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TECHNICAL AND MANAGERIAL SUPPORT FOR THE PERFORMANCE STANDARDIZATION WORKING GROUP OF THE INTERAGENCY CHEMICAL ROCKET PROPULSION GROUP

FINAL REPORT - CONTRACT NAS7-443

BY

S. HERSH

DYNAMIC SCIENCE, A DIVISION
OF MARSHALL INDUSTRIES
2400 MICHELSON DRIVE
IRVINE, CALIFORNIA

MAY 1970

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

TECHNICAL AND MANAGERIAL SUPPORT FOR THE PERFORMANCE STANDARDIZATION WORKING GROUP OF THE INTERAGENCY CHEMICAL ROCKET PROPULSION GROUP

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Dynamic Science, a Division of
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2400 Michelson Drive
Irvine, California

Prepared For
National Aeronautics and Space Administration

May 1970

SUMMARY

This report describes the work performed under Contract No. NAS7-443. The purpose of this contract was to provide engineering and management services in support of the Performance Standardization Working Group of the ICRPG.

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INTRODUCTION

The ICRPG Performance Standardization Working Group was formed in 1965 for the purpose of improving and recommending methodology suited to eventual adoption as national standards for the analytical and experimental evaluation of the performance of liquid propellant rocket engines. It was decided to accomplish this objective by bringing together key technical and management individuals from a broad spectrum of government agencies, propulsion, and space systems companies. Since its inception, the Working Group has been organized into three technical committees under the direction of a Steering Committee composed of senior government individuals from NASA, the Air Force, the Navy, and the Army. These three committees, the Overall Concepts Committee, the Theoretical Methods Committee, and the Experimental Measurements Committee have been meeting approximately every three months over the last four years developing: propulsion system performance analysis methodology, improved theoretical analysis techniques, and improved experimental measurement and data analysis methods.

Dynamic Science, a Division of Marshall Industries, has provided technical coordination and management services to the Working Group under contract NAS7-443. These services included maintaining records and files of the Working Group's activities, attending all Committee meetings and preparing and distributing minutes of the proceedings, issuing RFP's and monitoring progress on subcontracts initiated by the Working Group, and writing, technically editing, publishing, and distributing many of the reports issued by the Working Group.

DISCUSSION

The objective of the Performance Standardization Working Group was the recommendation of performance evaluation methodology for liquid propellant thrust chambers suitable for adoption as national standards by the Government. It was anticipated that such standard methodology, when used for the prediction and correlation of engine system performance in the proposal and development stage, would significantly improve the chances that the final system would actually meet application requirements. Further, it would provide additional insight into performance deficiencies by a better identification of the nature and magnitude of the various performance losses, and would provide a common basis for the evaluation, comparison, and/or use of performance predictions.

The Performance Standardization Working Group, to produce usable results in a definite period of time, had limited its initial effort in both scope and technical objectives. The scope of this first effort was limited to assembling into a compatible overall system, the best relevant, analytical and experimental techniques presently existing throughout the industry.

The performance evaluation methodology developed was based upon the application of techniques developed in three specific technical categories. First, the identification of the sources of performance inefficiency and the development of proper evaluation methodology. Second, the selection of specific analytical techniques for performance computations. Last, the development and/or selection of proper experimental methods and measurement techniques consistent with the desired performance extrapolation accuracy.

The first two of these technical areas were the responsibility of the Performance Standardization Working Group - Overall Concepts Committee and the Theoretical Methods Committee, respectively. The combined results and recommendations of these two committees are presented in ICRPG Liquid Propellant Thrust Chamber Performance Evaluation Manual, CPIA Publication No. 178, prepared for the ICRPG Performance Standardization

Working Group, September 30, 1968, prepared by J. L. Pieper, Aerojet-General Corporation, AD 843-051. The performance evaluation methodology described in this manual was limited by the Working Group to be applicable to thrust chambers having the following limitations:

1. Only steady-state thrust chamber performance is considered.
2. Only thrust chambers having fully developed turbulent boundary layers are considered.
3. Only thrust chambers having conventional De Laval nozzles are presently considered.
4. Only those liquid propellants which yield combustion products free of an appreciable portion of condensed phases are considered.
5. Only conventional subsonic propellant injection techniques are considered.

Five computer programs were selected by the Performance Standardization Working Group Theoretical Methods Committee as reference computer programs for the performance calculations of liquid propellant thrust chambers. The concept of reference rather than standard computer programs was adopted early in the effort (Summer, 1966). As used by the Working Group, a reference program is a program whose results are universally accepted and which can be used to perform the desired calculations directly or can be used to qualify a similar program as being equally accurate. In contrast, a standard program would be the only acceptable calculational program by definition. The reason for choosing reference rather than standard programs was that this would allow the user to choose his calculational tools on the basis of convenience and experience as long as he can verify their equivalence and accuracy. It was the concensus of the Theoretical Methods Committee at the time of the adoption of the reference program concept that if these programs were truly superior, then other program usage would decline to the point where the reference programs could be simply and universally adopted as standard programs. The adopted reference computer programs are:

1. A One-Dimensional Equilibrium Nozzle Analysis Computer Program, (ODE)

2. A One-Dimensional Kinetic Nozzle Analysis Computer Program, (ODK)

3. A Two-Dimensional Equilibrium Nozzle Analysis Computer Program, (TDE)

4. A Two-Dimensional Kinetic Nozzle Analysis Computer Program, (TDK)

5. A Turbulent Boundary Layer Nozzle Analysis Computer Program, (TBL)

The specific computer programs selected by the Theoretical Methods Committee for these calculations (described in Refs. 8-11) were the best available, fully developed, and documented programs for use in the performance evaluation procedures at the time of selection (June, 1967).

The third technical area listed above was the responsibility of the Experimental Measurements Committee. Their results and recommendations are presented in Handbook of Recommended Practices for Measurement of Liquid Propellant Rocket Engine Parameters, CPIA Publication No. 179, ICRPG Performance Standardization Working Group, AD 851-127, and ICRPG Handbook for Estimating the Uncertainty in Measurements Made with Liquid Propellant Rocket Engine Systems, CPIA Publication No. 180, ICRPG Performance Standardization Working Group, AD 855-130.

During the period of the subject contract, members of the Dynamic Science staff attended a total of thirty-two full committee meetings, and innumerable subcommittee and contract monitoring committee meetings. The proceedings of these meetings were documented and distributed to members of the Working Group.

Dynamic Science, at the direction of the three Working Group committees, prepared RFP's, assisted in the proposal evaluations, and issued the following major subcontracts:

Aerojet-General (Sacramento) -
- I. Write "Performance Evaluation Methods for Liquid Propellant Rocket Thrust Chambers," (Ref. 2).
- II. Write "ICRPG Liquid Propellant Thrust Chamber Performance Evaluation Manual," (Ref. 12)

Lockheed Missiles and Space Company - Conduct a Study to Determine the Effect of Nozzle Flow Striations on Engine Performance, (Ref. 4)

Rocketdyne - I. Conduct a Study to Determine the Effect of Nozzle Combustion on Engine Performance, (Ref. 5)

II. Write a Handbook for Measurement Uncertainty

Pratt & Whitney Aircraft, Florida Research and Development Center - Write "ICRPG Handbook for Estimating the Uncertainty in Measurements Made with Liquid Propellant Rocket Engine Systems," (Ref. 14)

Several small subcontracts were issued to the following organizations to cover computer set-up and running time for the Theoretical Methods Committee's comparison of computer programs study:

Aerojet-General
Cornell Aeronautical Laboratory
Grumman
Lockheed
McDonnell-Douglas
Pratt & Whitney Aircraft
Rao and Associates
Rocketdyne
TRW Systems

In addition to these outside subcontracts, the staff of Dynamic Science prepared references 1, 3, 8, and 10, and made the modifications necessary for the acceptance of ODK and TDK as ICRPG reference programs.

To put the studies discussed above in their context as part of the overall effort of the Performance Standardization Working Group, and to perhaps serve as a useful example to others planning such a joint endeavor, Appendix A contains a narrative chronology of the deliberations of the Working Group.

Listed as references are publications prepared by the Working Group or by subcontractors selected and technically directed by the three committees through Dynamic Science. Those with CPIA report numbers have been distributed directly to the propulsion community through the CPIA mailing list, while those having AD numbers are available through the Defense Documentation Center, Alexandria, Virginia. In addition to the several reports listed, the five performance evaluation computer programs adopted as reference programs, and their manuals, were made available through Dynamic Science.

