances to be excited from the leading edge in cases of extreme cooling. Previously, it was thought that such disturbances could be excited only from a position well downstream of the leading edge.

A preliminary version of a complete account of boundary-layer stability theory has been published. Some additional calculations were carried out for this volume and were mainly related to the behavior of the most-unstable three-dimensional disturbances at finite Reynolds numbers. The final version is now in preparation. For this purpose, some former calculations of disturbance amplitudes as functions of Reynolds number have been redone using the group velocity instead of the phase velocity to transform temporal to spatial amplification rates.

PUBLICATIONS

JPL Publications

1. Kendall, J. M., Jr., "Turbulent Boundary Layer on a Wavy Wall," JPL SPS No. 37-56, Vol. III, 1969.
2. Mack, L. M., "Boundary-Layer Stability Theory," JPL Document No. 900-277, May, 1969.
3. Mack, L. M., "A Class of Regular Neutral Solutions in the Inviscid Stability Theory," JPL SPS No. 37-56, Vol. III, 1969.
4. Mack, L. M., "Linear Stability Theory and the Unit Reynolds Number Effect on Boundary-Layer Transition," JPL SPS No. 37-56, Vol. III, 1969.

HEAT TRANSFER FROM ACCELERATING AND DECELERATING IONIZED GAS FLOWS

NASA Work Unit 129-01-05-10

JPL 329-10701-0-3830

P. F. Massier

OBJECTIVE

The general objective of this task is to experimentally and theoretically investigate fundamental heat transfer and fluid dynamic phenomena of high-temperature gas and plasma flows. Included is the evaluation of the influence of ionization, large property variations, swirl, acceleration and deceleration on convective heat transfer and fluid dynamics. The motivation for this investigation resulted from the high heat transfer rates that can occur to some of the elements of electrical propulsion devices. The fraction of the total energy of the gas that is transferred to the coolant in such devices can be significantly higher than that encountered in chemical propulsion thrust chambers.

The first objective for FY 69 was to complete the computer programming of a theoretical investigation of heat transfer from non-adiabatic core flows not including ionization, radial pressure gradients or swirl and compare the results with experimental data.

A second objective for FY 69 was to continue the experimental investigation, initiated previously, of heat transfer from high-temperature, weakly ionized, swirling flows. Swirl has commonly been introduced into arc-heated flows to help stabilize the arcs, and sufficient experimental evidence exists which indicates that convective heat transfer from such flows is generally higher than from non-swirling flows.

PROGRESS

Non-Adiabatic Core Flow Analysis

A method for predicting convective heat transfer from an internal laminar flow that has a non-adiabatic core has been formulated, and some solutions have now been obtained on a computer. The analysis includes the effects of flow acceleration and is applicable to variable area, axisymmetric channels. Other features of the analysis were discussed in more detail in a previous Progress Report, TM 33-322, Vol. II.

The computer program has been modified to incorporate a variable size mesh in the radial direction. A finer mesh is needed near the wall so that the heat transfer may be calculated with sufficient accuracy since it is evaluated from the radial gradient of the enthalpy. Comparisons with experimental data have been made for flow in a tube by establishing the starting condition using the boundary layer theory of Ref. 1. In the region where the boundary layer thickness has penetrated to the centerline, agreement with the experimental data is better than when the higher predicted values of the boundary layer theory are used throughout the tube. Calculations using a fixed radial mesh size and including computations through the sonic condition have also been performed throughout a supersonic nozzle. The predicted velocity and enthalpy distributions are poor near the wall so that the heat transfer cannot be calculated; however, the variable radial increment solution with a smaller increment near the wall is now being investigated. The computer program is in the final stages of modification; thus, additional solutions will soon be available so that comparisons with experimental data can be finalized and the non-adiabatic core investigation completed. The experiments both in tubes and nozzles have already been completed.

Swirling Flows

The swirling flow investigation has been discontinued because of insufficient resources and the experimental information that has been obtained is being evaluated so that the results can be reported.

The theoretical investigation of boundary layers with swirl which was previously submitted for publication in the AIAA Journal has now been accepted.

REFERENCES

1. Back, L. H., "Effects of Severe Surface Cooling and Heating on the Structure of Low-Speed, Laminar Boundary Layer Gas Flows with Constant Free-Stream Velocity," presented at the AIChE-ASME Heat Transfer Conference and Exhibit, Philadelphia, Pennsylvania, August 11-14, 1968, ASME Paper 68-H-23.

ANTICIPATED PUBLICATIONS

1. Back, L. H., "Flow and Heat Transfer in Laminar Boundary Layers with Swirl."

PUBLICATIONS

None

PLASMA HEAT TRANSFER WITH APPLIED MAGNETIC AND ELECTRIC FIELDS

NASA Work Unit 129-01-05-11

JPL 329-10601-0-3830

P. F. Massier

OBJECTIVE

The general objective of this task is to investigate the effects of applied electric and magnetic fields on the heat transfer and fluid dynamics of partially ionized gas flows. The regions of investigation include subsonic and supersonic internal laminar flows. Experimental information of this nature is not readily available but is important in the prediction of electrode heat transfer in electrical propulsion devices and power generators. In such devices, anode heat transfer may be very high and can easily cause failure by burnout.

Experimental measurements have been completed on the effects of an applied, transverse magnetic field upon heat transfer from partially ionized argon in a square channel, and a report is being prepared. A series of experiments is under way to determine the blowing effect and electrode heat transfer for cross flow between segmented, parallel-plate electrodes. A non-equilibrium analysis of electrode heat transfer has been completed.

PROGRESS

Experiments on Channel Flow with a Transverse Magnetic Field

The experimental work and the data analysis of the magnetic field experiments have essentially been completed, and a final report is in preparation. The apparatus and method of acquiring data for heat transfer experiments using partially ionized argon flowing in a 2 x 2 in. square channel have been described in SPS 37-51, Vol. III, pp. 130-135. Data has been acquired for two directions of the transverse magnetic field for laminar flow with and without a swirl component; in most cases, the flow was subsonic. Large changes in heat transfer due to the applied magnetic field have been observed to walls perpendicular to the direction of the field, and these changes in heat transfer are believed to result from current flow in the gas.

Electrode Boundary Layer Analysis

A theoretical investigation to determine heat transfer rates to electrodes in the presence of an electric field has been brought to a conclusion. The analysis is presumed the existence of a pre-ionized, two temperature plasma. A singly-ionized, quasi-neutral plasma is assumed in which the properties are variable and the flow is laminar. It is shown that the total heat flux to the wall consists of the convective heat flux (which can be computed from Nusselt's relations) plus additional terms representing energy loss or gain at the sheath edge near the surface. A sheath analysis is presented and expressions for the energy loss or gain terms are then obtained for special cases of a cathode, an anode, and other surfaces. Consideration of a simple geometrical model shows the importance of different non-dimensionalized parameters.

A more restrictive boundary-layer type flow, based on the more general analysis in which the deflection of the discharge caused by the "blowing effect" is neglected, gave heat transfer relations for flow over a flat plate. It also gave heat transfer relations for flow in the stagnation region of an axisymmetric body when the body surface is positive with respect to the plasma (anode heat transfer). The temperature gradient of the heavy particles is independent of the current density. It is shown that the elevated electron temperature has a negligible effect on the convective heat transfer, but is significant for the overall heat transfer due to the energy transport by the current. By an approximate analysis, an equation is derived for the heat transfer to the anode. Additional details of the analysis are given in Refs. 1 and 2.

The present work is being extended to incorporate the "blowing effect" of the electric discharge caused by the transverse motion of the gas stream. The extended analysis involves the solution of three dimensional elliptic type equations for the inviscid flow field, where the boundary conditions are given on all sides.

Electrode Heat Transfer Experiments

The configuration of the two parallel flat-plate electrodes, consisting of sixteen pairs of insulated segments which were described in the last progress report (R and D Program Document 701-23, Vol. II), has been modified. Preliminary experiments indicated that the discharge in the vicinity of the flat cathodes was not sufficiently stable to acquire good heat transfer data. Furthermore, the erosion rate was excessive, and the heat transfer exceeded that at the anodes. The thin-wall, thoriated tungsten plates were replaced by thoriated tungsten rods that have rounded ends which form the terminal of the discharge. The coolant passages are now approximately 2 in. from the ends; whereas, for the flat plate segments the cooled surface was only 0.10 in. from the gas-side surface.

Some tests have been conducted with the modified arrangement, and the data are presently being evaluated. Since the cathodes now form a bumpy surface for the gas stream, the emphasis is confined primarily to the anodes which still have flat surfaces and hence correspond more closely to restrictive configuration limitations of theoretical boundary layer predictions which will be made subsequently.

ANTICIPATED PUBLICATIONS

1. Bose, T. K., "Laminar Flow Heat Transfer from a Gaseous Plasma at Elevated Electron Temperature in the Presence of Electromagnetic Fields," in preparation as a JPL Technical Report.
2. Bose, T. K., "Anode Heat Transfer for a Flowing Argon Plasma at Elevated Electron Temperature," in preparation.

PUBLICATIONS

JPL Publications

1. Roschke, E. J., "Laminar Heat Transfer in a Square Channel," SPS No. 37-55, Vol. III, pp. 213-217, Feb. 28, 1969.
2. Roschke, E. J., "Observations on Flow Attachment in a Square Channel," SPS No. 37-55, Vol. III, pp. 217-220, Feb. 28, 1969.

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HEAT TRANSFER AND FLUID DYNAMICS IN ACCELERATING FLOWS

NASA Work Unit 129-01-05-12

JPL 329-10401-0-3830

P. F. Massier

OBJECTIVE

The general objective of this task is to investigate experimentally the structure of supersonic and subsonic, accelerating and decelerating, internal flows and the convective heat transfer from these flows. During FY 69 the intended emphasis was to be placed on three supersonic flow regimes:

(1) single shock boundary layer interaction

(2) flow between an oblique shock wave and a surface

(3) compression by multiple shock waves (referred to as pseudo shocks).

APPROACH

Both boundary layer and heat transfer measurements have been made in the oblique-shock flow regimes which will provide information related to hypersonic inlet research for air-breathing propulsion engines. These studies of heated air with turbulent boundary layers are being conducted within the range of Reynolds numbers and stagnation temperatures found in hypersonic inlets at a Mach number of 3.5. Because of a reduction in available resources, it was necessary to reduce the scope of the program. Heated air measurements were obtained only at one stagnation temperature, and the boundary measurements originally planned for in the pseudo shock region were not made.

Compressed air flowed through an axisymmetric upstream duct, a nozzle, and then through the diffuser where the measurements were made. The flow negotiated a 16° compressive turning near the diffuser inlet where an oblique shock was generated. Reflections occurred farther downstream. The flow then passed through the pseudo-shock structure and discharged into the atmosphere. Heat transfer to the cooled walls was determined by calorimetry; temperature and velocity distributions in the boundary layer and internal flows were determined from probe measurements; and static pressures were measured along the wall. Several tests have been conducted in which heat transfer measurements have been made to determine the longitudinal heat flux distribution. The gas stagnation pressure ranged from 80 to 150 psia, and the stagnation temperature of the heated air was 1500°R.

PROGRESS

Single Shock-Wave Boundary-Layer Interaction — Results

The rise in the heat transfer, where the shock was incident on the wall, agrees well with the empirical dependence of the heat transfer on the 0.8 power of the static pressure rise noted by other investigators for oblique shock reflections from turbulent boundary layers on a flat plate over a Mach number range from 2.4 to 10.

Probe measurements were made with small pitot and thermocouple probes at two locations upstream and two locations downstream of a shock boundary layer interaction for both unheated and heated air flow. The pitot probe was 0.005 in. high and the shielded aspirating thermocouple probe was 0.010 in. high. Two more sets of probe measurements were obtained for unheated air flow still farther downstream after the shock reflected from the centerline.

The boundary layers are typical of compressible turbulent flow upstream of the shock boundary layer interaction. The thermal boundary layers upstream and downstream of the interaction were similar. Downstream of the interaction the boundary layers are thinner and remain turbulent. The measurements extended from the sublayer near the wall to the centerline.

Additional boundary-layer measurements in the vicinity of the interaction will be made. Acquisition of these data has been delayed for approximately one month because of a bearing failure that occurred in one of the air compressors.

Flow Between an Oblique Shock Wave and a Surface - Results

Flow conditions along the convergent section of the diffuser are somewhat similar to those found along the initial portion of a spiked compression surface of a hypersonic inlet. In either case, the pressure decreases along the surface but for different reasons. In the inlet, the pressure decreases initially because of the leading edge interaction between the bow shock wave and the boundary layer, while in our studies the pressure decreases because of further expansion of the nozzle flow before being compressed by the oblique shock wave emanating from the diffuser inlet. Our heat transfer measurements indicate a decrease in heat transfer along this inlet surface.

A paper describing earlier studies of the flow and heat transfer in the inlet region of a nozzle with 45° conical convergent section was published in the International Journal of Heat and Mass Transfer.

PUBLICATIONS

Journal Articles

1. Back, L. H., Massier, P. F., and Cuffel, R. F., "Flow and Heat Transfer Measurements in Subsonic Air Flow Through a Curved Contraction Section," International Journal of Heat and Mass Transfer, Vol. 12, No. 1, January 1969, pp 1-13.

ELECTRO PHYSICS RESEARCH (129-02)

PHOTOCHEMISTRY

NASA Work Unit 129-02-01-04
JPL 329-21001-1-3280
W. B. DeMore

OBJECTIVE

The objective of this program is to contribute fundamental information on the photochemistry of gases which are present in planetary atmospheres. Current emphasis is in the area of photo-oxidation of hydrocarbons, a topic which is of particular significance to photochemical air pollution.

PROGRESS

Chemistry of Carbon Trioxide

We have shown in previous work that CO_3 is formed efficiently by the reaction of $O(^1D)$ with CO_2 in liquid carbon dioxide at about -45°C.

$$O(^1D) + CO_2 \rightleftarrows CO_3^* \overset{+M}{\rightleftarrows} CO_3 + M$$

We have now studied the $O(^1D)$-CO_2 reaction at pressures up to 20 atm., at room temperature, and CO_3 formation has not been observed under these conditions. The rate of $O(^3P)$ formation by this reaction has been found to be equal to the rate of CO_3 formation in the liquid, with both rates being measured relative to the reaction of $O(^1D)$ with propane. This result substantiates our suggestion that CO_3^* is invariably an intermediate in the electronic deactivation of $O(^1D)$ by CO_2.

Further experiments are in progress, using new apparatus which will permit operation at pressures up to 150 atm and at reduced temperatures.

The quenching efficiency of O_2 in the reaction $O(^1D) + O_2 \rightarrow O(^3P) + O_2$ has been a subject of controversy in the recent literature. To resolve this problem, we have measured the relative O_2 quenching efficiency by a technique employing the recently-acquired 40 meter infrared spectrometer. The method is based on the fact that $O(^1D)$ reacts rapidly with N_2O to give oxides of N_2, whereas $O(^3P)$ does not. In the presence of O_3, the nitrogen oxides are converted to N_2O_5, which can be monitored by its infrared absorption. The results show that the quenching efficiency of O_2 is equal to that of N_2, as was earlier predicted by us on semi-theoretical grounds (W. B. DeMore and O. F. Raper, The Astrophysical Journal, Vol. 139, p. 1381, 1964).

We have also measured $O(^1D)$ quenching efficiencies of various gases by a new technique which is capable of determining the relative steady-state $O(^1D)/O(^3P)$ ratio in a given photolysis mixture. The results of these measurements, together with earlier liquid-phase results, are shown in Figure 1 and are compared with results from other laboratories.

Oxidation of Carbon Monoxide

Early work in this laboratory (SPS 37-21, Vol. IV, p. 240) led to the conclusion that the reaction

$$O(^1D) + CO + M \rightarrow CO_2 + M$$

was inefficient in the gas phase and that the actual reaction is electronic quenching of $O(^1D)$:

$$O(^1D) + CO \rightarrow O(^3P) + CO$$

However, recent reports from other laboratories have stated that in fact CO_2 is formed at almost every collision in the $O(^1D)$-CO reaction. In view of the importance of this reaction in the chemistry of planetary atmospheres, we have conducted further experiments to resolve the discrepancy. The experiments have involved comparison of the rate of O_2 photolysis in gaseous CO with the rate of photolysis in other gas mixtures. The results show that no CO_2 is formed in the $O(^1D)$-CO reaction, even at CO pressures up to 20 atm, and confirm our previous conclusion that electronic quenching of $O(^1D)$ is the only outcome of this reaction.

Gas	Relative Rates					
	Yamazaki & Cvetanovic	Preston & Cvetanovic	Young, Black & Slanger	Snelling & Bair	Warneck & Sullivan	This Project
SF_6	0	0	---	---	---	0.00
N_2	0.26	0.24	0.22	0.29	0.067	0.22
O_2	---	---	0.17	0.005(?)	0.14	0.22
CO	---	---	0.22	---	---	0.22
He	0.02	---	---	---	---	0.00
Ne	---	---	---	---	---	0.01
Ar	---	0.01	---	0.001	---	0.02
Kr	0.09	0.06	---	---	---	---
Xe	0.82	0.78	---	0.78	---	---
CO_2	1.00	1.00	1.00	---	1.00	1.00
H_2	---	---	0.83	---	---	0.69
CH_4	---	---	0.96	---	---	0.81
C_2H_6	---	---	---	---	---	1.3
C_2F_4	---	---	---	---	---	1.1
C_3H_8	1.74	4.67	---	---	---	1.7
C_2H_4	---	---	---	---	---	1.8
$i\text{-}C_4H_{10}$	---	---	---	---	---	2.1
N_2O	2.4	1.02	0.78	---	1.86	---
NO_2	---	1.67	---	---	---	---
NO	---	---	0.65	---	---	---
O_3	---	---	---	4.5	2.23	3.0

Figure 1. Results on $O(^1D)$ Reaction and Deactivation

PUBLICATIONS

Meeting and Symposia Papers

1. DeMore, W. B., "Role of CO_3 in the Photolysis of O_3-CO_2 Mixtures," 157th National Meeting of the American Chemical Society, Minneapolis, Minnesota, April 13-18, 1969.

2. DeMore, W. B. "Recent Developments in the Chemistry of Singlet Atomic Oxygen," seminar presented at the University of California, Irvine, April 25, 1969.

Journal Articles

1. DeMore, W. B., "Reactions of $O(^1D)$ with Hydrocarbons in Liquid Argon," J. Phys. Chem. 73, 391 (1969).

2. DeMore, W. B., "Arrhenius Constants for the Reactions of Ozone with Ethylene and Acetylene," J. Chem. Kin. 1, 209 (1965).

THERMIONICS RESEARCH
NASA Work Unit 129-02-01-07
JPL 329-21101-1-3450

K. Shimada
S. Luebbers

OBJECTIVE

The long-range objective is to better understand the physics involved in thermionic energy conversion. With this understanding, possible methods for improving converter performance become apparent. The current work is concerned with ionization phenomena in cesium gases (pre-ignition characteristics) and the influence of geometry and impurities upon the electron emission from refractory metal emitters.

PROGRESS

Pre-Ignition Characteristics

Improved results were obtained for the pre-ignition characteristics by using two guard-ring research converters, the interelectrode gap of which is fixed in one and variable in the other. Electrode work functions were also measured in these converters since they were required for the analyses of pre-ignition characteristics. The work function of the cesiated tantalum emitter in the fixed-gap converter was nearly equal to that predicted by the Rasor-Warner theory for a material whose uncesiated work function equaled 4.7 volts. This value is considerably larger than that expected for "clean" tantalum whose uncesiated work function is 4.2 volts. Sources of possible error were carefully eliminated during these measurements and the discrepancy was attributed to bulk-absorbed oxygen in tantalum. The work function of the niobium collector in this diode was also determined. Although niobium is commonly used in experimental converters for in-pile applications of thermionic converters, little is published about its work function. Our result for the minimum collector work function was 1.5 ± 0.05 V occurring at a temperature ratio T_C/T_{Cs} of 1.8.

Side-wall current from the emitter support structure of a guard-ring converter to the guard ring was measured and compared with that calculated from the theory we previously reported. Agreement between the calculated and the measured currents was excellent. Thus, we have established the applicability of the theory to calculating side-wall currents in practical converters.

Theoretical analyses of pre-ignition phenomena are in progress to take advantage of the improved volt-ampere curves and electrode work-function measurements made with the guard-ring converters. Potential distributions are being calculated for a converter operating under collisionless pre-ignition conditions. The model is one-dimensional and both electrons and ions are emitted from the emitter and enter into the interelectrode space. Emitted particles are assumed to be in a thermal equilibrium at the emitter and to obey Boltzmann statistics in the interelectrode space. The underlying goal of this analysis is to relate the increase of diode current in the pre-ignition region to the decrease in the electron-retarding-potential minimum occurring in the interelectrode space. For the analysis of the avalanche region of the I-V curves, a source of ions in the interelectrode space will be incorporated to account for the rapid increase in current with voltage.

Electron Emission

The electron-emission properties of both contaminated tantalum and rhenium wire probes have been established from plasma-immersion-probe experiments. The experimental results from the rhenium-wire probe produced the anticipated emission behavior as has been observed by other investigators using different measurement techniques (i. e., guard-ring converters). The electron emission from the contaminated tantalum probe reproduced the observed enhancement reported during the last period. This behavior has lead to the suggestion of an impregnated oxygen-dispensing tantalum emitter (Ref. Invention Report 30-11138/1832). Further experiments are under way to study the diffusion and desorption of oxygen impurities within tantalum emitters. Cesium-ion sputtering is being used extensively to prepare clean emitter surfaces.

Differential experiments with planar rhenium probes were complicated by undesirable discharge currents between the probe itself and the guard-ring structure used to define the planar emission area. Before any significant results were obtained, the tube failed. This effort has, however, clearly indicated the necessary probe-design modifications required to eliminate the excess discharge current.

Fabrication of a metal-ceramic plasma-immersion probe tube, with an extended temperature range, has been completed and the tube is undergoing final processing before cesium distillation.

Electron Beam Welder

The design and fabrication of an electron-beam welder has been initiated during this reporting period. The welder components have been obtained at no cost, thus requiring only system design and assembly. The assembly work is being done by a contract technician under Purchase Requisition GP-505390 at a total cost of $4,450.

PLANS

Analysis of pre-ignition characteristics will be directed toward a satisfactory theory for explaining the current avalanche in a cesium diode due to impact ionization. A theory for charge-carrier transport in a cesium diode exhibiting current oscillations will be developed jointly with Prof. D. Shaw, State University of New York, Buffalo, who will be a summer faculty member working for this group. Experimental data on current oscillations have already been accumulated and explained qualitatively. The additional effort required to complete the theory will not be large, but the increased understanding obtained from this work will be valuable in advancing our progress toward reducing losses in cesium plasma.

Preliminary discharge experiments will be done with the metal-ceramic plasma-immersion-probe tube. The inclusion of a diagnostic probe will allow measurement of electron and ion-density profiles, charged-particle temperature, etc. A tube of this structure has not been developed elsewhere, and it is expected to yield emission-probe results over a wide range of temperatures and with a variety of probe materials.

The electron-beam welder will be assembled in July, 1969. After checkout, it will be used to fabricate the diagnostic probes for the metal-ceramic tube discussed above.

PUBLICATIONS

JPL Publications

1. K. Shimada, "Pre-ignition Characteristics of Cesium Thermionic Diodes: Part III," JPL SPS 37-54, Vol. III, pp. 70-73, December 1968.
2. S. Luebbers, "Plasma-Anode Technique for Determining Electron-Emission Properties of Metals," SPS 37-55, Vol. III, pp. 132-136, February 1969.
3. K. Shimada and P. L. Cassell, "Guard-Ring Thermionic Diode Experiments," JPL SPS 37-57, Vol. III, pp. XXX, June 1969.

RADIATIVE TRANSPORT AND INELASTIC RATE PROCESSES IN PARTIALLY IONIZED GASES

NASA Work Unit 129-02-01-08

JPL 329-21901-0-3830

G. R. Russell

OBJECTIVE

The overall objective is to study both theoretically and experimentally radiative transport and inelastic rate processes in partially ionized gases. A prerequisite and associated primary objective is the development of plasma diagnostic techniques. Particular attention is focused on the interaction of radiation and rate processes such as ionization, recombination, and the population of excited states in nonequilibrium plasmas. This research is fundamentally related to the basic problems associated with electrical propulsion devices, MHD generators, and gaseous lasers which operate almost entirely in a region where the working fluids are not in equilibrium. Determination of rate processes in static CO_2 and argon lasers and the study of instabilities in magnetogasdynamic lasers were emphasized in FY 69.

PROGRESS

Rate Processes in Magnetogasdynamic Lasers

The kinetic model augmented to include ten excited states, used previously to calculate excited state populations in recombining argon, has been modified to investigate the effect of a rapidly rising electron temperature in the entrance region of a cross-field accelerator. When the electron temperature is rapidly elevated by an electric field, in the subsequent ionization process it is found that for a band of electron temperatures and densities, population inversions are produced in the entrance region of the accelerator. These inversions are predicted for the transition array (5p-3d) in the infrared at about 2.5 microns.

Although the magnitude of the predicted population inversions is of the same order as would be expected in the recombining accelerator exhaust, the optical gain is generally not as large because the inversions occur at higher electron temperatures where the upper level laser populations are smaller. Thus, attainment of excitation in an optical cavity of the size currently being used for the accelerator exhaust, may be impossible. However, in a larger device, for a wide range of operating conditions, it is expected that laser power can be extracted from both the entrance and exit regions of an accelerator utilizing argon as a working fluid.

Instability in Nonequilibrium Plasmas

Theoretical work associated with instabilities in a slightly ionized plasma is continuing. An important facet of the theory is the consideration of inelastic collision processes. Development of model equations describing these processes has been completed during the last half of FY 69. Comparisons were made between Gryzinski electron-atom excitation cross sections and experimental measurements and other theoretical calculations. On the basis of these comparisons, use of the Gryzinski cross section formulas as a semi-empirical expression to give approximate excitation rates is justified. Also, effects of atom-atom excitation rates, important for levels with large quantum number, were studied. Criteria for neglecting these rates were found and possible errors were estimated. Electron-atom rates and radiative energy losses from excited states energy levels of large quantum number can be estimated by an "extended continuum" model. In this model, these higher levels are looked upon as extensions of the free electron continuum. Using this extended continuum, the number of levels to be considered in the rate equations can be truncated with little resulting error and a consistent but finite set of equations can be formulated.

Rate Processes in Static CO_2 Lasers

The study of the inversion mechanisms in a discharge tube CO_2 laser has been initiated during the last half of FY 69. A conventional CO_2 laser tube has been constructed with potassium chloride windows arranged at Brewster angles. The reflectors of the optical cavity are gold-coated mirrors. A tripple electrostatic probe and a thermocouple are used to measure the electron temperature and density and gas temperature, respectively. A gold doped germanian detector is used to measure the laser output. A pulse generator capable of delivering 20 kw is used for the source of the discharge current. It is found that there is a time delay of the laser pulse behind the current pulse. The dependence of the time delay on the plasma parameters such as discharge current, pulse width, electron density, electron temperature, gas temperature and gas pressure has been investigated. The relative concentrations of CO and O have also been monitored by a spectroscope. From these data it is concluded that the mechanism responsible for populating the higher laser level is the recombination of CO and O into excited CO_2 molecules. The reaction rate of $CO + O \rightarrow CO_2$ can be inferred from the data obtained. The measured reaction rate utilizing a pulsed laser of this type is more accurate than that measured by other chemical means because the impurity effect, especially H_2O, has no influence on the measurement.

Atom-Atom Inelastic Collisions in the Rare Gases

Recently, it has become apparent that heavy particle collisions can have an appreciable effect on excited state populations in lasing gases when the degree of ionization is not too high. For this reason, a theory is needed analogous to the theory of Gryzinski which can be used to predict these inelastic collisional properties over a wide range of excited state energies.

In Ref. 1, Drawin has used Thomson's classical theory to calculate ionization cross sections for atom-atom collisions. This theory has been extended to include atom-atom excitation cross sections by classical methods. The theoretical results are compared with the experimental data of Kelly (Ref. 2) at the high excitation energies and with Abrams and Wolga (Ref. 3) at low energies. Considering the limited amount of available experimental data and the simplicity of the theory, the agreement with experiment is excellent. The surprisingly good agreement obtained for both ionization and excitation for atom-atom collisions where the orbital target electron energy is not taken into account leads one to speculate that for inelastic heavy particle collisions at energies near threshold, the energy of the target electron is not important in the determination of the cross section.

REFERENCES

1. Drawin, H., "On the Analytical Expression of the Ionization Cross Section for Atom-Atom Collisions and on the Ion-Electron Recombination in Dense Neutral Gases." Zeitschrift fur Physik, Vol. 211, 404-417, 1968.

2. Kelly, A. J., "Atom-Atom Ionization Cross Sections of the Noble Gases — Argon, Krypton, and Xenon," J. of Chem. Physics, Vol. 45, No. 5, Sept. 1966.

3. Abrams, R. l. and Wolga, G. J., "Direct Demonstration of the Validity of the Wigner Spin Rule for Helium-Helium Collisions." Review Letters, Vol. 19, No. 25, Dec. 1967.

PUBLICATIONS

Journal Articles

1. Russell, G. R., "Calculation of Atom-Atom Excitation Cross Sections by Classical Methods," J. of Chem. Physics, May 15, 1969.

2. Chen, C. J., "Collisional-Radiative Electron-Ion Recombination Rates in Rare-Gas Plasmas," J. of Chem. Phys., Vol. 50, No. 4, Feb. 15, 1969.

PHYSICS OF MOLECULAR INTERACTIONS

NASA Work Unit 129-02-01-09

JPL 329-20301-1-3280

D. D. Elleman

OBJECTIVE

The long-range objective of this task is to investigate the reaction and interaction of ions and excited species in the gas phase. A study of ion-molecule reactions is undertaken for the purpose of selecting those reactions with potential laser applications. The excited states produced in ion-molecule reactions will be studied both for their light emission characteristics and their subsequent reaction with neutrals to form other excited species.

PROGRESS

Using the ion cyclotron resonance spectrometer which is described in previous reports, the thermal rate constants of the reactions

$$H_2^+ + H_2 \longrightarrow H_3^+ + H \qquad (1)$$

$$D_2^+ + D_2 \longrightarrow D_3^+ + D \qquad (2)$$

$$HD^+ + HD \longrightarrow H_2D^+ \ D \qquad (3a)$$

$$HD^+ + HD \longrightarrow HD_2^+ + H \qquad (3b)$$

have been measured and the results have been reported in the open literature. An analysis of the energy dependence of the rates has shown that a dual reaction mechanism is operative in (1) to (3). At low energies (KE < 1eV) both complex formation and a stripping mechanism occurs while at higher energies the stripping mechanism becomes dominant. In addition, it has been observed that the H_3^+, H_2D^+, HD_2^+, and D_3^+ ions formed in reactions (1) to (3) are produced with an internal energy (vibrationally excited) of up to 2 eV. This excess internal energy can be dissipated by light emission, collision deactivation or through subsequent ion-molecule reactions of $\left[H_3^+\right]^*$ with other neutrals. At the present time we are investigating the latter two possible mechanisms. We have investigated the deactivation and reaction of H_3^+ with N_2, Ar and CH_4; the work on the N_2 and Ar systems has been submitted for publication while the CH_4 work is still in progress.

A new ICR cell has been constructed and tested so that we will be able to measure ion-molecule rates by a sequence of rapid pulses. The pulsed technique will allow us to measure rates more accurately than has been possible in the past.

We have continued the investigation of the complex ion-molecule reactions of ions formed by electron impact in methane-ammonia mixtures. This particular mixture of gases is of interest because it is believed by some to be the precursor of biological activity on earth. Some preliminary results on these experiments have been reported in the literature.

An ICR spectrometer with a UV ionization source is being constructed and will be completed in the next several months. In the interim, a specially constructed 1 meter vacuum UV monochromator that is eventually to be used in the ICR studies has been mated to a high speed (1000 l/s) vacuum pumping system. The optical alignment of the instrument has been completed and the resolution is approximately 0.2 Å, full width at half-maximum.

Until the new ICR is completed, the monochromator system will be used for the study of the pressure broadening of the wings of the Schumann-Rudge molecular oxygen bands in the 1800-2100 Å wavelength region. These studies will be important as a test of the hypothesis that greater amounts of solar flux than earlier postulated could be absorbed in the atmosphere by pressure-broadened O_2 absorption. The light source is a low pressure, 300 watt H_2 discharge lamp which generates a comparatively smooth continuum from 1750 to 2300 Å. A two meter absorption cell has been constructed for the monochromator, and photon-counting photomultipliers sample the photon beam before and after the absorption cell. Variations in lamp intensity are thus eliminated from consideration. Absolute pressure gauges will monitor the absorbing gas pressure over the range of 0.5 to 1500 torr.

ANTICIPATED PUBLICATIONS

1. Bowers, M. T., Elleman, D. D., and King, J., Jr., "Analysis of the Ion-Molecule Reactions in Gaseous H_2, D_2 and HD by Ion Cyclotron Resonance Techniques," J. Chem. Phys. (in press).

PUBLICATIONS

Meetings and Symposia

1. Bowers, M. T., and Elleman, D. D., "Kinetic Analysis of Concurrent Reaction Systems Using Ion Ejection and Ion Cyclotron Resonance Techniques," Seventeenth Annual Conference on Mass Spectrometry and Allied Topics, Dallas, Texas, May 18-23, 1969.

2. Huntress, W. T., Jr., and Elleman, D. D., "Ion Molecule Reactions in Methane-Ammonia Mixtures," Seventeenth Annual Conference on Mass Spectrometry and Allied Topics, Dallas, Texas, May 18-23, 1969.

Journal Articles

1. Bowers, M. T., Elleman, D. D., King, J., Jr., "Kinetic Analysis of the Ion-Molecule Reactions in Nitrogen Hydrogen Mixtures Using Ion Cyclotron Resonance," J. Chem. Phys. 50, 1840 (1969).

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DETERMINATION OF ELECTRONIC POPULATION INVERSIONS IN MAGNETOGASDYNAMIC DEVICES

NASA Work Unit 129-02-01-10

JPL 329-22301-0-3830

G. R. Russell

OBJECTIVE

The primary objective of this work unit is to determine the feasibility of producing electronic population inversions in magnetogasdynamic devices. A secondary objective is to study both theoretically and experimentally the detailed mechanisms responsible for the population inversions and the relationships that exist between device size and the magnitude of the coherent radiation and the device efficiency.

PROGRESS

Faraday Cross-Field Laser

The power distribution system required for the faraday cross-field laser experiment has been completed and operated successfully on and off design conditions. The accelerator duct has been instrumented with 27 tantalum probes arrayed on one insulator wall. An instrument panel has been constructed and wired to these tantalum probes. With this instrumentation it will be possible to measure the local faraday and hall electric fields in the plasma. Provision has also been included to make possible the use of these tantalum pins as Langmuir probes so that the electron temperature and density will be obtainable both along and across the accelerator duct. The insulator walls are made of aluminum, water cooled for thermal protection and hard anodized for electrical insulation. These walls have been successfully tested at design conditions.

A number of tests have been performed with single and multiple electrode pairs discharing across the supersonic jet of argon plasma. In these tests the anodes were found to discharge smoothly and reliably and with no apparent erosion. However, the cathodes were found to discharge irregularly and were often destryoed by a concentration of current at undesirable places. It was found that cleaning the cathodes by electrolysis in potassium hydroxide improved their performance considerably; however, they are still not as reliable as desired. Further testing, design to find a more reliable cathode for the faraday cross-field laser experiment, is being planned for an auxiliary test stand.

One third of the accelerator duct, containing the first eight electrode pairs, has been operated with reasonable success. With a Langmuir probe, located 30cm downstream of the last electrode and on the jet center line, the eight discharging electrodes were found to cause an elevation of the electron temperature at the downstream point by a factor of three and the electron density by approximately a factor of two. These Langmuir probe measurements also indicate a hall field exists along the jet center line due to the applied magnetic field.

The remainder of the duct has been assembled and is currently being installed in the vacuum tank. When this is completed, Langmuir probe measurements will be made in the exhaust of the accelerator duct to determine an optimum position for the placement of the laser cavity. Upon completion of the probe measurements the laser cavity, which as been previously checked out in a static discharge tube, will be installed and used to detect population inversions in the accelerator exhaust jet. These first measurements utilizing the complete cross field laser should be completed in the first quarter of FY 70.

MPD Arc

During the second half of FY 69, attempts to obtain direct evidence of population inversion of the excited argon ion energy levels were continued, and a number of ArII transition probabilities were obtained.

Conclusions concerning the distribution of the energy levels of the excited ions rely on the accuracy of the transition probabilities that are used in conjunction with the measured line intensities. For the upper energy levels, the transition probabilities have been largely limited to calculated values. A number of values were obtained experimentally in a 1.1 atmosphere free-burning arc and were found to be somewhat smaller but to agree reasonably well with the calculated values. Since these values were obtained, experimental results were published in Ref. 1, for some high energy lines appearing in the near uv.

These values were nearly an order of magnitude smaller than the calculated values. Because of this large discrepancy, additional measurements, for which quartz optical components were used, were made in the 1.1 atmosphere free free-burning arc. The results obtained indicated values that were lower than the calculated values but agreed much more closely with the calculated values than with the result of Ref. 1. A paper summarizing the experimental results has been submitted for publication.

Attempts to obtain definitive measurements of amplification of a laser beam directed through the exhaust beam of the MPD arc have been hampered by vibration of the experimental equipment and by degradation of the mirror surfaces. Both effects became increasingly troublesome as the number of passes of the laser beam through the multiple-pass mirror system was increased. Both problems are now believed to be solved to the extent that a 1% amplification of the laser beam can be detected. The degradation of the mirror surface, which was probably caused by deposition of material from the MPD cathode, has been alleviated through the use of shutters and baffles. In addition, the wide-band aluminum-coated mirrors are being replaced by laser-grade dielectric mirrors to examine the strongest lasing line at 4880°A. Definite results are expected to be obtained during the early part of the first quarter of FY 70.

Study of Population Inversions in Alkali Metal Plasma

Spectroscopic measurements on the RF-excited potassium jet are currently being carried out. Many spectral lines of both neutral and ionized potassium are observed. The three strongest ion lines that are seen are 4186.2A ($4s\,[3/2]_2 - 4p\,[5/2]_3$), 4263.3A ($4s\,[3/2]_1 - 4p\,[5/2]_2$) and 4340A ($3d\,[1/2]_1 - 4p\,[3/2]_1$), indicating that the electron temperature in the jet is the order of several electron volts. Since the atom temperature is less than one volt, the jet is in a highly non-equilibrium state.

Because potassium is spectroscopically similar to neutral argon, where lasing has been attained in several low lying exicted states, it is expected that spectral lines of KII similar to the neutral argon will also lase in the potassium jet.

The spectroscopic measurements of the potassium jet are being continued in an attempt to obtain quantitative information on the populations of excited states in both the neutral and ionized species. At the same time an optical cavity is being set up to try to produce lasing utilizing a number of the lower lying ion excited states. The cavity consists of two plane broadband mirrors, one of which is mounted on the vacuum chamber with a flexible bellows. The other mirror is mounted outside the chamber. A Brewster angle window is used in conjunction with the outside mirror. A procedure for optical alignment of the system has been tried and found to be satisfactory. Testing of the cavity with the ionized jet in operation awaits completion of some minor modifications to the experimental facility, which will improve its overall reliability and per performance.