Table I lists the subcontractors and funding levels for all the subcontracts issued and administered by Dynamic Science under this contract. Table II lists those individuals from government and industry who participated in and contributed to the success of the Working Group.

TABLE I

SUBCONTRACT FUNDING

Subcontractor	Subcontract Description	Amount
Aerojet-General	Definition of a Fluid Dynamic Model	$ 23,467
Aerojet-General	Definition of a Fluid Dynamic Model	13,686
Aerojet-General	Comparison of Computer Programs	2,091
Aerojet-General	Performance Evaluation Calculation Manual for Liquid Propulsion Engines	57,652
Cornell Aeronautical Lab	Computer Program Comparison	3,500
Grumman Aircraft	Comparison of Computer Programs	2,843
GVR Rao Associates	Comparison of Computer Programs	5,445
Lockheed	Comparison of Computer Programs	600
Lockheed	Effect of Nozzle Flow Striations on Engine Performance	19,460
McDonnell-Douglas	Comparison of Computer Programs	565
Pratt & Whitney	Comparison of Computer Programs	4,631
Pratt & Whitney	Modification of Two-Dimensional Method of Characteristics and Boundary Layer Computer Programs	19,587
Pratt & Whitney	Measurement Uncertainty Handbook for Liquid Rocket Engines	29,500
Rocketdyne	Comparison of Computer Programs	4,754
Rocketdyne	The Effect of Nozzle Combustion on Engine Performance	22,208
Rocketdyne	Development of a Measurement Uncertainty Model	41,052
TRW	Comparison of Computer Programs	7,000
TRW	Screening of Reaction Rates	39,482

TABLE II

PARTICIPANTS AND CONTRIBUTORS TO THE PERFORMANCE STANDARDIZATION WORKING GROUP

STEERING COMMITTEE

AFRPL - Edwards Air Force Base

C. J. Abbe

Army Missile Command

B. F. Wilson

National Aeronautics and Space Administration - Headquarters

R. S. Levine

Naval Weapons Center

D. Couch

PROGRAM MANAGER

National Aeronautics and Space Administration - Jet Propulsion Laboratory

D. R. Bartz

EXPERIMENTAL MEASUREMENTS COMMITTEE

Aerojet-General Corporation

V. R. Boulton
R. D. Wesley

AFRPL - Edwards Air Force Base

W. L. Buchholtz
R. L. Noblin

ARO, Incorporated

T. C. Austin
R. E. Smith, Jr.

Bell Aerosystems

H. Berke
R. M. Ransier

Dynamic Science

M. Beltran
H. Couch
S. Hersh
T. C. Kosvic

Greyrad Corporation

J. Grey
R. E. Thompson

Grumman Aircraft

N. C. Bossemeyer
R. O. Zupp

Jet Propulsion Laboratory

S. Rogero
J. H. Rupe

The Marquardt Corporation

B. Case
E. E. Fritz
J. P. McCarthy

National Aeronautics and Space Administration - Lewis Research Center

C. A. Aukerman

Naval Ordnance Test Station

O. E. Braun
H. J. Hoffman

Pratt and Whitney Aircraft Company

R. B. Abernethy
J. B. Fyfe
W. C. Missimer
B. D. Powell
H. J. Tiedemann

Rocketdyne Division - North American Rockwell

A. T. Bruschi
B. R. Ginsburg
B. F. Piper
S. Webb

Thiokol Chemical Corporation

A. D. Corbett

TRW Systems

A. W. Parnell

U. S. Army Missile Command

J. Collins
F. M. Hoke
S. R. Moore

OVERALL CONCEPTS COMMITTEE

Aerojet-General Corporation

J. L. Pieper
R. S. Valentine

AFRPL - Edwards Air Force Base

D. J. Alser
E. Haberman
C. W. Hawk

Arnold Engineering Defense Center

I. C. Lightner

ARO, Incorporated

I. C. Lightner

Bell Aerosystems Company

W. R. Scott

Douglas Aircraft Company

W. Gaubatz

Dynamic Science

M. Beltran
H. Couch
M. Gerstein
T. Kosvic

Jet Propulsion Laboratory

W. B. Powell
T. Price

Ling-Temco-Vought

J. B. Green
N.V.S. Mumford, Jr.

The Martin Company

G. R. Cramer
R. Knoll
W. Swank
G. Skartvedt

McDonnell-Douglas Aircraft Company

W. C. Trent

National Aeronautics and Space Administration - Manned Spacecraft Center

W. R. Scott

National Aeronautics and Space Administration - Marshall Space Flight Center

K. W. Gross
J. Igou

North American Aircraft - Space and Information Division

R. R. Koppang
D. J. Simkin

Pratt & Whitney Aircraft Company

J. J. Horgan

Rocketdyne Division - North American Rockwell

H. K. Georgius
H. A. Singer

Thiokol Chemical Corporation

J. Lovingham
W. Simon

TRW Systems

G. McLeod

U.S. Army Missile Command

J. W. Connaughton

United Technology Center

C. D. Weimer
T. D. Meyers

THEORETICAL METHODS COMMITTEE

Aerojet-General Corporation

J. L. Pieper

Aerospace Corporation

E. Cook
W. U. Roessler
L. Schieler

AFRPL - Edwards Air Force Base

E. C. Barth
E. G. Haberman
C. C. Selph

The Boeing Company

R. W. Carkeek
R. L. Green
E. D. Simon

Dynamic Science

M. Beltran
H. Couch
S. Hersh
T. Kosvic
G. Nickerson

General Applied Science Laboratories

W. Chinitz

Grumman Aircraft Engineering Corporation

A. Goldford
D. Migdal

Jet Propulsion Laboratory

R. Kushida

Lockheed Missiles and Space Company

C. N. Levy
R. J. Prozan
A. W. Ratliff

The Marquardt Corporation

G. S. Bahn

The Martin Company

J. A. Bowman

McDonnell Automation Center

T. Widmer

National Aeronautics and Space Administration - Lewis Research Center

S. Gordon

National Engineering and Science Company

G. V. R. Rao

Naval Ordnance Test Station

D. H. Couch
D. R. Cruise
J. R. Peoples

New York University

L. Dauerman

Pratt & Whitney Aircraft Company

T. F. Zupnik

Purdue University

J. D. Hoffman
H. D. Thompson

Rao and Associates

G. V. R. Rao

Rocketdyne Division - North American Rockwell

J. S. Divita
J. J. Kalvinska
R. Mitchell
J. Weber

Thiokol Chemical Corporation

W. Simon

TRW Systems

S. Cherry
J. R. Kliegel
L. Van Nice

U. S. Army Missile Command

J. Hoffman
R. E. Rhoades

United Aircraft Research Laboratories

W. G. Burwell
V. J. Sarli

United Technology Center

R. W. Hermsen

APPENDIX A

An organization meeting of the Performance Standardization Working Group was held on 18 October 1965 at Martin-Marietta Corporation, Denver, Colorado. At this time the initial membership of the three committees was established with J. R. Kliegel (TRW Systems) selected as Chairman of the Theoretical Methods Committee, W. B. Powell (JPL) Chairman of the Overall Concepts Committee, and A. D. Corbett (Thiokol/RMD) Chairman of the Experimental Measurements Committee, Figure A-1.

The similarities of interests and goals between the Theoretical Methods Committee and the Overall Concepts Committee necessitated close interaction between these committees, while the Experimental Measurements Committee was able to operate in a more autonomous nature. This division has been used in the discussion below.

The 2nd meeting of the Experimental Measurements Group was held at the Rocketdyne Division of North American, 18 and 19 January 1966. At this meeting, definitions of accuracy, precision and bias were discussed and decided upon, and a subcommittee was formed to implement the derivation of a mathematical model to systematically evaluate the errors in measured parameters.

It was decided to assign specific committee members to determine present methods, limitations, and problems with the measurement of the parameters listed below. In addition, suggestions on areas of subcontract work considered necessary to define more accurate methods were solicited.