REFERENCE

1. Beth, M. U., Bohn, W. L., and Nedder, G., "Absolutmessung von Ubergangswahrscheinlichkeiten an Argonlinien im nahen Ultraviolett," F. Naturforschg, 21A, 1203 (1966).

ANTICIPATED PUBLICATIONS

Journal Articles

1. Nerheim, N. M., and Olsen, H. N., "Experimental Measurements of Some AII Transition Probabilities and a Comparison of Published Values," submitted to Journal of Quantitative Spectroscopy and Radiative Transfer.

PUBLICATIONS

JPL Publications

1. Goldstein, R., "Numerical Calculations of Electron-Atom Excitation and Ionization Rates Using Gryzinski Cross Sections," JPL Technical Report No. 32-1372, March 1, 1969.

OPTICAL PHYSICS RESEARCH

NASA Work Unit 129-02-05-01

JPL 329-20101-1-3450

A. R. Johnston
R. J. Stirn

OBJECTIVE

The objective of this work unit is to characterize experimentally the electro-optic effect in certain materials with device potential. The feasibility of new applications is also investigated; in particular, an electro-optic direction sensor has been examined.

The objective in the area of metal-photoconductor contacts is to study the barrier heights of blocking contacts in CdS with respect to their dependence on the amount of photocurrent flowing through them and their effect on photoconducting gain factors.

The objective of the work on the photoelectric response of barriers is to develop a photodetector, sensitive over a selected range of wavelengths, which can generate a modulated signal without the use of mechanical parts, and generally to aid in investigations of energy conversion by barriers in semiconductors.

PROGRESS

Electro-Optic Effect

While interpreting our data on $BaTiO_3$ in terms of the independent oscillator model of Di Domenico and Wemple, we found that our data on birefringence, Δn, as a function of wavelength for flux-grown $BaTiO_3$ did not agree with the model. Since their data on melt-grown $BaTiO_3$ did fit, a remeasurement of Δn on both types of material was made in order to resolve the difference. Our earlier measurement of n was an interference measurement in which the interference order was determined by using the literature value for Δn at 5461 Å. Our new measurement included both an independent check of interference order, and determination of n itself vs. λ by the minimum deviation method. Our conclusions are:

(1) The value of approximately 0.07 for Δn at 5461 Å that has been generally accepted for the past ten years or more is apparently too large. Instead, we now obtain 0.055.

(2) The Δn-vs-λ curves for flux-grown material are somewhat different than for the melt-grown crystals, but are of the same form. Our measurement for melt-grown cyrstals agrees closely with that of Di Domenico et al.

(3) Our new data fit the independent oscillator model fairly well, although our data cover a wider spectral range than that of Di Domenico <u>et al.</u>, and there is some deviation at the ends of the range. The fit is good enough so that the interpretation of our electro-optic data can now be continued.

Contact is being maintained with P. Klein at ERC.

The paper describing the electro-optic measurements in $NaNO_2$, with T. Nakamura, is scheduled for publication in the August issue of the Journal of Applied Physics.

<u>Direction Sensor</u>

A simple laboratory breadboard model of an electro-optic direction sensor was constructed, and used to demonstrate the feasibility of the concept. ADP crystals which were on hand were used for birefringent element and modulator. The aperture was approximately 3 mm and a bright point light source was used. With elements scaled such that the linear range was 1 deg and the angular field 2 deg, the angle readout was stable to 0.01 deg. Although crude, the experiment showed that the concept is workable. Future work will aim at construction of a laboratory model with quality optical elements which could be tested at actual starlight illumination levels. Measured and predicted performance could be compared. Continuing work will be under NASA Work Unit 125-17-15-03.

Optics-in-NASA Contribution

During the last quarter, emphasis has been placed on preparing an article to be titled "Optics at JPL," to appear in the January 1970 issue of Applied Optics, which will feature technical articles covering NASA activities in optics. The article will summarize the current efforts at JPL and introduce several regular technical articles contributed from JPL.

Metal-Photoconductor Contacts

The experimental part of the stationary high-field-domain analysis of blocking contacts in photoconducting CdS has been completed. This work and continuing phases of related work are being done in collaboration with Dr. K. W. Böer and Gustavo Dussel at the University of Delaware. The analysis of this part of the investigation will be presented at the Third International Photoconductivity Conference at Stanford University and published in the December issue of Journal of Physics and Chemistry of Solids. The barrier heights were found to be completely independent of the metal work function and to vary logarithmically with the amount of photocurrent at a fixed temperature. The extrapolated photocurrent (shown to be thermionic and not tunneling) for zero barrier height was found to be within 5% of the theoretical value in the Schottky-Richardson model for pure thermionic emission. The measured values of barrier heights at room temperature and at current densities of about 10^{-2} A/cm^2 are 40 to 50% lower than those measured for zero current flow, allowing for measured gain factors of 1000 and above, whereas gains less than unity would be expected for "blocking" contacts. A search for a theoretical model for this strange behavior of metal contacts on photoconductors which would also explain the independence of the metal electro-negativity for determining the barrier height is being made. The techniques used in the contact analysis will be employed in an investigation of the energy-conversion process (photovoltaic effects) in heterojunctions on CdS. This latter investigation and continuing work on photoresponse of barriers will be funded under NASA Work Unit 129-02-21-08 beginning in FY 70.

Photoresponse of Barriers

The photoresponse optical apparatus has been described in the previous report and now has a calibrated thermopile for monitoring purposes. Barrier heights of gold-CdS contacts have been measured on semiconducting CdS and found to be nearly twice as large as those found on the contacts discussed above, in agreement with published results. Similar measurements on the miniscule samples of photoconducting CdS used in the high-field-domain study, which have resistivities of about 10^8 ohm-cm, have not yet been successful. The same apparatus, when used with a photomultiplier placed behind the CdS sample, will be used in the photovoltaic investigation for direct-field probing near the p-n junction. By this technique, using band-gap illumination and the Franz-Keldysh effect, a direct measure of the field distribution can be made with high spatial resolution. Because of the promising CdS effort and because the thin-film metal-AℓN-metal diodes grown to date have shown low efficiencies, no results in the latter area are presented, and it is not anticipated that such structures will be fabricated in the future. However, various thin-film sandwiches are being made by others in this section, and supporting photoresponse measurements will be performed and the results published when the opportunity arises.

ANTICIPATED PUBLICATIONS

Journal Articles

1. Johnston, A. R., "A Polarimeter for Measurement of Transient Retardation Changes," to be published in Applied Optics.

2. Johnston, A. R., and Nakamura, T., "Determination of the Low-Frequency Electro-Optic Coefficients of $NaN0_2$," to be published in the Journal of Applied Physics, August 1969 issue.

3. Stirn, R. J., Böer, K. W., Dussel, G. A., and Voss, P., "Work Function of Metal-CdS Contacts at Higher Current Densities," accepted for presentation at the Third International Conference on Photoconductivity, Palo Alto, California, August 12-15, 1969, and for publication in the Proceedings of the Conference, Journal of Physics and Chemistry of Solids, December 1969 Issue.

4. Johnston, A. R. and Powell, R. V., "Optics at the Jet Propulsion Laboratory," submitted for publication in the Journal of Applied Optics (Special NASA Issue).

Presentations

Nakamura T. and Johnston, A. R., "Analysis of Low-Frequency Electro-Optic Response in $NaNO_2$," to be presented at the International Meeting on Ferroelectricity, Kyoto, Japan, September 4-9, 1969.

PUBLICATIONS

None

CRYOGENICS RESEARCH

NASA Work Unit 129-02-05-02

JPL 329-20201-1-3450

P. V. Mason

OBJECTIVE

The goal of the Cryogenics Research Group is to study low-temperature phenomena in order to develop knowledge of physical principles and technological methods that will lead to improvements in spacecraft guidance, control, and power generation and conditioning.

Our studies are presently in three areas: (1) Josephson-effect devices, with particular emphasis on their use as ultra-high-speed memory elements, (2) thin-film superconducting transmission lines, for use in pulse storage and manipulation, (3) the problems of providing the necessary low-temperature environment aboard a small spacecraft.

PROGRESS

Josephson Junctions

Josephson devices offer possible improvement over those presently used in large random-access memory units of 100 to 1000 in speed (see SPS 37-51, Vol. III, p. 72). If they are to be useful, it must be possible to fabricate large numbers of them with high yield and reproducible, uniform and stable characteristics. To this end we have studied a number of methods of fabrication. The principle problem lies in obtaining a thin insulator (on the order of 10 atomic layers) between two superconductors. Most investigators do this by vacuum evaporating a metal base strip, oxidizing the surface under more or less controlled conditions, then evaporating a counter electrode on top.

We have experimented extensively with thermal oxidation under closely controlled conditions, using lead as the metal because of its high transition temperature. We have found this process to be unsatisfactory because of low yield, poor reproducibility, and poor storage characteristics. We have experimented with plasma anodization (Ref. 1), a process of oxidation in a glow discharge in an atmosphere of 10 to 100 millitorr of oxygen. We found the process to be even more difficult to control than thermal oxidation.

We are now experimenting with another technique — that of oxidation in a dry oxygen atmosphere with ultraviolet light illuminating the metal surface. The effect of the UV is probably to generate ozone, which reacts more rapidly and completely with the metal. This process has increased yield and reproducibility considerably.

At present, it is necessary to remove the metal-bearing substrate from the vacuum to put it in a UV oxidation chamber, then return it to the vacuum to form the counter electrode. Since we expect exposure to room atmosphere to reduce yield and reproducibility, we are now constructing a system with suitable quartz windows to allow introduction of UV into the vacuum chamber used for vapor deposition. We plan continued experiments to improve the device properties.

One fundamental property we plan to measure is the switching speed of the junctions. Since switching speeds are in the 0.1 nanosecond range, this must be done in a transmission-line geometry if the measurement is to avoid circuit limitations. Attempts to fabricate a device in suitable form have not been successful. An improved fabrication method using photo-resist techniques is now being developed and it is hoped that measurements will be made in the next six-month period.

Studies of fabrication of Josephson junctions using anodization of niobium and tantalum are also under way.

Transmission Lines

Thin-film superconducting transmission lines transmit electromagnetic waves at a velocity much less than that of light (Ref. 2). In an attempt to study a further velocity reduction in films of short mean free path predicted by our previously developed theory, we have constructed an ultra-high vacuum system with simultaneous evaporation of indium and tin from separate heated sources. Attempts to produce films with a few percent tin impurity to produce the required short mean free path have not worked well. We are now evaporating from a single boat containing a mixture of indium and tin. While this procedure is not as controllable as simultaneous evaporation, we can obtain films with the necessary range of impurities. Studies of the velocity reduction will be made in the next six-month period.

Low-Temperature Environment

We have continued to remain informed of industrial and governmental projects in the field of spacecraft-compatible refrigerators. Several Air-Force-sponsored projects have resulted in hardware suitable for aircraft application; with some further refinements these might be suitable for use aboard spacecraft. Use of gas-film bearings in either turbine or reciprocating refrigerators gives hope of attaining the necessary reliability. Size, weight, and power consumption remain problems, however.

At a recent conference, Pitcher and du Pré (Ref. 3) reported on a refrigerator using a Vuilleumier cycle. Since it can operate directly from a heat source without motor drive, it would be attractive for use where power is available in the form of heat, e.g., from a radio-isotope or nuclear generator. Although thermodynamic efficiency is low, the avoidance of the losses in electric power generation and conditioning could be expected to make over-all efficiency competitive with that of other refrigerators.

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1. J. L. Miles and P. H. Smith, "The Formation of Metal-Oxide Films Using Gaseous and Solid Electrolytes," J. Electrochem. Soc. 110, 1240 (1963).

2. P. V. Mason and R. W. Gould, "Slow-Wave Structures Utilizing Thin-Film Transmission Lines," J. Appl. Phys. 40, 2039 (1969).

3. G. K. Pitcher and F. K. du Pré, "Miniature Vuilleumier Cycle Refrigeration," presented at the 1969 Cyrogenic Engineering Conference, June 16-18, 1969, Los Angeles, Cal.; to be published in Advances of Cryogenic Engineering.

PUBLICATIONS

Journal Articles

P. V. Mason and R. W. Gould, "Slow-Wave Structures Utilizing Thin-Film Transmission Lines," J. Appl. Phys. 40, 2039 (April 1969).

LOW TEMPERATURE PHYSICS

NASA Work Unit 129-02-05-04

JPL 329-20401-1-3280

D. D. Elleman

OBJECTIVE

The objective of this program is to investigate a variety of low temperature phenomena in Fermi surface studies of metals using the de Haas-van Alphen effect, superconductivity effects, and nuclear magnetic resonance effects under high pressure.

PROGRESS

Experimental studies of the Fermi surface in a number of metallic systems are currently being conducted using the de Haas-van Alphen effect. The experimental method uses radio-frequency modulation techniques to measure a small component of the magnetic susceptibility which oscillates as the magnetic field changes. By collecting data as a function of crystal orientation, temperature and magnetic field, it is possible to determine not only the size and shape of the Fermi surface, but also to see fine details of the surface structure such as small energy gaps at critical points. This knowledge is necessary for a qualitative and quantitative description of the electronic structure of the metal and for predicting transport properties.

Of particular interest is a non-linear coupling effect between de Haas-van Alphen oscillations which has been found and characterized in both indium and white tin. Experimentally one observes large numbers of oscillations whose frequencies are harmonic and combinational frequencies of the fundamental susceptibility oscillations, and an abnormal behavior in the field dependency of the amplitude of the oscillations. Figure 1 shows de Haas-van Alphen spectra of white tin, clearly illustrating harmonic and combinational frequencies.

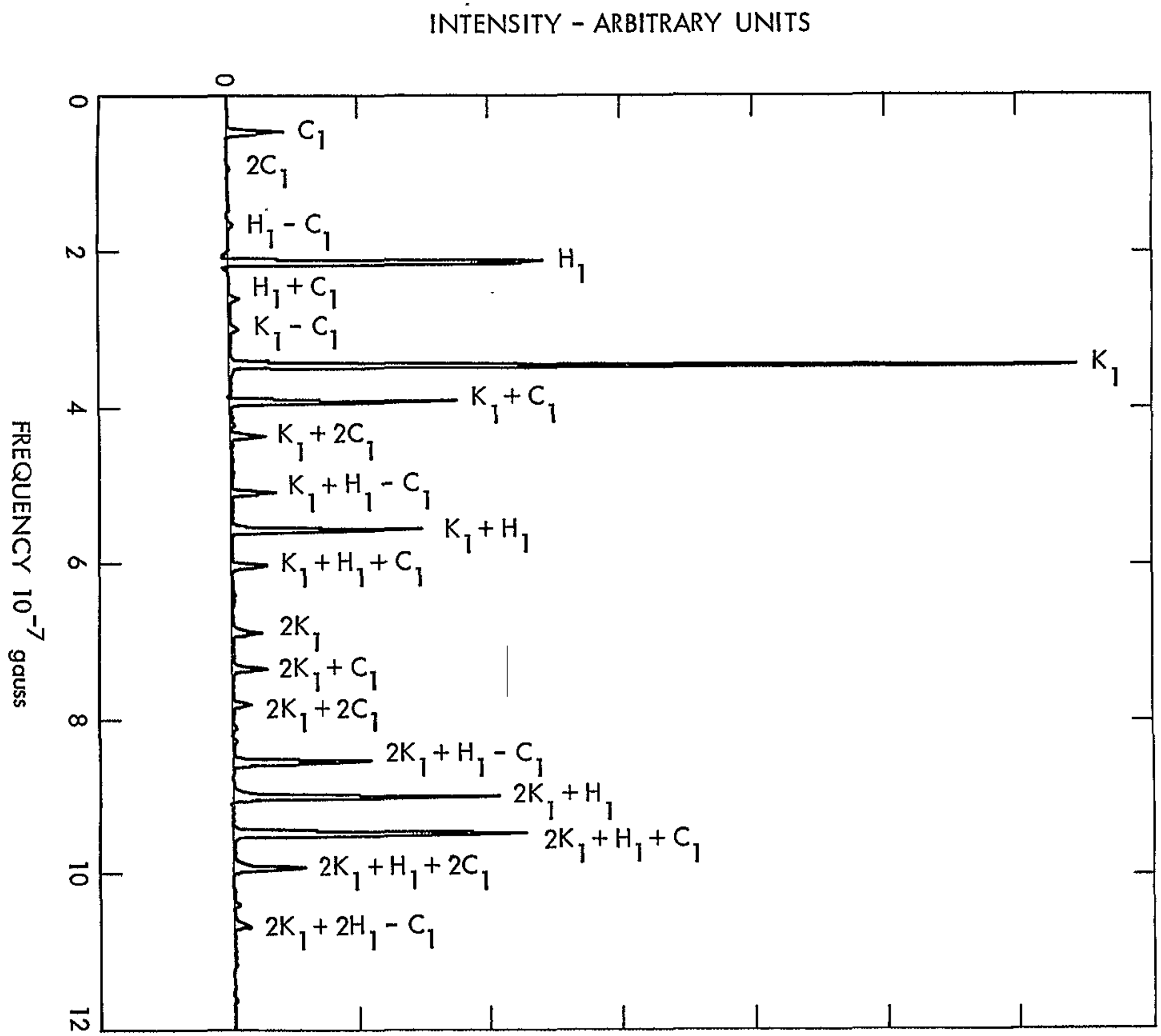

Figure 1. Haas-van Alphen Spectra of White Tin

Such coupling is not rigorously explainable from the one electron model of the Fermi surface and involves many-body corrections. One of several proposals to account for such interactions appears possible of explaining our results. Known as the Shoenberg-Pippard B-H effect, it includes the possibility of coupling in the one electron model by replacing H, the external magnetic field, with B, which is the field including the contribution due to the motion of the other electrons. This proposal has received considerable attention as the measurement of the amplitude of the combinational frequencies produced by this mechanism would furnish information on the curvature of the Fermi surface difficult to obtain otherwise. Although several studies specifically designed to look for this non-linear effect have been published, no one has previously reported seeing more than single sum of difference frequencies, while our results in Figure 1 show up to 5th and 6th order combinational frequencies.

We are in the process of determining if this proposal, as well as any of several other mechanisms, could account for our results. Preliminary results do indicate that the gross features can be accounted for by simply the B-H effect, although not all details of the spectra have yet been accounted for. This represents a severe test of the proposal because of the numerous opportunities for self-consistency checks with the data available, and also offers the possibility of furnishing information on the Fermi surfaces of the materials involved not presently available.

In addition to the rather extensive work being conducted on indium and tin from the point of the non-linear effects, several other experimental investigations are also underway. Preliminary evidence has been obtained for the occurrence of the non-linear effect in lead; the second zone hole surface in indium is being examined; and work is being initiated to try to observe the de Haas-van Alphen effect in specific semiconductors, mainly PbTe, where it has been proposed that defects should produce semi-metal like behavior.

Though work in high resolution nuclear magnetic resonance is no longer funded in the task, several papers were in various stages of completion when funding was stopped. In the interim, these papers have been submitted for publication and are included in the list of publications for the task.

ANTICIPATED PUBLICATIONS

Journal Articles

Vaughan, R. W., Elleman, D. D., and McDonald, D. G., "The de Haas-van Alphen Effect in White Tin," submitted to J. Chem. Phys. Solids.

Cohen, E. A., Bourn, A. J. R., and Manatt, S. L., "On the NMR Spectra of Pentafluorobenzenes," J. Mag. Res. 1, May 1969 (in press).

Manatt, S. L., and Bowers, M. T., "Analysis of the Nuclear Magnetic Resonance Spectrum of Hexafluoro-1,3-butadiene," J. Am. Chem. Soc. 91, June 1969 (in press).

Bowers, M. T., Chapman, T. I., and Manatt, S. L., "Energy Level Iterative NMR Method for Sets of Magnetically Nonequivalent, Chemical Shift Equivalent Nuclei," J. Chem. Phys. 50, June 1969 (in press).

PUBLICATIONS

None

MAGNETICS RESEARCH

NASA Work Unit 129-02-05-06

JPL 329-21401-1-3450

G. W. Lewicki

OBJECTIVE

The long-range objective of this work unit is to study the feasibility of magneto-optic information storage on MnBi films in which a laser beam is used both to store and retrieve information from the film. The immediate objective is to gain an understanding of Curie-point switching so that the limitations of this storage method for mass memory and recording applications can be defined.

PROGRESS

Characterization of MnBi Films

In the Curie-point-switching technique, a laser beam focused on the film momentarily raises the temperature of a small area past its Curie temperature. The area, upon cooling in an applied magnetic field, acquires an average magnetization dependent on the value and direction of that field. The magnetization within areas not heated by the laser is not affected by the field. The viability of a magneto-optic information-storage system based on MnBi is related to the requirement that Curie-point switching be controlled by a narrow range of magnetic field, a range extending only some tens of Oersteds.

To characterize MnBi films in terms of Curie-point switching, an opto-electronic readout system has been made operational within the past six months to accurately read out the average magnetization within micron-sized areas Curie-point-switched in various applied magnetic fields (SPS 37-55, Vol. III, pp. 136-139). MnBi films have been and are being characterized in terms of what we call a Curie-point-switching transfer characteristic. This characteristic relates average magnetization within an area following

Curie-point switching to magnetic field applied during switching (SPS 37-56, Vol. III, p. XXX).

On the films investigated, we have found that a magnetic field varying over a range of some 150 Oersteds completely controls Curie-point switching within micron-sized areas. We have defined the magnetization distribution responsible for the gray scale encountered in Curie-point switching by observing areas switched in various fields with high-numerical-aperture oil-immersion optics. We have also observed a tendency for the range of field controlling switching to become narrower as the size of the spot being switched was made smaller and as the bismuth content of the films was increased. These findings were presented at the International Conference on Magnetics held in Amsterdam, the Netherlands.

Preparation of MnBi Films

In the hopes of narrowing the range of field controlling switching, an effort was made to define the procedure for successfully preparing films with larger bismuth content — films with stoichiometric contents of manganese and bismuth. Such a procedure has recently been defined.

The newer films are of higher optical quality than those made previously, and should yield a higher signal-to-noise ratio for optical readout. Furthermore, we have found them to be less susceptible to corrosion by water vapor than previous films with larger manganese content, which had to be stored in dessicators if they were to survive. The newer films with higher bismuth content can be left out in open air for long periods of time.

PLANS

MnBi films having a higher bismuth content will be characterized in terms of their Curie-point-switching transfer characteristics, so that for the first time a realistic comparison of MnBi films can be made with other materials being considered for magneto-optic information storage.

Some simple recording experiments based on the gray scale encountered in Curie-point switching will be carried out with the newer films. Tracks on the films will be Curie-point-switched by scanning a focused laser beam along the film. The magnetic field applied to the film will be varied during the scan to modulate the average magnetization and, thus, the magneto-optic density on the track.

Such simple recording experiments will characterize Curie-point switching of tracks on MnBi films rather than of discrete spots.

PUBLICATIONS

Meetings and Symposia Papers

G. W. Lewicki, "Curie-Point Switching in MnBi Films," presented at the International Conference on Magnetics (INTERMAG), April 15-18, 1969, Amsterdam, the Netherlands; to be published in IEEE Transactions on Magnetics.

Journal Articles

J. A. Baldwin, Jr., "A Method for the Measurement of Domain-Wall Energy Intensity in Thin Magnetic Films," J. Appl. Phys. 40, No. 1, 432-433 (January 1969).

JPL Publications

G. W. Lewicki and J. E. Guisinger, "Automatic Gain Control for Laser Used in Magneto-Optic Measurements," SPS 37-55, Vol. III, pp. 136-139, February 1969.

G. W. Lewicki, "Curie-Point Switching in MnBi Films," SPS 37-56, Vol. III, pp. 145-148, April 1969.

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SEMICONDUCTOR RESEARCH

NASA Work Unit 129-02-05-09

JPL 329-21801-1-3450

J. Maserjian
A. Shumka

OBJECTIVE

The long-range objective of this work is to exploit various semiconductor and related phenomena in search of new active electronic devices for eventual applications in space missions. Two specific areas are being investigated: (1) the control and modulation of space-charge-limited (SCL) current in semiconductors directed toward the realization of a solid-state triode, and (2) the properties of very thin insulating and semiconducting films and their application to new devices.

PROGRESS

SCL Currents in Solids

We have demonstrated the feasibility of controlling and modulating SCL currents in germanium and have published the results in the Journal of Applied Physics. Furthermore, our efforts have led to the realization of a solid-state triode (SST) which holds great potential as a practical device because of its expected good frequency response, low noise figure, high radiation resistance, and insensitivity to temperature changes. At present, a separate in-house program has been initiated to advance the SST from the feasibility stage to a qualified component. Our work on germanium will be extended to less pure wide-band-gap materials in which the effects of impurities and high temperatures on SCL current can be studied. The selection of the material will be based on availability and suitability for device application.

The anticipation of a low noise figure and the lack of a clear understanding of the fluctuation phenomena in solid-state diodes motivated us to perform noise measurements on specially designed and fabricated germanium solid-state diodes (SPS 37-51, Vol. III). Our results were the first conclusive and unambiguous demonstration of the existence of a limiting noise spectrum which is attributed to noise of thermal origin. However, we were unable to resolve differences between several published theories based on the thermal noise hypothesis because in our devices hot carriers were present. A simple model involving mechanical statistics and quasi-thermodynamic arguments was constructed to account in a semiquantitative manner for the influence of the hot carriers. The results of this effort have been submitted for publication. A more detailed analysis of noise in SCL currents in solids due to hot carriers is being carried out. Before this analysis could be made final, we had to first resolve the differences between three published theories relating to thermalized carriers. By a careful analysis based on Langevin's equation, we have been able to disprove one of the theories. One of the other theories has been tentatively discarded on the basis that it does not consider the nonlinearities of the solid-state diode. The above results are being prepared for publication.

A cold-gas thermostat for providing an accurate variable heat sink at temperatures ranging upward from liquid nitrogen to 70°C is nearing completion. Electronic equipment is being designed to be used with the thermostat to make noise measurements at different temperatures. This work is being carried out in collaboration with Dr. M. Nicolet at Caltech.

Semiconducting and Insulating Thin Films

The effect of electron trapping on the ac impedance of space-charge barriers was treated in detail. The theory was shown to agree with the ac characteristics of the space-charge barriers in our anodized Nb_2O_5 capacitors. These results were presented at the International Thin Film Conference in April and will be published this September. The theory is particularly useful in establishing precise design principles for our thin-film capacitive bolometer. We therefore delayed publishing our earlier work on the bolometer so that these principles could be included; the final draft has since been submitted for publication in the Special NASA Issue of Applied Optics Journal.

The dependence of the ac impedance on trapping also offers a means of experimentally determining the distribution of energy levels within the energy gap. This information would be valuable for either verifying or disproving the energy-band models of amorphous semiconductors and some of the interpretations given to the "Ovonic" switching phenomena. However, to obtain an unambiguous result, we need a Schottky-type space-charge barrier in an amorphous semiconductor at only one contact opposite a good ohmic contact. We are presently seeking an appropriate system.

Our main effort has been shifting to the preparation and study of near ideal thin insulating films for eventual application in charge-storage memory devices and possibly in thin-film photoelectric detectors and solar cells. Our approach has been to concentrate on three promising methods of preparing the films: (1) oxide growth under intense ultraviolet (UV) illumination, (2) dc plasma anodization, and (3) microwave frequency plasma reaction. The initial results with method (1) gave excellent $A\ell_2O_3$ films, as judged from their electrical properties. These films were very thin ($\lesssim$30 Å) but increased in thickness with UV intensity, temperature and oxygen pressure. Our results indicated that the use of higher temperatures during formation causes aluminum migration. Consequently, we have designed a system within the evaporation chamber to operate at room temperature, but at higher UV intensities and up to one atmosphere of oxygen pressure. Preliminary results indicate thicknesses greater than 50 Å are possible.

Much thicker films can be obtained by methods (2) and (3). Method (2) has already been extensively used and studied by Dr. Lewicki for preparing $A\ell N$. His excellent results provide a convenient standard for comparisons. We will be making continued use of this proven method. Thus far, method (3) has been tested only under rather crude conditions, but has already shown that highly insulating $A\ell_2O_3$ films, as thick as hundreds of angstroms, can be readily formed. A special microwave cavity, more suitable for this purpose, is presently under construction.

Our immediate plan is to make direct comparisons of the three methods. We will be examining in detail the electron-tunneling characteristics and photoresponse data and will relate them to the band structure of the films.

These studies are already in progress with method (2) in collaboration with Prof. Mead and his students at Caltech.

Experiments on solar-cell contacts were made in support of the solar-cell program at JPL. Our technique of using evaporated alloyed contacts to the base and flash-evaporated non-alloyed aluminum contacts to the diffused layer looks very promising. We are awaiting test samples prepared by production methods for comparison.

PATENT APPLICATION

J. Maserjian, "Thin Film Capacitive Bolometer and Temperature Sensor," Invention Report 30-1413, CIT 1234.

ANTICIPATED PUBLICATIONS

Journal Articles

J. Maserjian, "AC Impedance of Space-Charge Barriers," accepted for publication in Journal of Vacuum Science and Technology, September 1969 issue.

M. A. Nicolet, A. Shumka and H. R. Bilger, "Hot Holes in Germanium: Noise Temperature and Mobility," submitted for publication to the Physical Review.

A. Shumka, "Thermal Noise in Space-Charge-Limited Solid-State Diodes," submitted to Solid-State Electronics for publication.

J. Maserjian, "A Thin-Film Capacitive Bolometer," submitted for publication in the Journal of Applied Optics (Special NASA Issue).

J. Maserjian, "Frequency Response of Thin-Film Thermal Detectors," accepted for publication in Journal of Applied Physics, July 1969 issue.

PUBLICATIONS

Meeting and Symposia Papers

J. Maserjian, "AC Impedance of Space-Charge Barriers," presented at the 1969 International Thin Film Conference, Boston, Mass., April 28-May 2, 1969.

Journal Articles

A. Shumka, "A Germanium Space-Charge-Limited Triode," IEEE Transactions on Electron Devices, Vol. ED-15, No. 6, p. 434 (1968).

A. Shumka, "A Germanium Solid-State Triode," J. Appl. Phys. 40, No. 1, 438-439 (1969).

M. A. Nicolet, A. Shumka, and H. R. Bilger, "Hot Holes in Germanium: Noise Temperature and Mobility," Bull. Am. Phys. Soc. 14, Series II, No. 2, 194 (February 1969).

JPL Publications

M. A. Nicolet, "Thermal Noise of Injected Carriers," JPL SPS 37-57, Vol. III, pp. XXX, June 1969.

MOLECULAR SPECTROSCOPY

NASA Work Unit 129-02-06-01

JPL 329-22001-1-3280

R. L. Poynter
S. Trajmar

OBJECTIVE

Microwave spectroscopy will be used to study the molecular parameters of various stable molecules and free radicals. Molecular rotational, spin reorientational, and doubling transitions will be examined. Energy states which give rise to maser or laser action will be studied. Low energy, high resolution electron scattering from atoms and molecules will be studied to obtain the cross sections for elastic, vibrational and electronic excitations to levels which are not observable by optical spectroscopy.

PROGRESS

Microwave Spectroscopy - R. L. Poynter

A preliminary account of the OD spectral analysis has been published. Recent results on this problem have been submitted for presentation at the Molecular Spectroscopy Symposium (Ohio State University).

Attempts were made to measure the OD Stark effect in order to determine its dipole moment. There was interference between the weak Stark signals and main absorption lines thus making the Stark effect measurements unreliable. Further measurements have been postponed until suitable signal averaging equipment can be obtained and integrated with the microwave oscillator system.

An optical spectrometer has been mounted so that it can simultaneously observe light absorption or emission occurring within the spectrometer during a microwave experiment. Preliminary alignment of the optical system has been completed. Combined operation tests are being performed to eliminate interface problems between the two systems. Suitable high intensity short wavelength optical source lamps are being constructed.

The microwave spectral lines of three ^{13}C isotopic species of 2,4-dicarbohexaborane(6) have been assigned. These results, together with our earlier work, complete the study of this molecule. A final report is in preparation.

The OD radical dipole moment will be determined within the next year. A final report on the OH radical in its ground vibrational state will be completed in the next report period.

Vibrationally excited OH radicals may be observable by microwave spectroscopy. If so, their study would illuminate the energy transfer processes leading to maser and laser action in OH. An exploratory experimental examination of such radicals will be conducted.

Attempts to observe the microwave spectra of other important free radicals will be continued. Preliminary work with simultaneous optical and microwave observations has been very encouraging. A more thorough application of this method will be attempted.

Electron Scattering - S. Trajmar

High-resolution electron-impact spectral results have been obtained for CO, He and N_2 by employing nearly continuous operation of the spectrometer. The electronic energy loss spectrums of He and N_2 have been determined. The vibrational progression within the Cameron electronic band system of CO was investigated. Pure vibrational excitation of CO as a function of angle has been determined, at several impact energies.

Experimental and theoretical results are being prepared for both publication and symposia presentations. A comprehensive review of recent advances in electron impact spectrometry was prepared and submitted for publication.

By using a computer program obtained from NBS, a complete new set of electron optics has been designed and is now being built. The new optical system will improve the angular and energy resolution of our spectrometer.

An instrument for measuring the absolute differential cross sections is being assembled. This instrument is scheduled to be completed and tested during the next report period. The present high resolution spectrometer has provided intensity ratios for the inelastic to elastic features. The new machine will put all measurements on an absolute scale.

ANTICIPATED PUBLICATIONS

Trajmar, S., Rice, J. K., and Kuppermann, A., "Electron Impact Spectrometry," Advances in Chemical Physics (in press).

Truhlar, D. G., Rice, J. K., Kuppermann, A., and Trajmar, S., "Differential and Integral Cross sections for Excitation of the 2^1P State of Helium by Electron Impact," Phys. Rev. (in press).

PUBLICATIONS

JPL Publications

Poynter, R. L., "The Microwave Spectrum of the OD Free Radical," JPL SPS 37-54, Vol. III, p. 166.

THEORETICAL PHYSICS

NASA Work Unit 129-02-07-02

JPL 329-20901-1-3280

M. M. Saffren

OBJECTIVE

The objective of this work unit is to define and solve specific problems which mark out the frontiers of modern theoretical physics and are relevant to the long-range goals of NASA. The current work is in quantum theory.

PROGRESS

Work still centers about the attempt to understand the electronic behavior of molecules and solids. Geller continues his study of polyatomic molecules by means of the Hartree-Fock method. Saffren is still engaged in his study of the band structure of solids and now has attacked the problems of devising pseudopotentials for both the transition and rare-earth metals. In other work (with R. Vaughan and D. Elleman) he has suggested an experimental technique which may prove useful in the study of catalytic reactions taking place on crystal surfaces. Zmuidzinas is now well into his study of the electron gas at metallic density.

Geller (with L. Sachs of RIAS) has completed extending their computer program MOSES so that it may be used in the study of open-shell molecules. Calculations cannot be carried out, however, until the program is rewritten for the UNIVAC-1108 computer, which has replaced the IBM-7094 at the Laboratory. Calculations should resume within the next two months on the molecules H_3O^+, N_2C^+, $NC_2{}^+$, and N_2H^+. All are molecules that appear to be intermediates in ion-molecule reactions that are difficult to study experimentally. The particular reactions in which they occur are of extreme interest to chemists studying abiogenesis.

Work (with E. W. Ng) on integrals that stemmed from an analysis of the integrals used in the program MOSES has been completed, and published.

A completed study of the NF_2^+ molecule is being prepared for publication, as is a study of the correlation energy of the isoelectronic series Be, B^+, C^{++}, ... From this study the understanding of the correlation energy associated with each atomic shell can be applied to further refine Hartree-Fock energies of molecules.

Saffren continues work on the band structure of crystals. He has completed his work on the separation of the band structure into potential-sensitive and potential-insensitive parts for three crystal lattices; the body-centered cubic, the face-centered cubic, and the tetragonal; and this work is being prepared for publication. The study shows that the band structures of all three lattices are correlated and the predicted correlations have been successfully tested for iron. These relations can now be used to predict the band structure of one phase of a material once the band structure of its other phase is known. This work in all of its aspects should be of some use in an experimental study of the change of band structure with pressure to be carried out in the near future in the Physics Section by Professor R. Vaughan of Caltech.

Another result that has come out of Saffren's study has led him to a new method of generating crystal pseudopotentials. In the study it was shown that pseudopotentials for the transition and rare-earth metals are of little value, unless the pseudopotential is non-local. Using the Green's function formulation of the periodic potential problem, Saffren has found a natural way of generating non-local pseudopotentials for the rare earths and transition metals, and he is now attempting to reduce it to the stage where it can be applied to actual computation of the band structures. These metals are of extreme interest for not only do they comprise the only ferromagnetic elements but they also comprise the bulk of the metallic catalysts.

In other work, Saffren (with Vaughan and Elleman) has suggested that catalytic reactions taking place on metallic surfaces can be studied as they take place. By studying the energy losses of electrons field emitted from the metal by the action of an applied electric field, it should be possible to identify the chemical intermediates on the surface. Electrons coming through the surface excite the molecules in the surface to higher states and, in so doing, lose a characteristic amount of energy. By comparing energy losses before all reactants are present on the surface with those after all the reactants are present, the energy losses caused by the intermediates can be isolated, the spectrum of the intermediates deduced, and the intermediates identified. Another possibility is to use field emission to affect the actual catalytic activity, enhancing it or diminishing it with changing field. Also, using the same ideas, it may be possible to study the geometrical disposition of the reactants on the surface by electron diffraction but with the electrons coming from <u>inside</u> the metal.

Zmuidzinas has been concerned with the problems of the electron field at metallic (intermediate) densities. After considerable exploration, he has settled on a method based on the equation of motion of the so-called "pair operators," corresponding to electron-hole excitations in the gas. The procedure ultimately leads to an equation in which the density matrix elements are determined in terms of a non-linear expression involving the density fluctuations. If this term is neglected, the well-known RPA results for the electron-gas is recovered. To go beyond RPA, one has to consider the nonlinear terms. At the moment he is exploring a quasilinear approximation in which one factor of the nonlinearity is treated exactly and the other approximately, in the RPA, in fact. In the immediate future we hope to calculate various physical quantities in this approximation and thereby explore its validity. Later, we hope to undertake numerical solution of the full nonlinear equation — using the quasilinear results as a start — in order to study the interesting and controversial question of the phase transition thought to occur at metallic densities.

PUBLICATIONS

<u>Meeting and Symposia Papers</u>

J. Zmuidzinas, "Pair Operator Approach to the Electron-Gas Problem," presented at the American Physical Society, Rochester, New York, June 1969.

Journal Articles

E. W. Ng and M. Geller, "A Table of Integrals of the Error Function," J. Res. NBS, B. Math Sci. 738, 1 (1969).

C. S. Wu and J. S. Zmuidzinas, "Enhanced Fluctuations in a Magnetized Plasma Due to a Degenerate Ion-Wave Instability," Phys. Rev. 177, 2239 (1969).

JPL Publications

J. S. Zmuidzinas, "Dielectric Function of a Low-Density Electron Gas," JPL SPS 37-54, Vol. III (1969) (in press).

INTERPLANETARY AND SOLAR FLUID PHYSICS

NASA Work Unit 129-02-08-04

JPL 329-22101-0-3280

A. Bratenahl
C. M. Yeates

OBJECTIVE

To identify the mechanism of the rapid reconnection of field lines (flux transfer) and accompanying energy release at magnetic X-type neutral points, a basic problem in plasma dynamics whose solution is of crucial importance to understanding certain solar and interplanetary observational data, e.g., solar flares, "open" magnetospheres with plasma injection, etc.