1. Thrust	
High Frequency Response	Marquardt Corp.
Six-Degree-Freedom Test Stand	Bell Aerosystems Co.
High Altitude	ARO, Inc.
High Thrust Levels	Rocketdyne
2. Exit Pressure	JPL
3. Ambient Pressure	ARO, Inc.
4. Chamber Pressure	NASA-Lewis Research Center

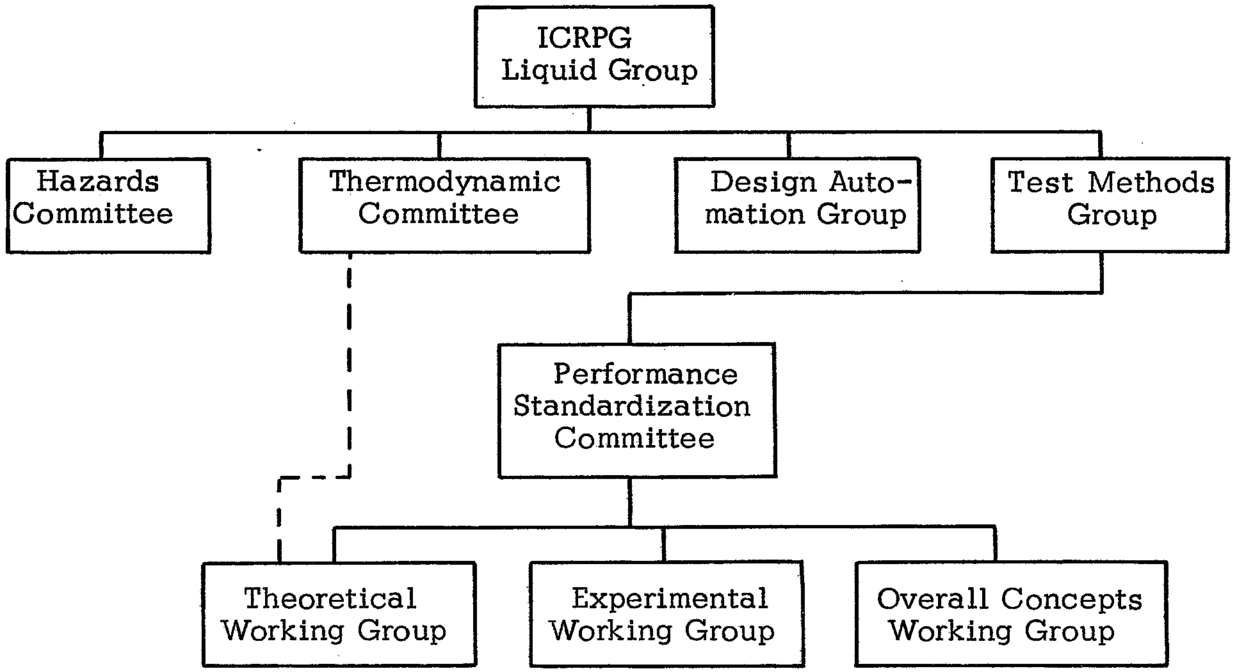
ICRPG Liquid Group
Hazards Committee
Thermodynamic Committee
Design Automation Group
Test Methods Group
Performance Standardization Committee
Theoretical Working Group
Experimental Working Group
Overall Concepts Working Group

Figure A-1

5. Flow Rate (Including Propellant Temperature and Pressure)

Storables	Thiokol-Chemical Corp. AF Rocket Prop. Lab. Grumman Aircraft Eng.
Cryogenics	Pratt & Whitney Aircraft Aerojet-General
Slurrys and Gels	AF Rocket Prop. Lab.

6. Exit Area and Throat Area — Rocketdyne; USAMC-Redstone

7. Flight Methods — USAMC- Redstone

At the 3rd meeting of the Experimental Measurements Group held on 30 and 31 March 1966 at the Reaction Motors Division of Thiokol Chemical Company in Denville, New Jersey, a list of possible work areas and company assignments to write up work statements for these work areas was established along with a proposed outline for the format of the work statements.

The 4th Meeting of the Experimental Measurements Committee was held on the 8th and 9th of June 1966 at the Lewis Research Center in Cleveland, Ohio. The factors involved in funding the outside work packages, felt by the Committee to be necessary, were discussed. Funding would be accomplished through RFP's with a required response of four weeks. Proposal evaluation would be conducted by a team composed of members of the Steering Committee, the funding agency, and Dynamic Science.

The goals of the Experimental Measurements Committee effort were discussed. These included:

1. Defining what was a valid measurement
2. How was it made?
3. Specifying the statistical treatment of the resultant test data

The scope included:

1. A consolidation of the best or most acceptable methods within the current state-of-the-art in measurement technique and application.
2. Identifying acceptable approaches that would give best values.

The Committee formulated a work statement for the proposed funded study for the refinement of a basic model of Measurement Uncertainty and the publication of a handbook describing its use. The model would recommend the method of combining the measurements and associated errors used in the calculation of Isp, and would include calculations for sample cases for each of the various types of calibrations:

1. Total (end to end)
2. Lumped
3. Individual

The question of NBS participation in the group's activities was discussed. A. D. Corbett had spoken with representatives of the National Bureau of Standards about their participation in the development of the Measurement Uncertainty Model. They expressed interest in participating in the effort but their present work load prevented extensive activity. They did, however, request a chance to review the final document before publication.

Dynamic Science was asked to prepare a work statement for a study to formulate and verify a model for turbine flow meter performance. The work statement was to be divided into two parts, development of a theoretical model including the factors affecting performance, and recommendations for an experimental program to verify the model and determine the magnitude of influence of the various factors.

It was decided that the Committee would publish a handbook describing good practices that should be used in the measurement of those parameters needed to calculate specific impulse. The quantities to be measured, how they should be accurately measured, and what calibration procedures should be used, were some topics to be included. As a start, each Committee member was asked to describe the above for the specific measurement he reported on previously.

Initially, the techniques were confined to a low pressure (100 to 200 psia) 5K to 20K thrust level liquid propellant space engine. The suggested format for each measurement was:

1. Design principles
2. Check-out and installation methods
3. Calibration techniques
4. Operation practices
5. Data acquisition and processing

The Committee also established priorities for the desired funded studies:

1. Refinement of a measurement uncertainty model
2. Turbine flow meter performance model
3. Good measurement practices handbook

At the 5th meeting of the Experimental Measurements Committee held on 13 and 14 September 1966 at Aerojet-General Corporation in Sacramento, California, the question of whether the good practices handbook should be generated by subcontracts or by the members of the Experimental Measurements Committee, was discussed. It was decided that each member of the Committee would, using thrust as a parameter, generate a sample handbook, including all necessary information required for the good practices handbook.

A work statement for a study to develop a measurement uncertainty model was formally approved and distributed to members of the Committee and interested companies.

The 6th meeting of the Experimental Measurements Committee was held on the 9th, 10th, and 11th of November 1966, at the Lewis Research Center at Cleveland, Ohio. At this meeting, it was reported that the Steering Committee agreed to fund the measurement uncertainty model. Proposals were received and evaluated and it was anticipated that negotiations with the intended Contractor, Rocketdyne Division of North American Aviation, would be completed and work started within several weeks. A technical monitoring subcommittee was selected to monitor the work on the measurement uncertainty model, and the contract was issued by Dynamic Science on January 4, 1967.

In addition, it was anticipated that an RFP for a turbine flow meter theoretical model would be issued by the Army for bids within several weeks.

The 7th meeting of the Experimental Measurements Committee held on the 18th and 19th of January 1967 at AEDC, Tullahoma, Tennessee, emphasized comments and additions to the draft copies of the Good Measurement Practices Handbook for Thrust Measurement. Dynamic Science was instructed to compile and formulate the comments of the Committee into a rough draft which would be distributed before the next meeting. A status report on the measurement uncertainty model contract was given by Rocketdyne.

The 8th meeting of the Experimental Measurements Committee was held on the 12th and 13th of April 1967 at Marquardt Corporation, Van Nuys, California. The Committee received a report by B. F. Wilson of the Army on the awarding of the turbine flow meter model contract to Greyrad Corporation of Princeton, New Jersey. The three phase study was to:

1. Conduct a literature search.
2. Develop a model which would encompass many more of the parameters which affect calibration and performance than were then accounted for in available models.
3. Outline a program for the experimental verification of this model.

A subcommittee to monitor this work was established.