PROGRESS

A considerable breakthrough has been achieved during this six-month period, and a detailed report is near completion for The Physics of Fluids. Schlieren photographs (Fig. 1) and other recent data filled critical information gaps, and it is now clear that in our double inverse pinch device: (1) the double source-flow satisfies $B^2/\mu\rho > u^2 > \gamma p/\rho$; and therefore, shock-like transitions are required in the collision region, not only at the X-point where $B = u = 0$ (hyperbolic pinch), but also just downstream of the separatrix, where pairs of slow-mode switch-off shocks may be seen branching off to the sides of the central collision layer. These shocks have been studied in some detail. (2) For a time, flux transfer is a quasi-steady state process controlled by resistive diffusion in the pinch region, which is shrunk to small size by the influence of the slow-mode shocks (this is the first time such shocks have been identified in laboratory experiments). The X-point current and electric field are proportional (normal ohmic conduction), and the flux merging rate is 4 cm/μsec, but the plasma density decreases while the pinch current increased. (3) The quasi-steady state (2) is abruptly terminated as the carrier drift velocity approaches the thermal agitation speed (critical

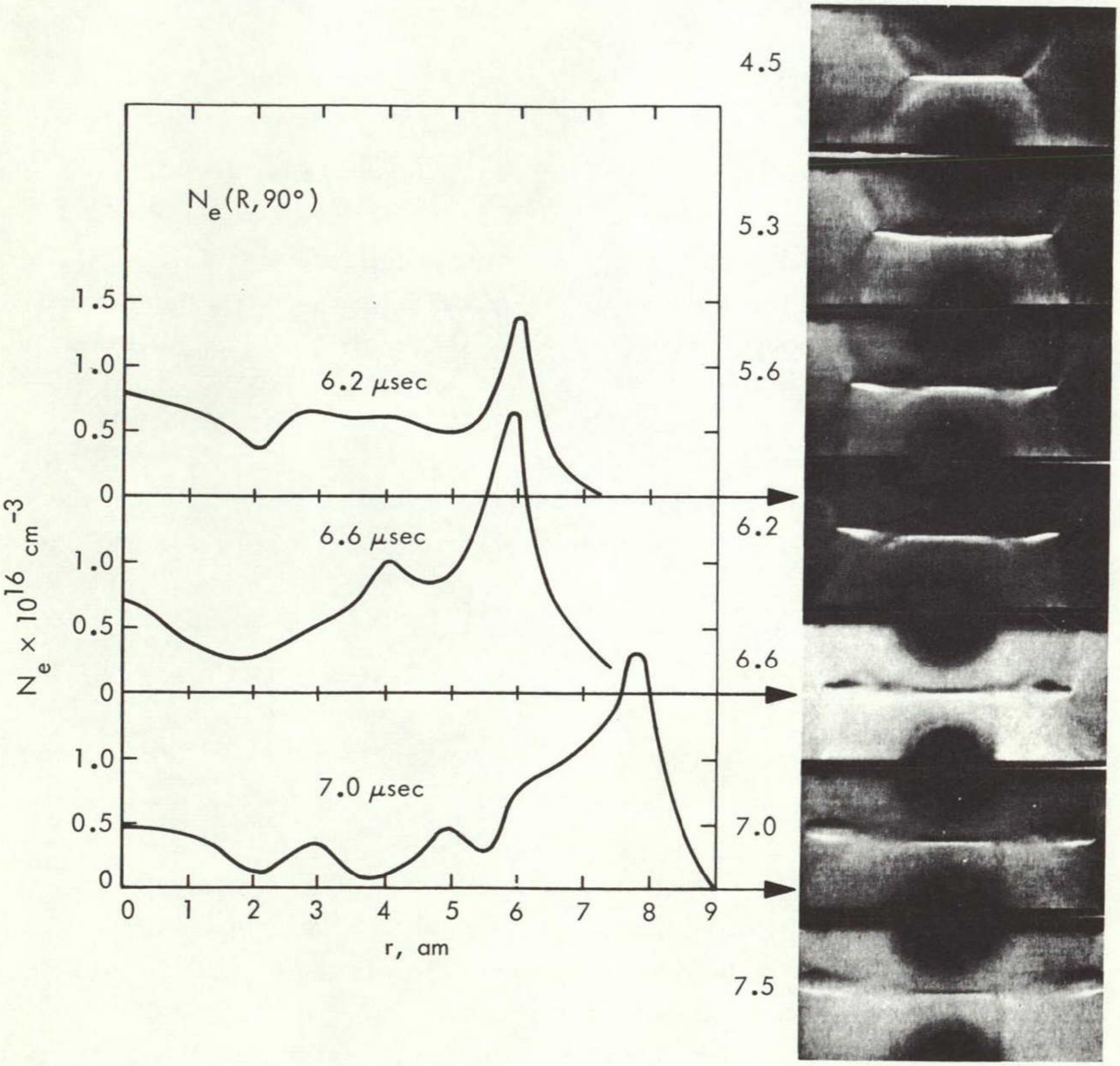


Figure 1. Sequence of Schlieren Photographs Compared with Profiles of Ne along the Collision Layer

condition), the current is cut off and electric field shoots up with sudden appearance of anomalous resistivity (>10-fold increase), and the merging rate jumps up to match fast-mode wave speed, 16 cm/μsec. This new rate bottleneck takes the place of resistive diffusion, thus, we find an ultra-fast reconnection rate which is controlled by the maximum possible rate of transport of flux into the X-point region. A number of other highly significant conclusions have been drawn which stand well-supported by the experimental evidence. At the moment of onset of the instability, the energy source is supplying 150 megawatts. The event induces an additional surge of 15 megawatts. This unique experiment has demonstrated nature's solution to a very basic problem which has widespread application in both space research and plasma technology and confirms certain theoretical predictions[1,2] in a clear-cut manner.

PLANS

We intend to pursue the matter of anomalous resistivity, looking into emissions of microwaves, X-rays, runaway and high energy particle acceleration, and generation of ion-acoustic waves and turbulence, all of which are presently indicated, and the experiment affords an unusually fine opportunity for this study. We also intend to relate the results more directly to the role played by the structural morphology of magnetic fields, developing ideas on the synoptic sequences leading to solar flares, thus utilizing this new and valuable technical resource to fulfill the primary motivation for this work.

REFERENCES

1. Petschek, H. E., AAS-NASA Symposium on the Physics of Solar Flares, NASA SP-50, 1964, p. 425.

2. Friedman, M., and Hamberger, S. M., Ap. J. 152, 667, 1968.

ANTICIPATED PUBLICATIONS

Bratenahl, A., and Yeates, C. M., "Experimental Study of Magnetic Flux Transfer at the Hyperbolic Neutral Point," in final stages of completion for submission to <u>The Physics of Fluids</u>.

PUBLICATIONS

None

LIQUID METAL FLUID DYNAMICS

NASA Work Unit 129-02-08-05

JPL 329-22401-0-3280

H. Ashkenas
T. Maxworthy

OBJECTIVE

The objective of this work unit is to study the astrophysically and technologically important subject of magneto-turbulence. In particular, there is considerable interest in trying to understand the role of the magnetic Reynolds number (Rm) in changing the structure and evolution of turbulence in a conducting fluid which is in the presence of a magnetic field. The liquid sodium tunnel at JPL is uniquely suited to such a study, and a program to measure the properties of turbulent jets at high Rm has been initiated.

PROGRESS

Previously reported tests of contained, turbulent air jets prompted design of two systems of the modified liquid Na tunnel, and the simpler one has been installed. It consists of a 1/4"-diameter sharp-edged hole in a 4"-diameter plate. For this particular ratio of jet area-test section area, the turbulent jet spreads as if in an infinite medium for twenty jet diameters before wall effects are noticeable. This is thought to be sufficient for initial tests. A more sophisticated system with a 1/2"-diameter jet and a small secondary flow will be used at a later stage.

A continuing number of subsidiary tests have been performed in the NaK tow tank in order to visually observe the effects of a magnetic field in a turbulent jet. Previous tests had suggested some interesting effects caused by the interaction of the jet with a free surface. It was found that what had previously been thought of as an instability of the radial flow at the surface was, in fact, due to reflections of the side wall in the mirror-like, liquid-metal surface.

PUBLICATIONS

Journal Articles

Maxworthy, T., "Experimental Studies in Magneto-Fluid Dynamics: Flow Over a Sphere with a Cylindrical Afterbody," J. Fluid Mech. 35, 2, 411-416 (1969).

MATERIALS RESEARCH (129-03)

IONICALLY BONDED POLYMERS

NASA Work Unit 129-03-11-03

JPL 329-30401-1-3820

A. Rembaum

OBJECTIVE

The immediate objective is to determine the effect of ionic bonds on the mechanical, optical and electrical properties of covalently bonded polymers. The ultimate goal is the synthesis of a polymer exhibiting superconducting properties at relatively high temperature.

APPROACH

The study of ionene polymers of well defined structure permits the elucidation of electronic transport properties. By increasing the distances between positive charges, semiconducting elastomers may be synthesized and a correlation between electrical and mechanical properties becomes possible.

PROGRESS

Ionene Elastomers

Ionically bonded polymers may be prepared from commercially available "prepolymer diisocyanates" using the compounds represented symbolically in Fig. 1.

Reactions of X with Y, Y with X and X with Z compounds yield a very large number of homo, block or copolymers varying in tensile strength and hydrophilic character. In particular, solithane 113 after reaction with tetramethylamino propanol and subsequently with dibromohexane leads to an ionene the mechanical properties of which are compared with a conventionally prepared solithane (Fig. 2). The ionic solithane after complexing with LiTCNQ has a glass transition approximately 40°C higher than solithane 113 cured with castor oil. This high glass transition was also determined by plotting resistance versus temperature (Fig. 3). The resistivity of ionene elastomers complexed with TCNQ varies from 10^6 to 10^9 ohm cm.

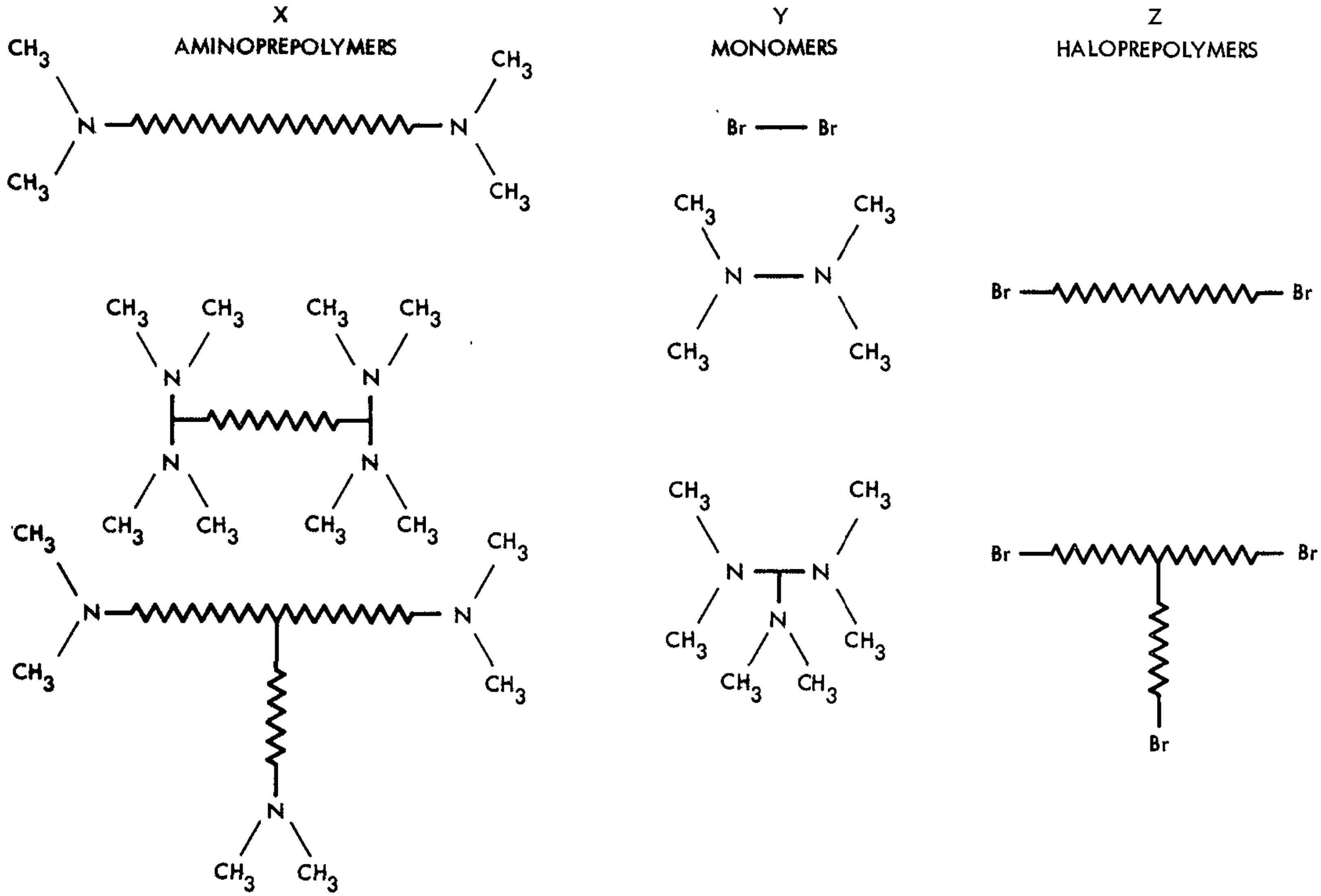


Figure 1. XYZ Elastomers

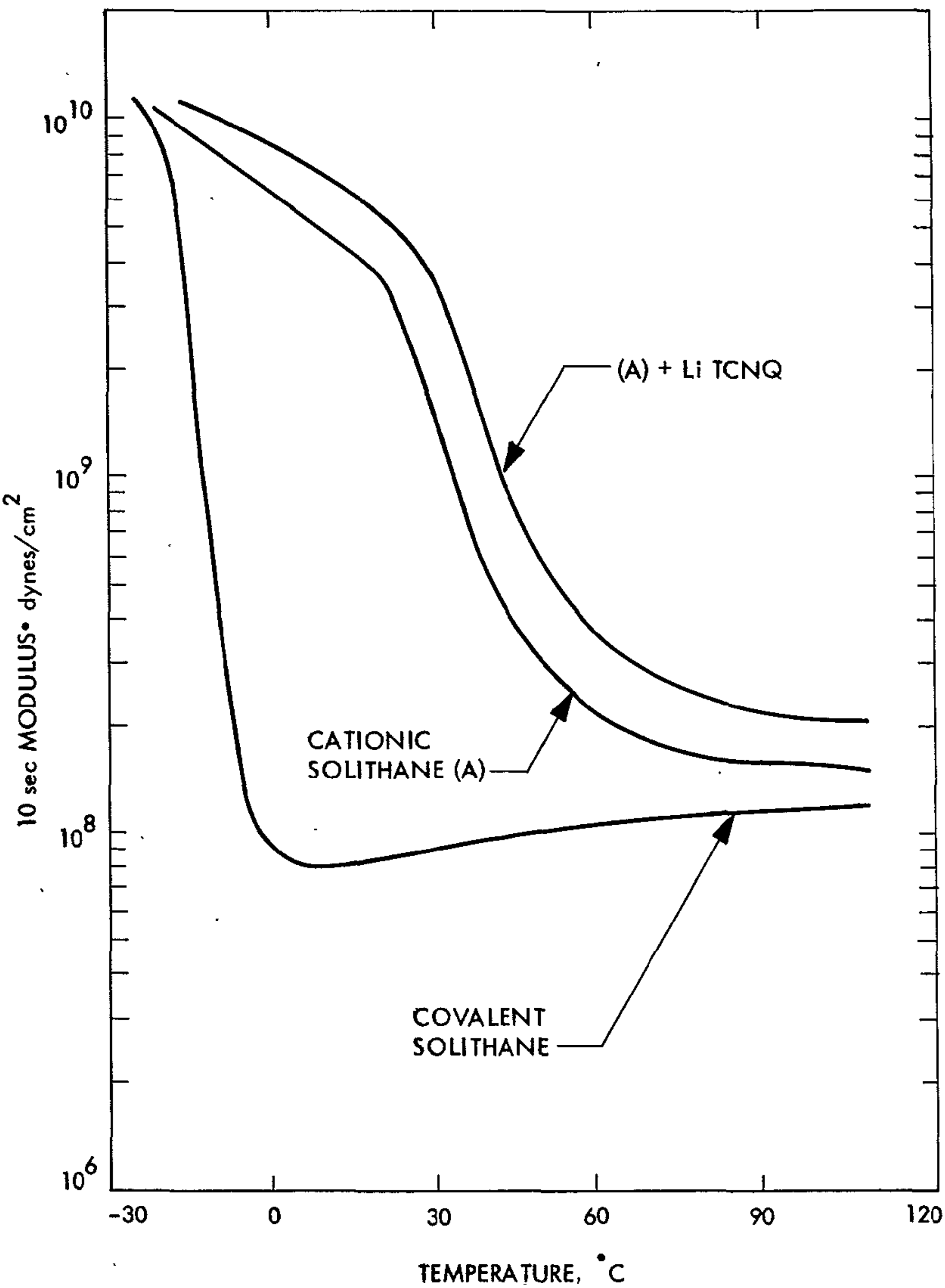


Figure 2. Dynamic Modulus Versus Temperature of Elastomeric Ionenes

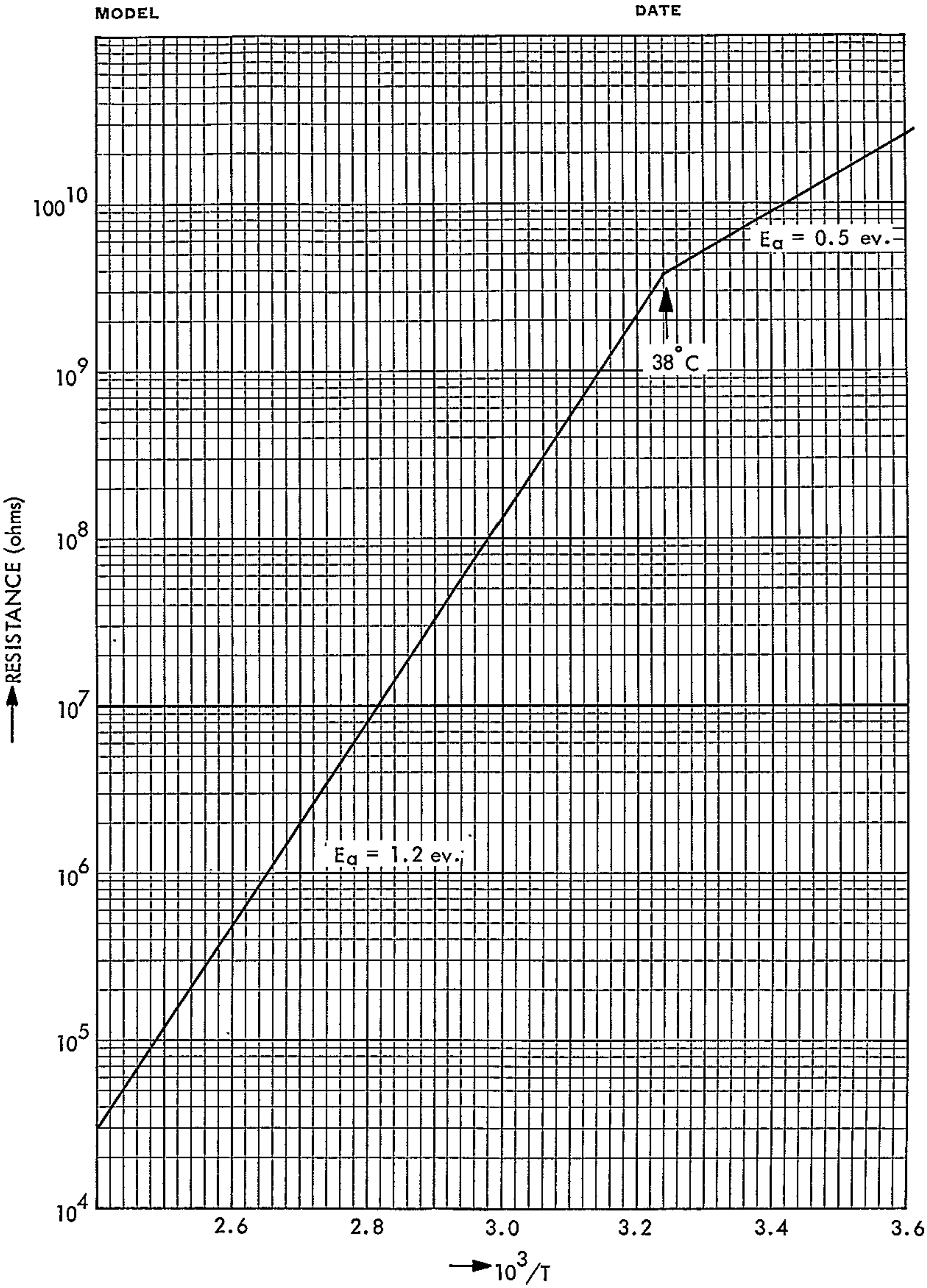


Figure 3. Electrical Resistance Versus 1/T of a Conductive Ionene

Conjugated Polymers with Cyanine Side Chains

An exploratory condensation polymerization of pyridine carboxaldehyde was carried out in order to synthesize a polymer of the following structure (Fig. 4).

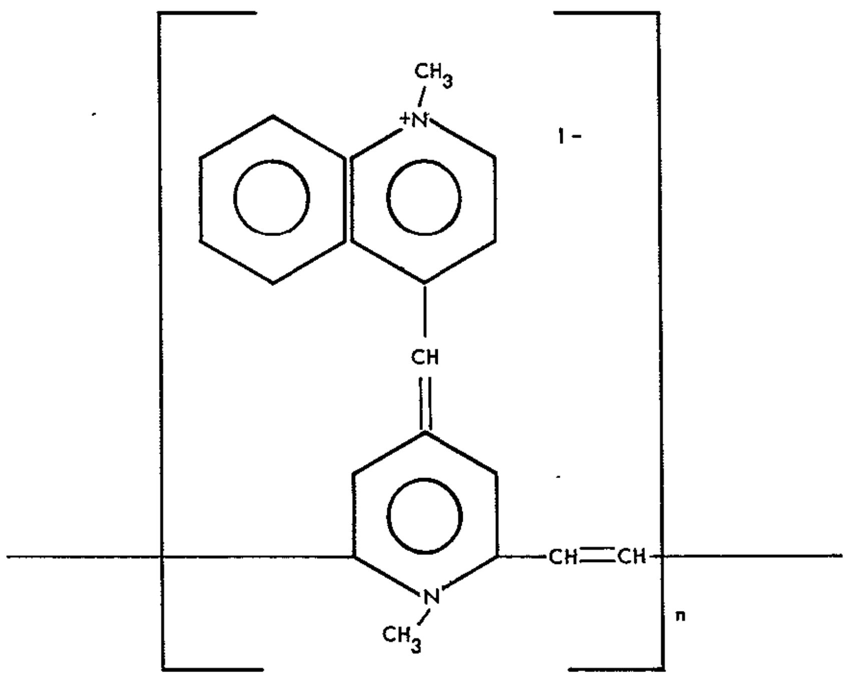
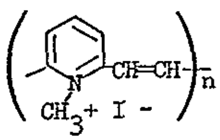


Figure 4. Conjugated Polymers with Cyanine Side Chains

The above polymer contains all the features suggested by W. A. Little for an organic superconductor.

The spectrophotometric characteristics of intermediates and model compounds for structure shown in Fig. 4 are recorded in Table I.

Table I. Spectrophotometric Absorption Features

Compounds	Location of Absorption Peaks (millimicrons) (Intensity indicated by S. strong; W. weak)
	210 S, 223 (shoulder), 230 (shoulder), 315 (shoulder), 338 S
methiodide of above	200 S, 220 (shoulder), 270 W, 300 W, 365 S
cyanine from above	205 S, 230 (shoulder), 290 W, 305 (shoulder), 330 S, 555 W, 705 W
	221 S, 273 W, 325 W
rose, water-soluble methosulfate as above	211 S, 275 S
green, methanol-soluble methosulfate as above	200 S, 275 S, 315 W, 600 W
cyanine from above	200 S, 235 S, 315 W, 456 S, 555 W, 706 S

PLANS

It is planned a) to explore the mechanism of conductivity of elastomeric ionenes by D. C. and A. C. measurements, b) to continue the synthesis and proof of structure of a conjugated polymer with cyanine side chains, c) to establish the possibility of superconductivity in liquid ammonia solutions.

PATENTS ISSUED

1. A. Rembaum, R. Landel, "Preparation of Alkali Metal Dispersions" U.S. Patent 3, 419, 384.

2. A. Rembaum, A. W. Henry, "Thermally-Stable Polymeric Semiconductors" U. S. Patent 3, 419, 537.

PATENT APPLICATIONS

1. A. Rembaum, "Heat Detection and Compositions and Devices Thereof: JPL No. 1409 CIT No. 1245.

2. A. Rembaum, "Cationic Polymers" JPL No. 1471, CIT No. 1248.

PUBLICATIONS

Meeting and Symposia Papers

1. A. Rembaum "Ionene Polymers," Akron and Detroit University, June 5 and 9, 1969 respectively.

Journal Articles

1. A. Rembaum, A. Hermann, F. Stewart and F. Gutmann, "Electronic Properties of Some TCNQ Complexes" Journal of Physical Chemistry 73 (3) 513 1969.

2. A. Rembaum, "Polyelectrolyte Complexes" Journal Macrom. Sci. Chem. A 3 87 (1969).

3. F. Gutmann, A. Hermann, A. Rembaum, "Activated Carrier Mobility In Organic Solids," Nature 221, 1237 (1969).

JPL Publications

1. H. Noguchi, A. Rembaum, "Ionene Polymers: Formation of Cyclic and Linear Compounds or Polymers 37-55 Vol. III.

2. A. Rembaum, A. Hermann, "Dependence of the Conductivity of Pyrene-TCNE Charge Transfer Complex Upon Pressure" 37-55 III.

RHEOLOGICAL PROPERTIES OF POLYMERS

NASA Work Unit 129-03-11-04

JPL 329-30501-1-3820

J. Moacanin
S. H. Kalfayan

OBJECTIVE

The objective of this task is to determine the molecular parameters which control the mechanical properties of amorphous, single-and multi-phase polymeric systems.

PROGRESS

During the previous period, a theoretical analysis of the viscoelastic behavior of elastomers undergoing scission reactions was developed. This initial analysis provided a conservative estimate of fatigue life. The present development takes into detailed account the effect of sample history on the creep behavior.

For networks undergoing scission, we assume that the elastomer will exhibit at a given time the same response as a non-degrading elastomer of equal ν. This is illustrated in Figure 1 for the case of a single change in crosslink density at t* from $\nu_1 \longrightarrow \nu_2$. The dashed curves represent the response for non-degrading elastomers having densities ν_1 and ν_2, respectively. The "degrading" system, represented by the solid curve, follows the response of curve ν_1 until t*. After t* it follows curve ν_2 translated horizontally by the amount a. The necessary physical assumption to justify this shift is that all the load is uniformly distributed among the network chains before reaction, and that when scission occurs the load is uniformly redistributed instantaneously among the remaining chains. In terms of a model representation, this would imply that we start with a sufficient number of Voigt viscoelastic elements in parallel to simulate the response of the network with ν_1 chains; at t* we remove the elements corresponding to ν_1-ν_2 network chains. By restricting our treatment to a

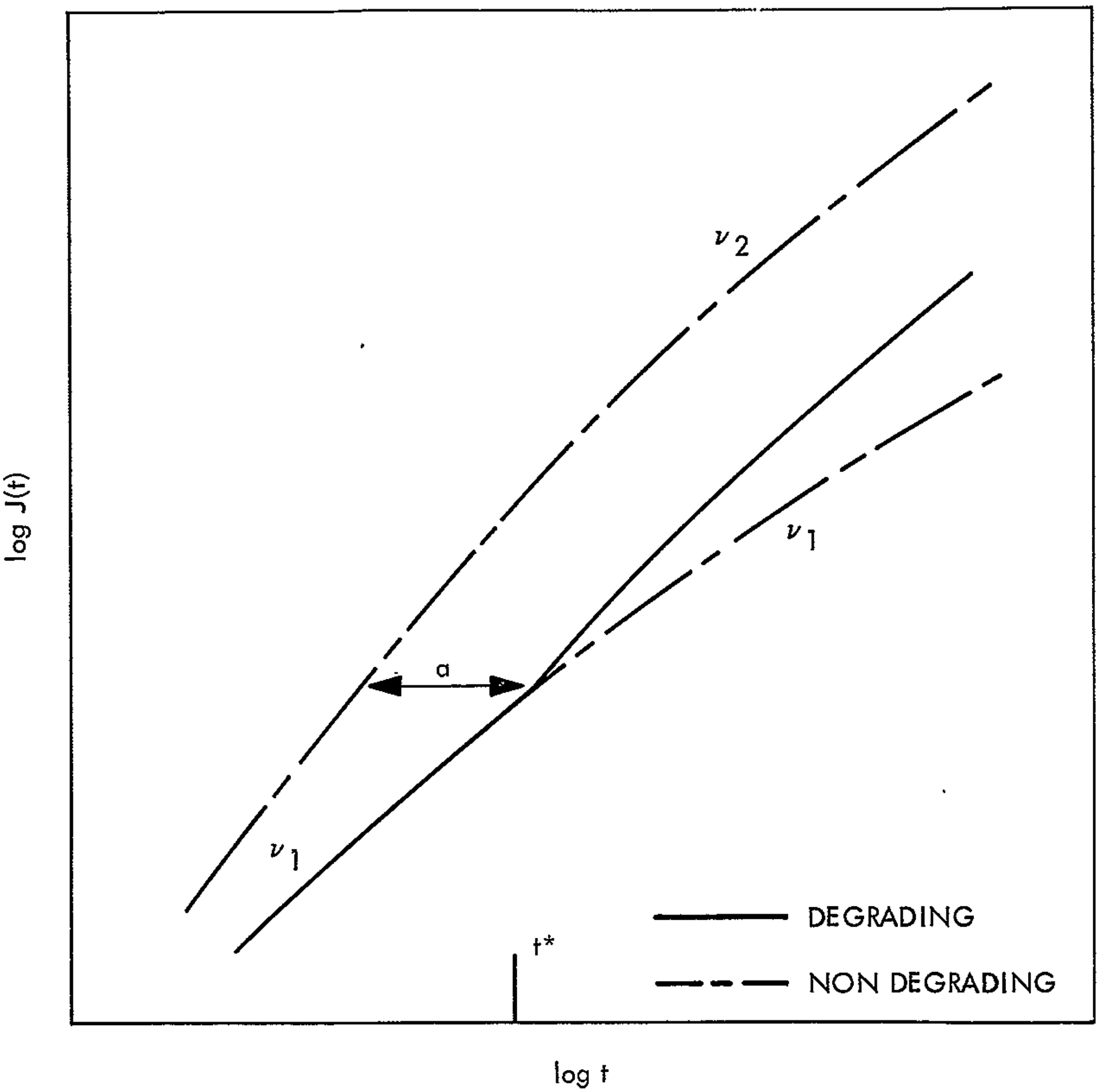


Figure 1. Response for Elastomers—Degrading and Non-Degrading

horizontal shift, we neglect the possibility of an instantaneous Hookean response when the load per element is increased.

In order to arrive at a mathematical representation of this treatment for a system undergoing continuous chemical change we have assumed that the shear creep compliance J(t) can be represented by the following equation

$$J(t) = G_g^{-1} \frac{1 + t^{\frac{1}{n}}}{1 + \epsilon t^{\frac{1}{n}}}$$

where t is in dimensionless units of time, n is an integer and ϵ is the ratio of rubbery to glassy modulus. For a degrading system ϵ will be a function of time. If at t a change in ϵ occurs, we impose the condition

$$J_{\epsilon}(t + a) = J_{\epsilon+\Delta\epsilon}(t+a+\Delta a)$$

The appropriate differential equation was derived by substituting the above function and going to the limit $\Delta a \rightarrow 0$.

The degradation kinetics will determine the time dependence of ϵ. The case for zero order kinetics, was analyzed, i.e.:

$$\epsilon = \epsilon_o (1 - kt)$$

Experimental evidence for such a scission rate law has been observed to apply to natural rubber.

Under certain conditions, the response of a network can be dominated by either viscoelastic retardations (i.e., very slow chemical scission) or scission phenomena (i.e., very fast retardation). Since our development is designed to treat the situations where both of these effects contribute substantially to the observed behavior, it will be necessary to determine the range of values of the parameters ϵ_o and k in which a coupling of the two mechanisms will occur. Figure 2 illustrates the range of values for the rate constant k where this coupling is observed.

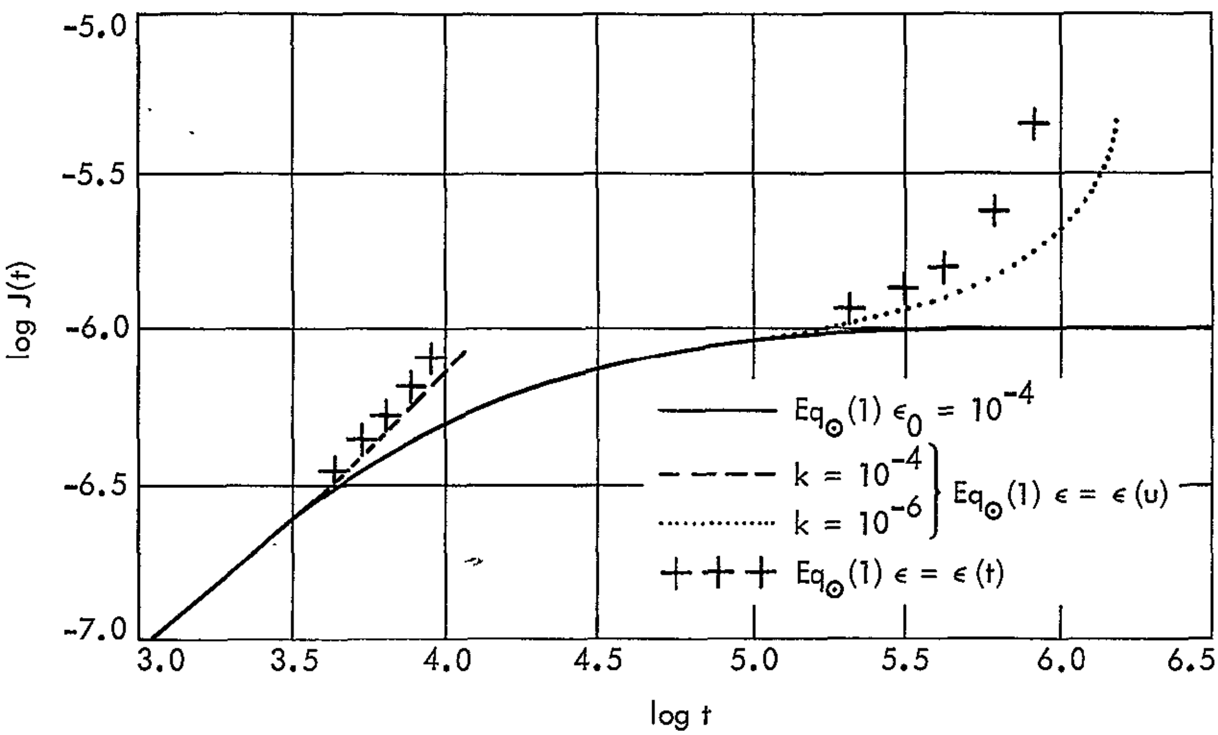


Figure 2. Coupling of Viscoelastic Retardation and Chain Scission

Aging of SBR: Spectral Investigation

The usefulness was explored of spectrographic methods in: (i) the investigation of the chemical changes that occur during the aging of SBR in air at elevated temperatures (100 - 125°C; (ii) the study of the kinetics of the oxidation of SBR. Both infrared (IR) and near infrared (NIR) spectral analyses were carried out. After 1 hour of heating at 100°C, the dicumyl peroxide cured SBR showed no observable changes in the IR spectra. Heating 4 hours at 120°C, however, increased the intensity of absorption of the carbonyl (1840 - 1630 cm^{-1}), the hydroxyl (3730 - 3000 cm^{-1}) and the ether (1250 - 1050 cm^{-1}) regions.

The NIR spectrograms, likewise, showed no change after the 100°C treatment. The general appearance of the spectrum was not altered even after exposure to 125°C for 4 hr. This apparent lack of change was due to the fact that the stretching vibration bands of the hydroxyl and carbonyl groups that lie in the 2.5 to 3.0 micron region, were not adequately excessible to the spectrophotometer used.

There is some indication, from these preliminary investigations, that a kinetic study of the oxidation of SBR may be possible by following the change in the absorbance of, for example, the carbonyl peak. For such a study, only purified SBR should be used to avoid interference from the additives present in the rubber. This possibility will be explored.

Aging of SBR: Stress Relaxation Studies

The relaxation of natural rubber has been reported to be due to two factors: aging and viscoelasticity. Aging is found to prevail at temperatures above 65°C, and viscoelasticity below this temperature. A linear relationship is observed when log f/f_o, where f and f_o are tensile forces at time t and time zero, is plotted against time. The energy of activation, ΔE, for natural rubber vulcanizate has been calculated by using rate values from stress relaxation data in a graphical solution of the Arrhenius equation:

$$k = Ae^{-E/RT}$$

This method was employed for SBR crosslinked with dicumyl peroxide. Since it is of interest to examine stress relaxation due to aging, temperatures above 85°C were used. At 125°C and above, test specimens broke down too rapidly for proper rate determinations. Stress relaxation measurements were made in air at 85, 100, 108 and 115°C, at 28% extension. Measurements were stopped when the rubber was completely relaxed. The rate of relaxation at each temperature was characterized by the rate constant, k, which is the slope of the line obtained by plotting log f/f_o vs. t. The following values were obtained:

$$
\begin{aligned}
k &= 1.22 \times 10^{-2} \text{ at } 85^\circ \text{ C} \\
&= 3.86 \times 10^{-2} \text{ at } 100^\circ \text{ C} \\
&= 1.25 \times 10^{-1} \text{ at } 108^\circ \text{ C} \\
&= 3.07 \times 10^{-1} \text{ at } 115^\circ \text{ C}
\end{aligned}
$$

The energy of activation, ΔE, was calculated from Arrhenius plots. The value obtained was 29.8 Kcal/mole, comparable to those obtained for natural rubber.

PLANS

The theoretical approach discussed above will be used in an analysis of experimental results which are available in the literature. The results of this analysis will provide an assessment of the theory. If found to be substantially correct the theory will be extended to include crosslinking reactions.

The relaxation rates of SBR of different crosslink densities will be determined, in air as well as in inert atmosphere.

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Meeting and Symposia Papers

1. J. Moacanin, J. J., Aklonis, R. F., Fedors, and R. F. Landel "Creep of Elastomers Undergoing Aging II," SPS 37-57, Vol. III; Presented at the Meeting of the Rubber Division, American Chemical Society, Los Angeles, California, April 29 to May 2, 1969.