There was some concern over the precise meaning of steady-state as it appeared in the Thrust Measurement Practices Handbook. After some discussion, the following wording was accepted by the Committee as an adequate definition: Steady-state measurements ideally require a measuring system that is capable of producing an exact electrical analog of what may be a slowly varying force (thrust). In this generalized statement, the term "slowly" must be considered as relative to the response of the overall measuring system. A period of observance for the specified value for the parameter (or in reality, the average of that value) must be at least 5 times the natural time constant of the thrust system as determined from response to a step change in load. The system is considered to be at steady-state conditions for the period of observance when the average value of the parameter for this period of observance differs by no more than .25% from the preceding or succeeding average over a like time period. Three additional subcommittees were appointed to prepare preliminary drafts for the flow measurements, temperature measurements, and pressure measurements section of the Good Practices Handbook.

The 9th meeting of the Experimental Measurements Committee was held on the 27th and 28th of June 1967 at the Redstone Arsenal, Huntsville, Alabama. A discussion of the preliminary contents of the Measurement Uncertainty Model Handbook was conducted. The subcommittee appointed to monitor this work discussed the previous meeting with the contractor, and discussed plans to meet again to review this work and make whatever suggestions were considered désirable to the contractor prior to his writing his final report. Dr. Jerry Grey of Greyrad Corporation also gave the Committee a short presentation covering Greyrad's progress on the turbine flow meter performance model. The full Committee's attention on the four sections of the Good Measurement Practices Handbook was deferred.

Copies of a preliminary draft of "A Handbook for Estimating the Uncertainty in Measurements Made With Transducer Systems" was distributed by Dynamic Science to members of the Experimental Measurements Committee prior to the 10th meeting of the Committee held on the 20th and 21st of September 1967 at Grumman Aircraft Engineering Corporation, Bethpage, New York. The subcommittee appointed to monitor this study felt that the preliminary draft of the Handbook did not meet the criterion for an ICRPG document on this subject in the following areas:

1. <u>Concepts of Model</u>

   The desired conception of the "Measurement Uncertainty Model" as a basis for interpreting the uncertainty in specific impulse from the various elemental uncertainties (biases and precisions) was not adequately represented. The sources of important elemental bias and precision terms were not all identified and a scheme for combining these individual terms to yield uncertainty in measured specific impulse was not presented.

2. <u>Four Number Representation of Uncertainty</u>

The subcommittee felt that the original instructions to produce a single number characterization of uncertainty were technically unsound, and that these instructions should be revised in accordance with the recommendations of NBS so that the overall uncertainty, U_o, is recorded as some function as overall bias, B_o, and overall precision, P_o. The subcommittee recommended that the Handbook should include instructions for identifying and reporting, U_o, B_o, and P_o, along with the overall degrees of freedom, ν_o, associated with the precision term. The subcommittee further recommended that elemental bias and precision terms never be combined.

These and other recommendations were generally accepted by the whole Committee after some discussion and modification and were compiled as an enclosure to the minutes of the meeting. The subcommittee appointed to monitor this work planned to review the final Rocketdyne report when available, and make recommendations towards a phase 2 effort to the general Committee when and if applicable.

The Thrust Measurements Handbook was generally accepted by the Committee and A. D. Corbett planned to review the manuscript and turn in comments and decide what future action, if any, seemed most appropriate to make this Handbook acceptable to the Experimental Measurements Committee as an ICRPG document. The Temperature, Pressure and Flow Rate Handbooks were to be reviewed by all Committee members with comments being sent to Dynamic Science for compilation and distribution. The question of the definition of steady-state was again raised and a subcommittee was appointed to resolve this question and report to the full Committee at the next meeting.

The 11th meeting of the Experimental Measurements Committee was held on the 15th and 16th of November 1967 at TRW Systems, Redondo Beach, California. The three members of the Experimental Measurements Committee who had agreed to investigate the steady-state operating requirements for a .25% accuracy in measured specific impulse reported the results of their investigation to the full Committee. In this regard, the philosophy behind the requirement that "the system is considered to be at steady-state conditions for the period of observation when the average value of the parameter for this period of observation differs by no more than .25% from the preceding or succeeding average over a like time period," which appeared in the current edition of the Recommended Thrust Measurement Practices Handbook was "in order to insure high quality thrust measurements, the total system must be in statistical control. To insure complete statistical control, unsteady variations in the measured parameters (operating transients) must be characterized. As an alternative in the case of thrust, if time dependent variations in the measured thrust can be reduced to a tolerable level, (say $\pm$ 0.25%), it can be assured that the component uncertainty in computed specific impulse which arises from this source (i.e., from the presence of unsteady fluctuations from the steady-state value) would be less than or at worst equal to the absolute magnitude of the variation because the measurements will tend to reflect average values. The discussion over the .25% limitation on the maximum allowable variation between successive measurements as a requirement for steady-state (and hence statistical control) developed according to:

1. The belief by some members that this requirement could not be satisfied by many engine systems which are currently being tested because the steady-state variation in engine performance is greater than this.

2. The belief that the uncertainty in measured thrust (and/or computed specific impulse) which can be attributed to the presence of small variations between successive measurements is much smaller than the variations themselves. This point was not resolved by the full Committee and was planned for further consideration by the subcommittee appointed to revise the existing Recommended Thrust Measurement Practices Handbook.

Although several editions of the Good Measurement Practices Handbooks were at various levels of completion for thrust, flow rate, temperature and pressure, none of these documents were completely satisfactory to the full Committee, therefore, working subcommittees in each one of these areas, each of which would have total responsibility for writing a handbook which would be acceptable to the full Committee, were established. When completed, the subcommittee would submit their portion to the full Committee and any subsequent comments or suggestions concerning each handbook would be referred back to the chairman of the appropriate subcommittee for resolution. These subcommittees were to prepare rough drafts of a recommended practices handbook in their respective areas utilizing or not utilizing previous work in these areas at their discretion. In addition, each of these working subcommittees was responsible for itemizing all the important elemental bias and precision terms which should be included in the Measurement Uncertainty Handbook.

The subcommittee appointed to monitor the Uncertainty Handbook reported that it was their determination that a list of recommended modifications prepared by the subcommittee comprised the minimum necessary modifications to the subject Handbook which would be required for an ICRPG document on measurement uncertainty. It was reported that the subcommittee intended to meet with the contractor and discuss what additional effort might be required to satisfy the terms of the subject contract. This meeting was held on the 21st of November 1967. The provisions of the recommended modifications were reviewed with the contractor at this time and some minor changes in content were approved. The subcommittee requested that the contractor submit a fixed price quotation for modifying the preliminary draft of the subject Handbook to conform with the remainder of the required modifications. The subcommittee requested that this quotation be received by Dynamic Science by 27 December 1967. The subcommittee further resolved to consider this quotation relative to any other estimates received by this time from other organizations, and to make appropriate recommendations to the Performance Standardization Working Group. Regarding the disposition of the contract, the subcommittee recommended that the contractual obligation to deliver one master copy of a final draft within 30 days from approval be postponed until the contractor's quotation could be given due consideration.

If an extension of the existing contract was not awarded to Rocketdyne, the subcommittee recommended acceptance of a final draft of "A Handbook for Estimating the Uncertainty in Measurements Made With Transducer Systems," subject to modifications, as satisfying the terms of the existing contract. It was reported that the time for the completion of the turbine flow meter model had been extended for 30 days because the programming of the turbine flow meter model was requiring more time than had been originally anticipated.

A discussion was also held of possible future work areas to follow after the Committee completed its objective of publishing ICRPG documents on measurement uncertainty and recommended measurement practices. The following subject areas are the ones which were finally generated for consideration by the members of the Experimental Measurements Committee as possible topics for future work in coming meetings:

1. Pulse engines - measured performance
2. Cryogenic engines (flow rate measurements)
3. Deeply throttable engines
4. Jells and slurried propellants (flow rate measurement)
5. Simulated altitude testing
6. Transient measurements
7. Flight testing
8. Multiple component thrust stands
9. Engine systems - extended to include turbines and pumps
10. High pressure systems
11. Mass flow meter (density meter)
12. Air-augmented rockets measured performance

Of these work areas, numbers 5 and 6 had the greatest support.