JPL Publications

1. R. Rakutis, S. H. Kalfayan "Aging of SBR: A Spectral Analysis," SPS 37-57, Vol. III, June, 1969.

APPLIED MATHEMATICS (129-04)

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APPLIED MATHEMATICS
NASA Work Unit 129-04-01-01
JPL 329-40101-1-3910
C. B. Solloway

OBJECTIVE

The objective of this work unit is to conduct research in statistical estimation theory, optimal control theory, applied mathematics, computer science studies, and general relativity.

PROGRESS

Most of the activities in this half year concerned the study of optimal nonlinear estimation and its applications. TR 32-1366, "Optimal Nonlinear Estimation Based on Orthogonal Expansions" (Ref. 1) appeared, which contains the main theoretical framework of the approach. The central idea has been to obtain optimum estimates (both statistically and computationally optimum) based on evaluating the likelihood function and avoiding the use of the partial derivatives of the observables with respect to parameters being estimated. This has the advantage of avoiding the use of quantities which can only be calculated approximately in the problems of celestial mechanics. Even in problems where one can evaluate these derivatives exactly, it may require a great expenditure of computer time to do so. Therefore a routine which avoids these may be worthwhile even though the machine time expended on production may be greater. A revision of TR 32-1366, in which some theorems are sharpened and certain conjectures proved, is being prepared for publication.

The practical side aspects of these methods are discussed in an internal memorandum. One development that is given is the possibility of improving the estimate of a maximum likelihood estimator by only varying some of the parameters to be estimated. This technique is currently being applied to estimate the mass of Mercury.

Variations of these methods are also being used to estimate the gas leak parameters of Pioneer VI. The final result is not yet available, but a considerable reduction in the sum of the squares of the residuals has been achieved.

Future plans include the publication of a modified version of TR 32-1366 in the open literature, and the exploration of more efficient techniques for handling problems where a large number of parameters are to be estimated. More studies on the effect of nonlinearities in orbit estimation are being considered, as is the feasibility of including process noise. The mathematics involved in extending the present program to include process noise is relatively trivial, but the practical aspects involving the amount of computation are formidable.

Error analysis techniques have been developed for least squares and sequential filters. A new method, the sensitivity matrix method, was introduced and related to the consider option. The advantage of the sensitivity matrix method is that it allows one to perform an error analysis of many error sources simultaneously and distinguish among different effects. The method was applied to a Mars orbiter and the results showed that gravitational perturbations were the major sources of error (Ref. 2, 3).

Consider option and errors in suboptimal sequential filters neglecting certain state variables and process noises are being studied. Kalman filter equations are used in the analysis. The application to orbit estimation problems is being considered. A preliminary internal report (Ref. 4) has been published. A statistical model of the polar motion and universal time is being formulated and analysis of its properties will be made. The auto-correlation and power spectral density study were made for a 40-year series of the polar motion observations.

A similar analysis was made for a 12-year series of the universal time observations. The state and measurement equations with process and measurement noises will be determined. The application to orbit determination will be studied.

Optimal Control

Work continues in this area. New insight on conjugate point theory was obtained using a dynamic programming formulation (Ref. 5).

A new numerical technique "the (modified) successive sweep method," a Newton-Raphson algorithm in function space was used to compute optimal solutions to control problems which are characterized by terminal constraints and discontinuities in the control functions. The techniques were applied to the three-dimensional attitude control of an orbiting vehicle and to the two-dimensional transfer of a low thrust vehicle in a gravitational field, with gratifying results (Ref. 6).

Literal Series Expansions and Applications

The last six months have been spent exclusively in further implementing the research topics which were described in Ref. 7.

Computerized Series Expansions

Work is now being done to adapt these computer programs to the Univac 1108. It is expected that they will be operational by August 1.

Applications to Planetary Perturbations

Several programs have now been completely terminated for the IBM 7094. They have been used for the computation of partial derivatives for use in other research programs described elsewhere in this volume. These programs are now also being converted to the Univac 1108. The conversions should be terminated by September 1969. The different versions of these programs can handle planetary perturbations, relativity and solar oblateness. Some programs are limited to first-order perturbations only while others are designed to compute higher order perturbations.

Four documents describing this work have been published internally and as SPS articles and two of these have been submitted to a journal for publication. The subject matter was presented at the 7th Annual Yale Symposium in Celestial Mechanics, at Austin, Texas in January 1969.

General Relativity

In an SPS article (Ref. 8) a critique of the scalar-tensor theory of relativity is developed. The results here differ from those of Brans-Dicke as regards the advance in the perihelion of Mercury. The outcome will depend on further tracking and ephemeris work at JPL-CIT.

A primary objective of the research done in this field is the problem of testing the General Relativity by means of radar observations. The expressions for effects of the relativistic perturbations on osculating orbital parameters have been developed in closed forms for Robertson's, isotropic, and Schwarzschild's line elements in Ref. 9, based on a first-order perturbation theory. The relativistic effects on the range and range-rate of a spacecraft in the gravitational field of the Sun are derived in Ref. 10.

However, these perturbations do not necessarily represent observable deviations from Newtonian motion and, as a matter of fact, the osculating conics, used in the theory, do not represent the Newtonian conic. Moreover, these osculating conics are different for different line elements and an effort has recently been made to determine the relationships between the osculating orbital parameters for different line elements.

The current research is devoted to the problem of determination of relationships between the osculating initial orbital parameters, used in the theory, and the Newtonian orbital parameters, either by a possible coordinate transformation or some other method. Once these relationships have been established, the use of the already developed formulae for the relativistic effects on range and range-rate in Ref. 10 will yield the observable deviations of these quantities from the corresponding Newtonian values.

Attendance at Scientific Meetings

1. Seventh Annual Yale Symposium in Celestial Mechanics, Austin, Texas, January 13-15, 1969.

2. Ninth Special Projects Branch Astrodynamics Conference, Goddard Space Flight Center, Greenbelt, Maryland, April 21-22, 1969.

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7. Semi-Annual Review of Research and Advanced Development, Document 701-23, Volume II, July 1 - December 31, 1968, pp. 687-692.

8. Lass, H., "A Critique of the Scalar-Tensor Theory of Relativity," SPS 37-57, Volume III, June 30, 1969.

9. Georgevic, R. M., "Relativistic Perturbations of Osculating Orbital Parameters of a Spacecraft Moving in the Gravitational Field of the Sun," TM 311-94, January 24, 1969.

10. Georgevic, R. M., "Relativistic Effects on Range and Range-Rate of a Spacecraft Moving in the Gravitational Field of the Sun," TM 311-110, February 28, 1969.

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3. Dyer, P., and McReynolds, S. R., "Optimization of Control Systems with Discontinuities and Terminal Constraints," IEEE Transactions PGAC on Automatic Control.

JPL Publications

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1. Broucke, R. A., "Computerized Series Expansions: Applications to Lunar Theory," SPS 37-55, Volume III, February 28, 1969.
2. Broucke, R. A., "A Program for the Computation of First-Order General Perturbations," SPS 37-56, Volume III, April 30, 1969.
3. Broucke, R. A., "Computation of Periodic Terms in General Relativity Perturbations," SPS 37-56, Volume III, April 30, 1969.
4. Georgevic, R. M., "Relativistic Effects on the Motion of a Spacecraft in the Gravitational Field of the Sun," SPS 37-56, Volume III, April 30, 1969.

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6. McReynolds, S. R., "The Sensitivity Matrix Method for Orbit Determination Error Analysis with Application to a Mars Orbiter," SPS 37-56, Volume II, March 31, 1969.

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LUNAR AND PLANETARY FLIGHT MECHANICS

NASA Work Unit 129-04-01-02

JPL 329-40201-1-3910

C. B. Solloway

OBJECTIVE

The objectives of this work unit are to conduct basic research in celestial mechanics, to evaluate astronomical and physical constants from postflight analysis of tracking data, to improve planetary ephemerides from radio tracking data and planetary radar data, and to study advanced techniques for trajectory calculation and orbit determination more realistically that account for the physical features of the solar system and the spacecraft.

In the coming period, the objectives of this task will be modified to the extent of deleting evaluation of astronomical and physical constants and improvement of lunar and planetary ephemerides. They have been expanded to include the study of advanced techniques for the treatment of systems of differential equations which occur in almost every branch of applied mathematics. The title of the task unit will be renamed 'Mathematics of Flight Mechanics'.

ASTRODYNAMICAL AND PHYSICAL CONSTANTS

Icarus and the Mass of Mercury

During the period from January 1 to June 1, 1969, an attempt was made to experimentally determine the mass of Mercury and the solar oblateness second harmonic coefficient (J_2) and to attempt to separate the effects of general relativity and solar oblateness through use of optical data from the asteroid Icarus and radar and optical data from Mercury, Venus, and Mars. The results using strictly Icarus data were reported in Ref. 1.

The results for the planets were accomplished using a Fourier series to approximate the variational equations of the inner planets with respect to planetary masses, relativity, and solar oblateness to at least three significant digits. The series were incorporated in a special version of the JPL ephemeris development program (SSDPS); the use of series for variational equations has apparently not been done previously.

Preliminary results indicate that the planetary data completely outweighs the Icarus data in determining the parameters of interest, that the Einstein model for general relativity in the equations of motion is confirmed to 1/2% provided zero solar oblateness is assumed (confirming an earlier result by Clemence), and that a small oblateness ($|J_2| < 5. \times 10^{-6} \pm 2. \times 10^{-6}$) is obtained if general relativity is assumed to be correct. This value of dynamical oblateness is about ten times smaller than that inferred from the visual oblateness observed by Dicke. It was not possible, with currently available data, to obtain a significant separation of the oblateness and relativity effects or to obtain significant information about general relativity from the relativistic propagation effect on radar signals passing near the Sun. The solution for the mass of Mercury is similar to that obtained earlier by Melbourne and O'Handley. It is not sensitive to the inclusion of the relativity and oblateness parameters in the solution, but is sensitive to whether optical data is used so that further analysis is required. It is intended that these results will be presented in a joint paper at the American Astronomical Society meeting in August, 1969. Further work is in progress on this task.

Mariner IV C. M. Experiment and the Mass of Mars

The second task has been to reanalyze the new encounter Mariner IV mass probe doppler tracking data as part of the Mariner IV Celestial Mechanics Experiment. The object is to improve the accuracy of the results initially reported in 1967 (Ref. 2) by using a more precise computer program. Major improvements are a gravitational constant for Mars improved to better than $\pm 1.0\ km^3/sec^2$ and an independent (but less accurate) confirmation of the second harmonic of Mars than that which was obtained from the Martian satellites. The delay in reprocessing the MA IV data taken in 1965 has been to permit use of the JPL Double Precision Orbit Determination Program (DPODP), a 16 decimal digit program which became operational in 1969. It is intended to present these results at the AAS meeting in August, 1969. Further work is in progress using DPODP to obtain a solution for the Earth-Moon mass ratio and the in-plane elements of the Sun - (Earth Moon Barycenter) ephemeris. These results will be compared and published jointly with the Pioneer and MA II, MA 6, MA 7 cruise results since it is generally accepted that significant answers for the Earth ephemeris require this combined approach. It is also intended to combine the cruise S/C results from the above missions with the planetary data using a combination of DPODP and SSDPS programs.

Mass and Dynamical Oblateness of Venus

Planetary masses (GM) derived from spacecraft tracking data measurements are expressed in reciprocal solar mass units obtained from the ratio GM/GS where GS is the solar mass. The value of the mass of the Sun is related to the astronomical unit (AU) through the relation $GS = k^2 (AU)^3$. Thus, a knowledge of both GM and AU is required in order to correctly obtain the reciprocal mass ratio. Earlier solutions for the mass of Venus from Mariner II radio tracking data made use of values for the AU which differed from the currently used value which is determined to better than 3 parts in 10^8.

Radio tracking data from both MA II and MA V have now been used to establish a value for the mass of Venus with considerably more confidence than before because of the following three recent developments:

(1) Planetary ephemerides, particularly for the Earth and Venus, have been improved by optical and radar bounce data to the point where they can be neglected as sources of systematic error in the Mariner mass solutions. Range measurements to Mariner V near Venus encounter have been used in the compilation of the planetary ephemerides used in this study.

(2) Mass solutions from the single precision computer program used in the older work have essentially been duplicated by independent double precision programs.

(3) Mass solutions from encounter Doppler data for Mariner II and Mariner V, considered separately, agree to better than one part in 10^6.

As a result of these recent developments, the reciprocal mass of Venus can be given as 408521.8 ± 1, where the uncertainty is a conservative estimate of the standard deviation. Covariance analyses of the Mariner II and Mariner V solutions yield formal standard deviations of ± .8 and ± 0.24 respectively.

The dynamical oblateness of Venus as determined by the Mariner V data is very small, most likely less than 1/100 that of the Earth. Solutions for the second harmonic bulge coefficient J_2 indicate that within the range of single precision calculations, a value of $J_2 = (-5 \pm 10) \times 10^{-6}$ results in a satisfactory set of Doppler residuals. Double precision calculations and the addition of a Venus oblateness model having the tesseral harmonic C_{22} are needed to refine the value further and to reduce the uncertainty. The software necessary to accomplish this has recently become available and efforts are now in progress to obtain further results.

MARINER MARS '71 CELESTIAL MECHANICS EXPERIMENT

An objective of the MM '71 Celestial Mechanics Experiment is to attempt to measure general relativistic effects in the orbit of Mars by means of high precision ranging data to the orbiting spacecraft. By tracking a planetary orbiter over one or more revolutions, it should be possible to obtain the geocentric distance to the center of mass of the planet to an accuracy of a few meters. Radar bounce measurements made from the ground are about two orders of magnitude less accurate and a considerable improvement in the ephemerides of the Earth and Mars can be expected as a result of the MM '71 mission.

Perturbations in the orbit of Mars resulting from a ring distribution of asteroidal material at 2.8 a.u. have been computed and compared with those from general relativity to see if there is any problem in separating the general relativistic and asteroidal perturbations. There are two basic conclusions of this study.

The first is that the secular advance of the perihelion of Mars, which arises from general relativity, could be explained equally well by a ring of asteroidal material with a total mass equal to 0.031 Earth mass (a value which is not observationally unreasonable, although, a value ten times smaller than this is more likely).

The second conclusion of the study is that the periodic perturbations from general relativity or an asteroidal ring agree in phase, and a total mass of asteroidal material equal to 0.036 that of the Earth produces an amplitude of 550 m in the semi-major axis, a value equal to the Schwarzschild relativistic amplitude. Therefore it is impossible to tell the difference between general relativistic perturbations and those from an asteroid belt of unknown mass, at least from the first harmonic in the orbital frequency.

In order to obtain an estimate of the level at which the asteroidal and relativistic perturbations could be separated, the first harmonic term was filtered out of the periodic perturbations in both cases. Fortunately, the remaining times were less than one meter in amplitude for the asteroidal material if the total mass of the asteroids was assumed equal to 0.01 that of the mass of the Earth. On the other hand, the higher order terms in the relativistic perturbations produced observable effects on the order of 500 m. Therefore, it appears that a ranging system good to a few meters could possibly separate general relativistic motions from those produced by an asteroid belt of unknown mass.

SELENODESY

The original processing of differentiated doppler residuals from lunar orbiter was redone using an improved spline-fitter and extending the data set to permit mapping of the earthside lunar hemisphere between ±60° Latitude and ±110° Longitude. Results of this rework were reported in the proceedings of COSPAR for 1969. The map extended the list of identified positive mascons to 12, including two in unnamed features, names for which have been proposed.

A model for the gravitational shape of the earthside hemisphere was produced using hand-fit iterations through the JPL SPODP. This model appears to be the best available for determination of the spacecraft state vector at a time when it is on the frontside with nearby observations (as opposed to the more difficult task of predicting position). The backside uncertainties prevent significant improvement in prediction.

A quantitative model of the fine structure of the lunar gravity field was constructed, in iterative stages, from a representative portion of the Lunar Orbiter tracking data. The first stage model was constructed of masses chosen to reproduce the accelerations (slopes) of the doppler residuals remaining after orbit determinations using only a simple model (tri-axial) for the moon's gravitational field. The details of the procedure for obtaining this model is described in Ref. 3.

This first stage model was then used to integrate the trajectories for another round of determinations of selected orbits. The residuals were observed to be significantly lower, but still showed some residual accelerations, so further masses were added to the model. The iterative procedure consisted of adding masses, obtaining doppler residuals by integrating with the updated model, and then computing new additional masses from the accelerations (slopes) of these residuals. The results of the early stages of this iterative procedure are described in SPS Ref. 3 and 4. The more recent refinements are described in SPS Ref. 5.

The model was tested on the tracking data from the Apollo 8, lunar orbit phase, which became available after several stages of iteration. The residuals remaining were less than .4 Hz while the largest residuals from a simple tri-axial fit were over 1 Hz. The Lunar Orbiter residuals with the latest model are also less than .4 Hz (in most trajectories less than .2 Hz) compared with a maximum of 2 Hz remaining after a tri-axial fit.

Considerable progress has been made on a dynamical solution to the nearside gravity using individual mass-points in the solution set, arranged in a grid over the lunar surface. It is now apparent that completion of this task will require at least several more months.

The question of water on the moon as the basic cause of the mare and associated features as observed on the Lunar Orbiter pictures has been reopened partly through implications of the mascons as regards methods for producing gravity highs in basins, and partly through arguments based upon selected lunar orbiter photographs showing the well known lunar morphologies such as ghost craters, eroded craters, sinuous rilles, beaches and benches, arroyos, and the absolutely flat nature of the mare material and the playa lakes. The mascon discovery agrees with IMP satellite measurements of the changes in solar flux (indicating low lunar conductivity) as well as dynamical astronomers' earlier conclusions regarding the lunar figure, in indicating low lunar temperatures and structural strength in the upper 200-400 km of lunar material.

CONFERENCE

A conference on Scientific Applications of Radio and Radar Tracking in the Space Program was held at JPL's Von Karman Auditorium, 9-10 April 1969. The meeting provided a gathering place for specialists in the area of data taking, data processing, and data analysis for active radio and radar systems and a forum for discussion of current limitations and future plans.

Four half-day sessions were conducted during which 27 presentations, on a variety of topics, were made. Active discussions followed many of the talks. A proceedings of the conference is being prepared and will be published as a JPL Technical Report.

ATTENDANCE AT SCIENTIFIC MEETINGS

1. Seventh Annual Seminar in Celestial Mechanics, Austin, Texas, January 13-15, 1969.
2. Caltech Seminar on General Relativity, Pasadena, California, March 7, 1969.
3. 129th Meeting, American Astronomical Society, Honolulu, Hawaii, March 30 - April 2, 1969.
4. "Scientific Applications of Radio and Radar Tracking in the Space Program," Jet Propulsion Laboratory, Pasadena, California, April 9-11, 1969.

5. 50th Annual Meeting, American Geophysical Union, Washington, D. C., April 20-25, 1969.

6. American Physical Society Meeting, Washington, D. C., April 1969.

7. 12th Plenary Meeting of COSPAR, Prague, Czechoslovakia, May 11-24, 1969.

8. Goddard Institute for Space Studies Symposium on the Moon, New York, New York, June 1969.

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Gottlieb, P., "Mascons: Local Lunar Gravity Features," SPS 37-55, Volume III, February 28, 1969.

Lieske, J. H., "On the Compatibility of Radar and Optical Observations," SPS 37-55, Volume III, February 28, 1969.

Liu, A. S., Anderson, J. D., and Cain, D. L., "Effect of a Planetoid Ring at 2.8 AU on the Orbit of Mars," SPS 37-55, Volume III, February 28, 1969.

Anderson, J. D., and Liu, A. S., "Influence of the Asteroid Belt on an Experiment to Detect General Relativistic Effects in the Orbit of Mars," SPS 37-56, Volume III, April 30, 1969.

Gottlieb, P., "Local Lunar Gravity Features from Lunar Orbiter Tracking Data," SPS 37-56, Volume III, April 30, 1969.