At the 12th meeting of the Experimental Measurements Committee held on the 16th and 17th of January 1968 at the Rocketdyne Facility at the John F. Kennedy Space Center in Florida, the subcommittee assigned to monitor the Measurement Uncertainty Handbook reported that it was their unanimous recommendation that the Experimental Measurements Committee implement the initiation of a follow-on contract with Pratt & Whitney Aircraft, Florida Research and Development Center, to write the "ICRPG Handbook for Estimating the Uncertainty in Measurements Made With Liquid Rocket Engine Systems." It was felt that the Pratt & Whitney's unsolicited proposal was very complete and the subcommittee was convinced that a follow-on contract with them would result in a document which could be published as an ICRPG manual on measurement uncertainty. Pratt & Whitney's proposal was favored over the Rocketdyne proposal for program extension for a variety of reasons. Some of the more important of these were:

1. The subcommittee had come to the conclusion that extensive revisions would be necessary in going from the Rocketdyne preliminary draft of "A Handbook for Estimating the Uncertainty in Measurements Made With Transducer Systems," R-7086, dated 15 July 1967, to a satisfactory ICRPG document for measurement uncertainty, and the relatively low Rocketdyne estimate for a program extension did not lend confidence that a program extension initiated with the current contractor would yield the ICRPG document desired as a final product.

2. The subcommittee felt that Pratt & Whitney's unsolicited proposal was reasonable in cost to the amount of work required, and in view of their technical substantiation (which was in accord with the monitoring subcommittee's view of what was necessary) was confident that the initiation of a follow-on contract with Pratt & Whitney Aircraft would result in an excellent ICRPG document on measurement uncertainty. It was suggested that Dynamic Science terminate the original contract with Rocketdyne by accepting the contractor's original offer to submit a final draft of the subject Handbook. A meeting of the subcommittee appointed to monitor the contract with Rocketdyne was held at

Dynamic Science on the 13th of March 1968. At this time, the various interested government agencies were convinced that substantial modification was necessary in going from the available rough draft of the Measurement Uncertainty Handbook to a satisfactory ICRPG document on this subject, and that the subcommittee's recommendations to initiate a follow-on with Pratt & Whitney were in the government's best interests. At this time, Dynamic Science was asked to terminate the contract with Rocketdyne and initiate a contract with Pratt & Whitney Aircraft, Florida Research and Development, to complete the desired ICRPG document.

Jerry Grey of Greyrad Corporation summarized the results of the turbine flow meter study presented in Thompson, R. E., and Grey, J., "Turbine Flow Meter Performance Model," Final Report, Contract DA-AH01-67-C1609, October 31, 1967. The significant achievement of that contract was the development of a turbine flow meter computer program which can predict the turbine flow meter K factor as a function of Reynolds Number for turbine flow meters having an arbitrary number of either helical or flat blades with a maximum uncertainty which is on the order of 1% or less. It was emphasized that the cumulative effect of all retarding torques was very small relative to the differences in driving torque caused by a change in the velocity profile, and hence, that any follow-on effort should be aimed at the characterization of the velocity profile as it was affected by installation effects, swirl and flow straighteners.

Regarding a follow-on to the turbine flow meter contract, it was suggested that an experimental follow-on be broken into 2 phases:

1. Create several different (but known) experimental velocity profiles upstream of the turbine flow meter to verify the model's predicted response.

2. Investigate the different velocity profiles created by various installation configurations.

It was felt that these two work packages could be performed by different contractors, if desirable, but that both parts were necessary to promote the utility of and to increase confidence in the turbine flow meter model. It was therefore resolved to retain the present constituents of the turbine flow meter subcommittee at least through a rough draft of the follow-on work statement. Draft copies of the flow rate, pressure and temperature sections of the ICRPG Recommended Practices Handbook were reviewed as well as the general discussion of the format for all the introductory material for the four subject documents.

Summarizing the Committee's discussion on future work areas, it was concluded that the Committee's first objective would be to complete the Phase 1 activities which would include a follow-on contract to the turbine flow meter work and then implement the general acceptance of the published documents. After these objectives were accomplished, a need for another $100,000 funding was foreseen for the support of subcontracts associated with simulated altitude testing and transient measurements. Prior to the 14th meeting of the Experimental Measurements Committee, held on the 18th and 19th of June 1968 at Bell Aerosystems Company, Niagara Falls, New York, the final correction to the Rocketdyne report on measurement uncertainty was received by Dynamic Science. Funding for the follow-on contract had been obtained with the contract scheduled to begin 1 July 1968. The subcommittee in charge of the Rocketdyne work was officially disbanded and a new subcommittee to monitor the Pratt & Whitney work was established. The drafts of the four sections of the Recommended Practices Handbook were reviewed, and the chairmen of the four section subcommittees were appointed an overall subcommittee to combine the four sections into one handbook.

The 15th meeting of the Experimental Measurements Committee was held on the 10th and 11th of September 1968 at Edwards Air Force Base, Boron, California. It was the decision of the Experimental Measurements Committee to limit the initial distribution of the Rocketdyne version of the Measurement Uncertainty Handbook to the members of the Experimental Measurements Committee and the Performance Standardization Working Group

Steering Committee. The first chapter of the Pratt & Whitney Aircraft version of the Measurement Uncertainty Handbook was discussed and reviewed.

The general format of the Measurement Practices Handbook was discussed; that is, whether it should be issued as four separate handbooks or four sections on one handbook. It was decided that the "Handbook of Recommended Practices for Measurement of Liquid Propellant Rocket Engine Parameters" would be issued as a single document containing four self-sustaining parts.

Part 1 - Recommended Practices for Measurement of Liquid Propellant Rocket Engine Thrust

Part 2 - Recommended Practices for Measurement of Liquid Propellant Rocket Engine Flow Rate

Part 3 - Recommended Practices for Measurement of Liquid Propellant Rocket Engine Pressure

Part 4 - Recommended Practices for Measurement of Liquid Propellant Rocket Engine Temperature

A common forward, abstract and introduction was to be prepared by Dynamic Science.

The 16th meeting of the Experimental Measurements Committee was held on the 4th and 5th of March 1969 at the Army Missile Command, Redstone Arsenal, Huntsville, Alabama. It was decided that no further distribution of the Rocketdyne version of the Uncertainty Handbook be made.

The draft version of the Pratt & Whitney document on measurement uncertainty was reviewed and it was moved and accepted unanimously that this document be published as the "ICRPG Handbook for Estimating the Uncertainty in Measurements Made With Liquid Propellant Rocket Engine Systems," when corrections decided on at this meeting were incorporated.

A preliminary work statement for a flow meter follow-on was prepared and a list of recommended priorities for new work areas was also established. The following meeting of the Experimental Measurements Committee was planned as a technical interchange on several areas of technical interest to the Committee members.

The 2nd meeting of the Theoretical Methods Working Group was held at the United Aircraft Research Laboratories in East Hartford, Connecticut on the 27th of January 1966. A general discussion was held concerning the present state of kinetic rate data and the availability of this information. As a result of this discussion, one of the work packages tentatively considered was a parametric study to determine important reactions for propellant combinations identified as being of current interest.

Each Committee member, where possible, indicated how his company calculated rocket performance and what analytical tools were available or under development.

The 2nd meeting of the Overall Concepts Working Group was held on the 1st and 2nd of February 1966 at the Jet Propulsion Laboratory, Pasadena, California. The relationship of the Performance Standardization Committee to the ICRPG was discussed. (The general organization in shown in Figure A-1). It was announced that Dynamic Science Corporation was selected to support the working groups by taking the minutes of the meetings, maintaining group files, and supplying any other technical or administrative service deemed necessary by the working groups.

The Committee recommended that the Theoretical Group be requested to compile:

1. A list of losses and the degree of uncertainty of their magnitude
2. Establish a preliminary methodology for the prediction of engine performance
3. Start a list of reaction rate constants
4. Propose how to account for throat area change from ablation
5. Propose how to account for combustion down the chamber
6. Evaluate the effects of mass injection in the chamber and nozzle including film cooling

A 1% rms accuracy on the total losses (final value) was the requirement set by the Committee.

Calculation procedures were outlined which would define the performance of an engine. Basic model quantities would be corrected by influence coefficients for each of the previously recorded losses. For purposes of computational accuracy, it was decided to make the loss influence coefficient additive (δ's) rather than multiplicative. The Committee also recommended that the corrections be applied with units of percent rather than seconds.

A model was selected for consideration by the Committee. The model considered:

1. One-dimensional isentropic expansion (ODIE)
2. Simple nozzle geometry
3. A system of losses which would generate corrections to the ODIE model as follows:
   a. Mixture ratio distribution
   b. Chamber friction
   c. Chamber heat transfer
   d. Energy release efficiency
   e. Nozzle friction
   f. Nozzle heat transfer
   g. Nozzle geometry
   h. Kinetics
   i. Mass distribution
   j. Two-phase flow
   k. Nonstandard inlet conditions

The 3rd meeting of the Theoretical Methods Group was held March 31 and April 1, 1966 as a technical exchange with the Overall Concepts Group. A summary of the analysis scheme being examined by the Overall Concepts Group was presented. The validity of the proposed model was

was analyzed and an assessment made of the industry's capability of calculating the correction coefficients. A summary of the theoretical calculations that would be available for the analysis of these effects was presented by the Theoretical Methods Committee.

1. One-dimensional
   a. Kinetics
   b. Two-phase flow
   c. Multistreamtube (one run/streamtube)

Boundary layer losses would be determined separately.

2. Two-dimensional
   a. Kinetics
   b. Two-phase flow
   c. One or two stream zones
   d. Curvature

Boundary layer losses would be included in the two-dimensional programs. It was emphasized that each of the above were available separately and the best calculations for each effect could be combined into one program.

The Committee considered two alternatives for the use of its adopted computer programs:

1. Select one particular program as an industry standard
2. Adopt one program as a reference for checking the accuracy of the others

Discussion on either 1 or 2 above followed with no apparent conclusions being reached. The Overall Concepts Committee meeting separately discussed the model with emphasis placed on the alternates of the simplified and rigorous methods. Alternative methods for applying the losses were discussed.

A. <u>Friction and heat transfer-combustion chamber and nozzle considered together</u>

1. Properties evaluated at bulk values

2. Properties evaluated at local wall values to account for radial variation

3. Use concentric ring at wall with its own O/F

4. Pick a representative number from experience

The Committee decided to ask the Theoretical Methods Group for the best calculation method for this loss. The limit of accuracy and the cost trade-off were to be examined, and three diverse sample problems calculated using each of the four models. The results of these calculations would then be compared to determine the best method.

B. <u>Mixture ratio distribution</u>

1. Use bulk O/F ratio

2. Use streamtube O/F without specifications of streamtube location

3. Concentric rings with their own O/F ratio

4. Account for radial and circumferential variation

C. <u>Energy release efficiency</u>

1. Select representative number from previous experience

2. Reduction in T_o (H_o)

   a. Treat unburned propellants as inerts

   b. Heat loss, no inerts

3. Base on element design and number

D. <u>Kinetic Loss</u>

1. Ignore interactions of O/F and energy release efficiency

2. Consider O/F only

3. Consider energy release efficiency only

4. Include interaction of both terms

Other investigation areas posed for the Theoretical Methods Committee were:

1. Location of the streamtube sonic points

2. Effects of combustion efficiency and the possibility of calculation

3. A list of recommended computer programs which characterizes their use and availability

The 4th meeting of the Theoretical Methods Committee was held on the 2nd and 3rd of June 1966 at TRW Systems, Redondo Beach, California. A brief summary of the streamtube model was presented. This concept allows characterization of the injector and expansion process as a bundle of streamtubes where variation of O/F and mass flow rate between streamtubes can be accounted for. Losses from one-dimensional isentropic shifting equilibrium flow are calculated for each streamtube and summed to determine motor performance.

Several experiments were seen as possible outside work packages:

1. A cold flow, simulated nozzle where the pressure, velocity, and location of the sonic line would be mapped experimentally. Some data from this type of experiment was known to be available, and these sources would be surveyed before action was taken.

2. A cold flow, simulated nozzle using two gases of different specific heat ratios; for example, air and argon. The gases would flow in separate stream zones as a simulation of the streamtube models. Nozzle geometry would be varied. The pressure, velocity and location of the sonic line would be determined experimentally. Members of the Committee affiliated with organizations having the capability of experimentally investigating the transonic flow region in rocket

type nozzle flows were asked to submit ideas for an experimental program that could meaningfully map the flow field. These experiments were planned to serve as an example against which the validity of the numerical calculations could be compared.

Comparison of Computer Programs

The computer programs currently being used by the industry to calculate performance would be compared by making comparison runs with specified input data. Several problems were posed and the input data specified to survey the ability of current computer programs to handle diverse propellant and engine systems. The most qualified people in each area of performance calculations were to run their programs on purchase orders issued by Dynamic Science to cover computer set-up and running expenses. A Comparison of equilibrium programs was to be made on a voluntary basis.

The calculations were broken down into nine tasks:

1. Chemical equilibrium
2. Two-dimensional axisymmetric perfect gas, constant γ
3. (a) Two-dimensional axisymmetric perfect gas, variable γ
   (b) Two-dimensional axisymmetric perfect gas, variable γ, with shock
4. One-dimensional kinetics
5. Axisymmetric kinetics
6. Boundary layer
7. Transonic, constant γ
8. Transonic, variable γ
9. Two-phase flow

Future discussion relative to selecting proposed programs as either reference or standard programs within the objectives of the Committee were expected to be based on the results of the comparative calculations.

In regard to chemical reaction rates, the Committee voted to propose a funded study for the determination of the controlling reactions for ten representative propellant systems. A one-dimensional kinetic program would be used to screen the reactions with values of the reaction rate constants being varied in a parametric study to determine the controlling reactions. Once identified, the reaction constants for the controlling reactions would be critically reviewed and remeasured if it was felt to be necessary.

A potential funded study was proposed to determine:

1. The limiting area ratio at which combustion affects performance
2. The losses in performance due to striations in supersonic flow

The variables to be considered were:

1. Propellants
2. Mixture ratio
3. Pressure
4. Nozzle configuration
5. Amount of unburned propellant
6. Kinetic rate constants

The analytical experiments conducted under part 1 would utilize both equilibrium and one-dimensional kinetic computer programs. Various amounts of unburned propellants would be carried in the flow in thermal equilibrium and analytically combusted at various area ratios to determine effects on performance. The unburned propellants would be added in chemical equilibrium and at finite reaction rates utilizing a one-dimensional kinetics program. The analytical experiments to be conducted under part 2 would solve the supersonic flow field with an axisymmetric method of characteristics program coupled to frozen equilibrium thermodynamic properties in order to determine the effects of nonuniform mixture ratio in the flow field downstream of an arbitrarily specified distribution or starting line. The result would be compared with that of a uniform mixture ratio flow. The Committee placed the proposed work packages in the following order or priority:

1. Comparison of computer programs
2. Screening of reaction rates
3. (a) Limiting area ratio for combustion
   (b) Loss in performance due to striations in supersonic flow
4. Transonic flow experiments
5. Computer program adoption

The 4th meeting of the Overall Concepts Committee was held on the 9th and 10th of June 1966 at Arnold Engineering Center, Tullahoma, Tennessee. The change in status of the Performance Standardization Working Committee to an ad hoc Working Group of the ICRPG was discussed. The subgroups of the Performance Standardization Working Group were made Committees with the revised organization chart shown in Figure A.2.

There was a general discussion of the Aerojet contract to write a source book of calculation procedures and do illustrative calculations. The use of the energy release efficiency as a variable in the iteration loop of the performance correlation procedure led to a discussion of the meaning of and the description of a physical model for energy release efficiency. It was felt that there was a need to determine the physical mechanism which accounts for the energy release efficiency effect so that a model which was both realistic and feasible for calculation purposes could be formulated and adopted. The Theoretical Methods Committee was asked to study the subject and to make recommendations. The Overall Concepts Committee also requested the Theoretical Methods Committee to determine whether supersonic combustion was a significant mechanism for developing thrust in a rocket engine for systems in which the energy release efficiency in the subsonic portion was greater than 90%. Also discussed was the meaning of the 1% error goal established by the Committee. Some members felt that the accuracy criterion should be expressed as a function of the phase of the engine development program and how much the engine departed from the current state-of-the-art. The