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NUMERICAL ANALYSIS
NASA Work Unit 129-04-04-01
JPL 329-40301-1-3140
C. L. Lawson

OBJECTIVE

The objective of this work unit is to bring sound principles of numerical analysis and computer algorithm design to bear on scientific computing problems at JPL. This includes research in numerical analysis, improvement of the general computational capability at JPL, and provision of consulting assistance on particular applications.

COMPUTATIONAL METHODS IN PARAMETER ESTIMATION

The modular software developed under this task in previous report periods was very effective again in facilitating the use of the techniques of Householder Orthogonal Transformations and Singular Value Analysis (SVA) in parameter estimation problems which were proving to be intractable to previously existing computing programs.

In collaboration with P. Dyer (Systems Analysis Research Section) these methods were used successfully in a spacecraft data analysis application in which the linear algebraic computations of the Double Precision Orbit Determination (DPODP) proved inadequate. Discussion is under way regarding the possible inclusion of these techniques in the DPODP.

The SVA software is being used in a 203-parameter problem being undertaken at JPL by Prof. D. Pierce of Yale University. This project involves the determination of corrections to fundamental star catalogs via the use of seven thousand observations of asteroids. The SVA technique has effectively identified the dependencies in this problem and it appears that a useful solution will be obtained.

CURVE REPRESENTATION USING CUBIC SPLINES

The work previously completed and reported on this problem was used in applications during this period and will be adapted (under other funding) during the next six month period to use on an interactive graphic terminal.

EIGENVALUES OF A - λB

In collaboration with K. K. Gupta (Applied Mechanics Section) an eigenvalue computation method is being developed and tested which is intended to be particularly efficient for the case in which A and B are large symmetric banded matrices. This is a computational problem of importance in structural analysis.

SPECIAL FUNCTIONS

In collaboration with M. Saffren (Physics Section) investigations have been made of the problem of "numerical conditioning" in computing series involving special functions. We have found by empirical studies that a well-known nesting algorithm is subject to many practical numerical difficulties, and we have supplied theoretical reasons for such difficulties, and have reforulated the algorithm to a form suitable for analytical investigations of numerical conditioning and stability. A manuscript is in preparation to be submitted for external publication.

In collaboration with M. Geller (Physics Section) we have extended previous studies of computation of some integrals of confluent hypergeometric functions to handle new problems arising from molecular structure.

We have investigated the computation of Debye functions which arise from problems in chemical physics, and have shown that these functions can be efficiently computed from our previous approximations of Bose-Einstein functions.

NUMERICAL SOLUTION OF ORDINARY DIFFERENTIAL EQUATIONS

Work on the derivation, development, and applications of a variable-order, variable-step algorithm (VODQ) for the numerical solution of systems of ordinary differential equations (O. D. E.) was reported in the previous period. Software implementing this algorithm is now included in the subroutine library directly available to JPL UNIVAC 1108 users, and this procedure is being recommended for use in all new applications requiring the solution of O. D. E.'s. We believe these subroutines are superior to any other general purpose integrators available at this time and are currently contacting others who might be interested in using them, including other NASA installations.

During the next six months we plan to begin work on improving the capability of these subroutines to handle stiff equations, and to describe (and justify) the various new algorithms being used in these subroutines.

A study has been initiated into the design of a reliable general purpose algorithm for two-point boundary value problems using VODQ and the Singular Value Analysis software.

CONSULTATION AND EDUCATIONAL SERVICES

A lecture was given at JPL on "Solving Large Linear Least Squares Problems with Possible Rank Deficiencies." Consultation was provided in a variety of applications, particularly in the problem areas mentioned previously in this report.

Contributions were made to the development of an organizational structure of programmers, writers, and analysts to develop a JPL library of mathematical subroutines available on the UNIVAC 1108, with coordinated computer-stored, user-oriented, documentation. A lecture at JPL by W. J. Cody of Argonne National Laboratory was presented on the subject of subroutine library development.

EXTERNAL PROFESSIONAL ACTIVITIES

External professional activities have included (1) Chairmanship of USE (UNIVAC users) committee on function subroutine accuracy, (2) Vice-Chairmanship of Los Angeles ACM Special Interest Group in Numerical Analysis, (3) Committee member for organization of Symposium on Special Functions at the Summer Meeting of SIAM, (4) Editor of the Scientific Applications department of the (monthly journal) Communications of ACM, (5) Attendance at research planning meeting for the Argonne Universities Assn. Institute for Computer Science, (6) Recipient of a NATO Senior Fellowship for a 60-day technical exchange visit to British computing facilities to be implemented in FY 1970, (7) Attendance at the University of Michigan summer conference on Numerical Analysis, and (8) Lectures on numerical analysis at UCLA, SHARE (IBM users), North American Rockwell, and Los Angeles ACM Special Interest Group in Numerical Analysis.

ANTICIPATED PUBLICATIONS

Hanson, R. J. and Lawson, C. L., "Extensions and Applications of the Householder Algorithm for Solving Linear Least Squares Problems."

Krogh, F. T., "On Testing a Subroutine for the Numerical Integration of Ordinary Differential Equations."

Krogh, F. T., "Efficient Algorithms for Polynomial Interpolation and Numerical Differentiation."

Ng, E. W., Devine, C. J., and Tooper, R. F., "Chebyshev Polynomial Expansions of Bose-Einstein Functions of Orders 1 to 10."

Tooper, R., Mark, J., and Ng, E., "Chebyshev Polynomial Expansions of Generalized Exponential Integrals."

Ng, E. W. and Saffren, M., "Stable Evaluation of Series for Special Functions."

PUBLICATIONS

Meeting and Symposia Papers

C. J. Devine attended the semiannual USE (UNIVAC 1108 users) meeting in St. Louis, Mo., March 23 through 28, 1969.

R. J. Hanson presented a lecture to the Mathematical Analysis and Matrix Methods Groups of North American Rockwell Corporation, on "Introductory Interval Arithmetic and Its Applications to Solving Rectangular Linear Systems," March 26, 1969.

R. J. Hanson presented a talk to the Los Angeles Chapter of SIGNUM on "Computerized Curve Fitting," April 9, 1969.

F. T. Krogh presented a lecture to the SHARE XXXII meeting in Los Angeles on "A General Purpose Subroutine for the Numerical Integration of Ordinary Differential Equations," March 5, 1969.

F. T. Krogh presented a talk at UCLA on "The Numerical Integration of Ordinary Differential Equations," May 16, 1969.

C. L. Lawson attended a symposium on "Approximation with Special Emphasis on Spline Functions," at the University of Wisconsin (Math. Research Center), May 5-7, 1969.

C. L. Lawson attended a meeting at Argonne National Laboratory to plan a summer numerical analysis research program for the Argonne Universities Association Institute for Computer Science.

E. W. Ng served on the organizational committee and attended the SIAM Summer Meeting, June 9-11, 1969.

Journal Articles

Ng, E. W., and Geller, M., "A Table of Integrals of the Error Functions," National Bureau of Standards, Journal of Research, B Math. Sciences, Vol. 73B, No. 1, January-March 1969.

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(The following references to SPS 37-53 were erroneously omitted from the previous semiannual report.)

Ng, E. W., "The Direct Summation of Series Involving Higher Transcendental Functions," SPS 37-53, Vol. III, Oct. 1968, p. 16.

Ng, E. W., "Integrals of Confluent Hypergeometric Functions, Part II," SPS 37-53, Vol. III, Oct. 1968, p. 17.

Lawson, C. L., "Survey of Computer Methods for Fitting Curves to Discrete Data or Approximating Continuous Functions," SPS 37-53, Vol. III, Oct. 1968, p. 18.

Hanson, R. J., "Sequential Linear Least Squares With Jacobi Reflections," SPS 37-55, Vol. III, Feb. 1969, p. 28.

Devine, C. J., and Lawson, C. L., "Accuracy of Single Precision UNIVAC 1108 Subroutine Library Functions," SPS 37-56, Vol. II.

Ng, E. W., and Devine, C. J., "Chebyshev Polynomial Expansion of Bose-Einstein Functions of Orders 1 to 10," SPS 37-56, Vol. III.

Ng, E. W., and Devine, C. J., "On the Computation of Debye Functions of Integer Orders," SPS 37-56, Vol. III.

Hanson, R. J., "Storage Saving Approximate Solutions to Rank Deficient Linear Least Squares Problems," SPS 37-56, Vol. III.

CELESTIAL MECHANICS

NASA Work Unit 129-04-04-02

JPL 329-40401-1-3910

W. G. Melbourne

OBJECTIVE

The objective of this task is to develop, analyze, and implement methods for the prediction of the motion of natural and artificial bodies in the solar system. This work is particularly oriented toward increasing the accuracy of the JPL planetary and lunar ephemerides. Increased accuracy is necessary to support planned space flight projects. Improved ephemerides will be made available to other NASA Centers and contractors.

The work unit is being terminated at the end of the FY 69, as no longer coming within the definition of the Basic Research (129) Program. The ephemeris improvement program is now considered as a development program. Those aspects of this work unit which remain basic research are being absorbed into other work units.

LUNAR EPHEMERIS

The major work activity during the reporting period has been a continuation of the lunar ephemeris activity discussed in Ref. 1. The ephemeris that was nearing completion at the writing of that report has been completed and designated LE 16. It is a numerical integration fit over a 20-year span to the Lunar Theory, with suitable, though inelegant, treatment of the effects known to be unmodelled by the integration. Subsequently, the ephemeris was extended an additional 20 years without a differential correction. Generally speaking, the residuals (theory - LE 16) are satisfactory, although a systematic feature with aplitude about 0.1 and period about 19 years appears in them. The cause is as yet unknown, but could lie in either set of data. This ephemeris will be used in the initial predictions for the Apollo Laser Ranging Experiment, which will mark the first operational application of an integrated lunar ephemeris.

During the last six months, the lunar version of the SSDPS for the IBM 7094 DCS system has been successfully completed, and the numerical integration with observations of Right Ascension and Declination for a short 100-day arc have been compared. Initial conditions for the Moon were taken from LE 16, and the planetary conditions and constants were taken from DE 19. A 12-year, non-relativistic integration was carried out and compared to a similar PLOD run; agreement to eight places in the coordinates was obtained. In the short run, to compare observations with numerical integration, residuals were obtained which supported the equinox correction as reported in Ref. 2. Recently, the perturbation of a tri-axial Moon, including J_2, C_{22}, and S_{22}, was coded for the action of the Moon on the Earth and checked out. An 18-year integration will be made and the observations compared in the near future. With the adopted values of the parameters for the tri-axial Moon, there should be but one effect not considered--tidal acceleration in the motion of the Moon which in LE 16 is added as an empirical term to LE 15, the integrated ephemeris according to PLOD.

In an independent effort, the Surveyor tracking data are currently being used to differentially adjust the lunar initial state vector. This effort to improve the lunar ephemeris is a two phase venture.

Phase one: The Double Precision Orbit Determination Program (DPODP) is currently being employed to fit each of the five lunar landed Surveyors tracking data samples. Once each and all Surveyor tracking data packages have been least squares fitted, the "observed minus computed" (o-c) residuals and the partials of the Surveyor two way doppler function with respect to the parameter list will be transferred to one combined normal equation matrix. The resultant solution will solve for:

Surveyor I, III, V, VI and VII (selenocentric spherical coordinates)

Deep Space Station 11, 42, 61 (geocentric cylindrical coordinates)

Lunar State Vector (16 March 1967)

The lunar state vector epoch is 16 March 1967. This permits the use of two body, Set III, partials to relate the data epoch to the 16 March 1967 reference epoch. Finite difference partials will then be employed to relate the 16 March 1967 reference epoch to the standard 1950.0 epoch.

Phase two: Recent efforts to fit Surveyor tracking data utilizing Eckhardt, Heyn, and zero lunar physical liberation coefficients (Ref. 3) have demonstrated that the present liberation modeling schemes fail. As to what extent this model failure will distort any ephemeris based on Surveyor data is being determined. Additionally a numerical integration scheme is being developed which will permit differential adjustment of the initial lunar angular position and velocity.

At this time, the following has been determined:

(1) Partials of f_2 with respect to 17 physical libration coefficients (5 coefficients for the libration of the longitude of the mean ascending node; 5 coefficients for the libration of the inclination of the lunar equator relative to the ecliptic; 7 coefficients for the libration of the lunar mean longitude) for the Surveyor I time span.

(2) The spatial displacement and velocity, and radial velocity of a Surveyor resulting from each of the 17 libration coefficients.

(3) A numerical integrator capable of integrating the differential rotation of the moon has been developed.

Several discussions have been held with the experimenters on the Apollo Laser Ranging Experiment, the result of which has been the co-option of J. D. Mulholland as a member of the experiment team. Work is underway to develop the computer software necessary for providing the predictions for driving the telescope and controlling the range-gating device on the laser. The first laser reflector package will be emplaced on the Moon in mid-July. Hopefully others will follow on subsequent flights. Dr. Mulholland will be providing predictions for two or more observatories on a continuing basis. Joint efforts with the other experimenters will be needed for the interpretation of the data collected. The first steps in including them in an improved lunar ephemeris will be taken. Occasionally, he will assist in monitoring the actual observing process.

PLANETARY EPHEMERIDES

During the period since the last report the research effort in planetary masses was continued and two new areas of research were undertaken. An ephemeris was delivered for Mariner VI and VII launch activities and the encounter study activities.

In the previous R/AD report it was stated that a 60 year ephemeris had been produced. Further studies on this ephemeris showed deficiencies. The causes were found and corrected and a much improved 60 year planetary ephemeris was delivered for general Laboratory usage including the Mariner '69 activities. The initial conditions have been given to a few members of the scientific community outside of JPL.

A number of presentations regarding this milestone effort were made. Initially a presentation stressing optical results and the power of radar was presented in Austin, Texas. This presentation was followed by one at the JPL conference on "Scientific Applications of Radio and Radar Tracking in the Space Program" where the emphasis was placed on the radar range and spacecraft data analysis. A joint paper, delivered by Dr. William G. Melbourne, was presented at the American Astronomical Society meeting in Honolulu, Hawaii and another paper, delivered by Dr. O'Handley was presented at the American Geophysical Union meeting in Washington, D. C.

The JPL Venus ranging data for 1967 was found to be in error and corrected. This problem has been the subject of a great deal of effort during this past year. In a continuing effort to check the adequacy and accuracy of the Solar System Data Processing System (SSDPS), a series of progressive tests were begun to compare the JPL system with those of the Naval Weapons Laboratory (NWL) and Lincoln Laboratory (MIT). As of this date NWL has cooperated and our testing is complete through the integration portion of the system. Further tests will be set up when we meet in August at NWL.

A program of basic research was continued throughout this period. The computer reconstruction of planetary range data from Venus was begun. This effort could possibly result in some radar ranging data being reduced to a precision of 0. 1 μseconds, all other error sources being accounted for.

Mars ranging data has just been received and the current effort is to improve the planetary ephemerides for the Mariner '69 encounter activities. Afterwards, an extensive study of topography will be started. It is expected that the bistatic planetary ranging data from the Goldstone-Haystack (MIT) Mercury ranging experiment will be reduced starting in November of this year.

Radar 10, the program used for accurate Radar predictions, has been active during the first part of the year. Computations for Venus, Mars, Mercury, and the Satellites of Jupiter were made for the Goldstone Venus and Mars sites.

Numerical differences for the planets as perturbed by the mass of Jupiter were made and compared with series generated for the perturbations; agreement to about three places was obtained.

The most urgent future project is the conversion of programs to the UNIVAC 1108 as the IBM system will be deleted. The program to compute geodetic and geocentric latitudes has already been converted and the results show the improved double precision arithmetic of the 1108. Most of the results obtained by conversion of the SSDPS can be used by the lunar version so that only the modifications need be converted.

Basic research on all the planetary masses continues. It is anticipated that in the next semi-annual period a simultaneous solution for the outer planetary masses will be made. A comprehensive article which includes much of this research will be forthcoming as will a new export ephemeris which will replace DE 19.

Dr. Mulholland was appointed to the Organizing Committee of the Division for Dynamical Astronomy by the Council of the American Astronomical Society.

ATTENDANCE AT SCIENTIFIC MEETINGS

Formal Meetings

1. 7th Annual Seminar in Celestial Mechanics, Univ. of Texas, Austin, 13-15 January 1969.

2. 129th Meeting, American Astronomical Society, Honolulu, Hawaii, March 30 - April 2, 1969.

3. "Scientific Applications of Radio and Radar Tracking in the Space Program," Jet Propulsion Laboratory, 9-11 April 1969.

4. 50th Annual Meeting, American Geophysical Union, Washington, D. C., April 20-25, 1969.

5. 12th Plenary Meeting of COSPAR, Prague, Czechslovakia, May 11-24, 1969.

Informal Meetings

1. Advisory committee to American Astronomical Society on the prospective formation of a Division for Dynamical Astronomy, Austin, Texas, 14 January 1969.

2. Apollo Laser Ranging Experiment team, College Park, Maryland, 12 March; Washington, D. C., 13 March; College Park, 1 May; Washington, 2 May.

3. Ad hoc ephemeris group, Jet Propulsion Laboratory, 11 April 1969.

REFERENCES

1. Semi-annual Review of Research and Advanced Development, Document 701-23, Volume II, July 1 - December 31, 1968, pp. 707-713.

2. Mulholland, J. D., and Holdridge, D. B., "Application of a Transformation of Equinox in the Lunar Theory: Lunar Ephemeris Number 16," SPS 37-57, Volume II, May 31, 1969.

3. Winn, F. B., "Lunar Landed Surveyor: Lunar Libration Sensitivities," SPS 37-56, Volume II, March 31, 1969.

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Meeting and Symposia Papers

Mulholland, J. D., "The Planetary Theories as Limiting Factors in the Lunar Theory," 7th Celestial Mechanics Seminar, Univ. of Texas, Austin, 15 January 1969.

Melbourne, W. G., O'Handley, D. A., and Reed, R., "Gravitationally Consistent Planetary Ephemerides based on Meridian Circle, Radar, and Mariner Observations," 129th Meeting American Astronomical Society, Honolulu, Hawaii, March 30 - April 2, 1969.

O'Handley, D. A., "Reconstruction of JPL 1967 Range Data for Venus and the Processing of Radar Data," JPL Conference - "Scientific Applications of Radio and Radar Tracking in the Space Program," April 9-11, 1969.

Melbourne, W. G., O'Handley, D. A., and Reed, R., "Recent Astronomical Constants of the Solar System based on Meridian Circle, Planetary Radar, and Radio Tracking Information," 50th Annual Meeting American Geophysical Union, Washington, D. C., April 20-25, 1969.

Melbourne, W. G., "The Determination of Planetary Masses from Radio Tracking of Space Probes and Planetary Radar," 12th Plenary Meeting of COSPAR, Prague, Czechoslovakia, May 11-24, 1969.

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Mulholland, J. D., and Liemohn, H. B., "Resolution" Bull. Am. Astronomical Soc., Volume 1, p. 168, 1969.

Mulholland, J. D., "Meeting Report: BSRL/JPL Seminar on the Lunar Motion" Celestial Mechanics, Volume 1, pp. 79-81, 1969.

Mulholland, J. D., "Numerical Studies of the Lunar Motion," Nature, in publication.

JPL Publications

SPS Contributions

O'Handley, D. A., and Melbourne, W. G., "Gravitationally Consistent Planetary Ephemerides based on Meridian Circle, Radar, and Mariner V Observations," SPS 37-55, Volume III, February 28, 1969.

Winn, F. B., "Lunar Landed Surveyor: Lunar Libration Sensitivities" SPS 37-56, Volume II, March 31, 1969.

Mulholland, J. D., and Holdridge, D. B., "Application of a Transformation of Equinox in the Lunar Theory: Lunar Ephemeris Number 16" SPS 37-57, Volume II, May 31, 1969.

Technical Reports

Mulholland, J. D. (ed.) "Proceedings of the Symposium on Observation, Analysis and Space Research Applications of the Lunar Motion," JPL TR 32-1386, 15 April 1969.