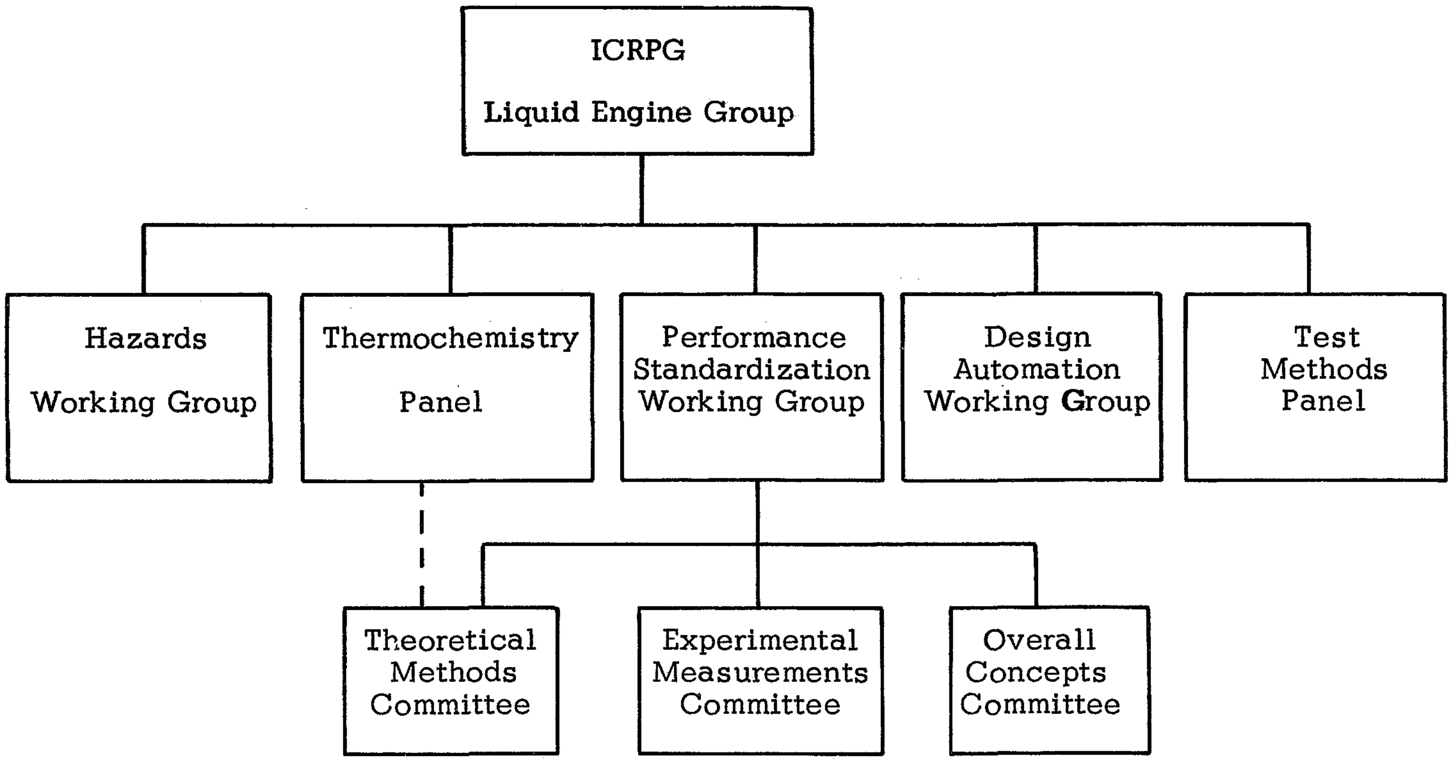
ICRPG
Liquid Engine Group
Hazards
Working Group
Thermochemistry
Panel
Performance
Standardization
Working Group
Design
Automation
Working Group
Test
Methods
Panel
Theoretical
Methods
Committee
Experimental
Measurements
Committee
Overall
Concepts
Committee

Figure A-2

allotment of allowable error between the various committees was also discussed. A subcommittee was formed to investigate this area.

The 5th meeting of the Overall Concepts Committee was held on the 13th and 14th of September 1966 at LTV, Warren, Michigan. Recent changes in the organization of the Performance Standardization Working Group were presented by D. Bartz. B. Levine has replaced D. Bartz as the NASA representative on the Steering Committee with D. Bartz holding the position of program coordinator for the three committees of the working group. The status of the work packages being funded by the various committees was discussed. Two contracts had been given to Aerojet-General Corporation by Dynamic Science at the request of the Overall Concepts Committee. The contracts were for a documentation of the performance evaluation method under consideration by the Overall Concepts Committee and for the running of approximately 100 sample cases. Representatives of Aerojet-General presented to the Committee the results of the Phase 1 contract (Performance Evaluation Methods for Liquid Rocket Thrust Chambers). Developed were:

1. Criteria for the selection of the performance parameter (Isp)
2. Rigorous performance model
3. Development of static pressure distribution expression for specific impulse
4. Perfect engine concept (ODIE)
5. Perfect injector/real nozzle
6. Real engine concept
    a. Nonuniform mixture ratio distribution performance loss
    b. Energy release performance loss
7. Scope of real engine performance evaluation
8. Procedure for extrapolation of Isp to altitude value
9. Particular, real engine performance models (input parameters) and calculation procedure charts

10. Advantages and disadvantages of the real engine concept

11. Results of sample calculations

The Committee considered a work package to obtain good experimental engine firing data to use in evaluating the energy release efficiency (η_{ER}), and the extrapolation from sea level to altitude performance prediction. The Experimental Measurements Committee would be consulted to see that the data was consistent with their measurement practices. Low and high expansion ratios as well as flight data was expected to be required. Committee members were asked to check on firing data for an engine they felt met these requirements.

The purpose of the Aerojet-General Phase 2 contract was to evaluate the alternatives shown in the first contract, and show what propellant systems and engine conditions demonstrate the interaction between losses. Additional parameters to be included in the study as a result of Committee discussion are the different energy release models and supersonic combustion. Preliminary results showed that mixture ratio distribution could cause the sea level performance ratio to be higher than altitude performance ratio at the same overall mixture ratio. The question was raised as to the correct application of the Bray criterion. This criterion appeared to be outmoded as two-dimensional exact kinetics could now be calculated. J. R. Kliegel, Chairman of the Theoretical Methods Committee, was asked to attend the next meeting of the Overall Concepts Committee and give a presentation of the state-of-the-art for exact kinetic programs.

The 5th meeting of the Theoretical Methods Committee was held on November 3 and 4, 1966 at Grumman Aircraft Engineering Company. No exact definition of what was required to make a computer program acceptable was reached. It was decided to examine the results of the comparison of the computer program study to see the differences between these results before reaching any conclusion in this regard.

The equilibrium cases were discussed and Dynamic Science was asked to examine the effect of the start line of the performance based on data that had been submitted.

In order to evaluate the results of the constant and variable gamma method of characteristics programs it was necessary to determine the computation procedure of the various programs. It was requested that the companies who recieved subcontracts on these two tasks present information in regard to the following 6 questions:

1. How was the nozzle axis treated?
2. How do they calculate thrust coefficients?
3. How does the program treat the wall including the derivative at the wall?
4. What methods of mesh size control are used, if any?
5. What is the criteria of convergence at the mesh point?
6. How are the gas properties at inbetween locations obtained in the variable gamma programs?

A discussion of the other tasks was held. In general, the sample runs were not available early enough to permit complete data presentation.

A lengthy discussion took place on how to calculate the effects of incomplete combustion. Possible alternatives examined were:

1. Suppression of temperature and enthalpy
2. Consider a certain portion of the propellant does not react

Using an unreactant propellant model several other alternatives were possible:

1. Equal proportion over-reacted fuel and oxidizer both in thermal equilibrium
2. Either fuel or oxidizer unreacted in thermal equilibrium
3. Unreacted oxidizer at wet bulb temperature
4. Unreacted fuel at wet bulb temperature

Dynamic Science discussed their droplet vaporization model and stated that considerable amounts (5%) of the propellant could exist in a liquid phase at the nozzle throat. Due to different vaporization rates of the propellants, it was also possible that extreme mixture ratio gradients could occur axially along the chamber. Thus, if exact kinetic calculations were based on injected mixture ratio, serious errors could result.

The 6th meeting of the Theoretical Methods Committee was held on 8 and 9, December, 1966 at Rocketdyne Division of North American Aviation, Canoga Park, California. D. R. Bartz discussed the proposals on Screening of Reaction Rates and the Effect of Nozzle Combustion and Flow Striations on Performance. On both of these RFP's no suitable proposals were received which met all the requirements of the Committee. It was decided that the Committee should come up with a consensus technical approach before issuing new RFP's. It was also decided that the Committee should formulate the work statement and the respondents should give details on the people they plan to use on the program, related background in this area, capability, and a detailed cost breakdown. A monitoring subcommittee would be formed to review the contract progress.

The bulk of the discussion concerned developing detailed work statements for:

1. Screening of Reaction Rates
2. The Effect on Performance of Nozzle Combustion
3. Effect on Performance of Flow Striations

Preliminary work statements for these RFP's were written. RFP's for the three work packages were mailed by Dynamic Science on the 6th of January 1967. A meeting of the proposal evaluation subcommittee was held at Dynamic Science on 17 February 1967 and contractors were selected. The Screening of Reaction Rates study was awarded to TRW, the Effect of Nozzle Combustion on Performance was awarded to Rocketdyne, and the Effect of Flow Striations on Performance was awarded to Lockheed, Huntsville. Results of the comparison of computer programs were compiled by Dynamic Science and distributed. The Committee decided to form a subcommittee to evaluate the results of this study and recommend the choice of a standard or reference program for each type of program.

The 6th meeting of the Overall Concepts Committee was held on 11 and 12 January 1967 at Aerojet-General Corporation, Sacramento, California. As a result of a discussion of Aerojet's performance evaluation manual, current problem areas were exposed. It was decided that a model to calculate energy release efficiency was required. Also discussed by the Committee and needed from the Theoretical Methods Committee were means of treating:

1. Effect of nonuniform mass distribution in the chamber
2. Propellant or other mass additions such as film cooling
3. Mixing and interaction between streamtubes
4. Noncylindrical shaped chambers

After considerable discussion, it was decided that the Committee could not recommend a standard performance evaluation method at this time. The Committee decided to establish a subcommittee to consider the following interrelated subjects and to formulate appropriate work package proposals for submission to the full Committee at its next meeting.

1. The selection of and preparation of a concise report describing one or more interim standard performance evaluation methods. The reason for more than one standard would be to use available programs for the cases where they applied best. During the time that the Committee was considering this subject, it was anticipated that several new programs and calculation techniques would become available.
2. The subcommittee will prepare a news release for a popular aerospace journal.
3. The application of a standard performance evaluation method to the analysis of independent experimental performance data. The subcommittee would examine the available data and select the sets suitable for use in the sample calculations.

The 7th meeting of the Theoretical Methods Committee was held on the 9th and 10th of March 1967 at Marquardt Corporation, Van Nuys, California. A discussion of the energy release model was held and it was decided to attempt to resolve this item at the joint meeting of the Theoretical Methods and Overall Concepts Committees scheduled for May at the United Aircraft Research Laboratories. A discussion of the approaches being used for the flow striation study, the reaction rate study, and the nozzle combustion study was held, and technical monitoring committees were appointed for these work packages.

The 8th meeting of the Theoretical Methods Committee was held on the 10th and 11th of May 1967 at the United Aircraft Research Laboratories, East Hartford, Connecticut. This was a joint meeting with the Overall Concepts Committee. The main topics of this meeting were:

1. To reach a consensus on the RFP requesting proposals for writing the "ICRPG Performance Evaluation Calculation Manual for Liquid Rocket Engines"

2. To resolve the areas of misunderstanding about the methods to be recommended in this manual, especially regarding energy release.

The subcommittee appointed by the Overall Concepts Committee during their 6th meeting had drafted a preliminary RFP to write the "ICRPG Performance Evaluation Calculation Manual for Liquid Rocket Engines." The issue of whether or not the authorization to write this manual would be open to competitive bidding or awarded to Dynamic Science as a sole source contract within the framework of their existing contract needed to be resolved. Several Committee members indicated that their organization might be interested in bidding on this contract and that they would determine within their organization whether or not a bid would be forthcoming should the writing of the manual be open to competitive bidding.

The preliminary version of the RFP was distributed to members of both Committees. This document indicated that the contractor would be expected to develop methods of chaining the standard ICRPG computer programs so that a complete engine performance calculation could be concluded with a single entry to the IBM's 7094 MOD 2 computer. After considerable discussion of the difficulties involved, the chaining requirement was eliminated entirely from the proposed work package. The Committee concurred that in its stead the manual should include specific information on the proper sequencing of individual computer programs. In addition, details of how the output of one program should be input into the next computer program should be included. The standard ICRPG computer programs required for the sample calculations in the ICRPG Performance Evaluation Calculation Manual for Liquid Rocket Engines were not currently available. It was anticipated that many of these programs would be selected and documented through the efforts of the subcommittee of the Theoretical Methods Committee chosen to meet as consultants at JPL during the two week period of June 5th through 16th, 1967.

The question of which one of the available energy release models to recommend as an interim standard to the industry was finally resolved. The model selected was the reduced stagnation enthalpy model. The reasons for the acceptance of this model for computing the effect of a reduced thermodynamic state on specific impulse at different area ratios as an interim standard only were:

1. The model is simple and readily lends itself to the computation of the kinetic loss.
2. The model was proven to be useful in correlating experimental results obtained with storable propellants.
3. There were indications that this model would give answers which correspond to the mean of those results which would be obtained with other models.

The reasons for dissent were:

1. The model is not physically realistic.
2. The model has not been sufficiently well tested to demonstrate a good correlation with data for systems other than N_2O_4/A-50.
3. There is no provision for the possibility of combustion downstream of the rocket throat.

The reasons for dissent were thought excellent but it was generally recognized that the strength of the "ICRPG Performance Evaluation Calculation Manual for Liquid Rocket Engines" would be severely limited if it did not recommend a standard for the treatment and extrapolation of the losses arising from energy release inefficiency to area ratios other than the test expansion ratio. With this purpose in mind, the reduced stagnation enthalpy model was adopted by the ICRPG as an interim standard with the provision that if a potential contractor felt that the reduced stagnation enthalpy model was inadequate for his purposes he could compute the effects of incomplete combustion on performance using a different model. However, he must still (a) present the results of an energy release loss computed using the reduced stagnation enthalpy model for comparison and (b) clearly demonstrate his reason for a different choice of models.

The screening of reaction rates being conducted by TRW Systems was discussed. It was the purpose of this study to identify those reactions where uncertainties in the rate constants used could effect nozzle performance by more than ± 0.5 seconds of Isp at an expansion ratio of 40. It was resolved that TRW would identify as many of the reactions as possible by the next meeting of the Theoretical Methods Committee. The remaining work on this contract would be decided upon at that time.

The progress on the Effect of Nozzle Flow Striations on Engine Performance being conducted at Lockheed Missiles and Space Company, Huntsville, Alabama, and the Effect of Nozzle Combustion on Engine Performance being conducted at Rocketdyne, Canoga Park, California, was also discussed.

A subcommittee composed of members of the Theoretical Methods Committee from Grumman, the Army Missile Command, Dynamic Science, Rao and Associates, and Pratt & Whitney Aircraft was appointed as consultant for the comparison of computer program study. This subcommittee met on June 5th to June 14th, 1967 at JPL to select a boundary layer program, an axisymmetric equilibrium and frozen expansion nozzle program, a one-dimensional kinetic expansion nozzle program, and an axisymmetric kinetic expansion nozzle program to be modified for use as the ICRPG reference performance programs.

After considering the computational accuracy, programming quality, ease of program operation, thoroughness of program documentation and the computer time required per case for the available programs, the following four programs were selected to be modified and be used as the ICRPG reference performance programs.

1. A modification of the Bartz Boundary Layer Program developed by Pratt & Whitney, under Contract No. AF33(615)-3128

2. The Axisymmetric Equilibrium and Frozen Expansion Nozzle Program developed by Pratt & Whitney, under Contract No. AF33(615)-3128

3. The One-Dimensional Kinetic Expansion Nozzle Program developed by TRW, under Contract No. NAS9-4358

4. The Axisymmetric Kinetic Expansion Nozzle Program developed by TRW under Contract No. NAS9-4358

The program modifications specified by the subcommittee consisted mainly of modifying the input and output of the various programs in order to make them compatible as a group.

In all cases, the final program documentation to be issued for the ICRPG program was to include an analysis section describing the analytical model and its methods of solution, engineering descriptions of all program subroutines including the equations solved in each subroutine, flow charts of each subroutine, description of the program error diagnostics, and sample cases illustrating the use of the program.

Discussions were also held concerning the performance evaluation manual. It was the recommendation of the subcommittee that this manual have an Appendix containing simplified nozzle divergence and viscous loss correlations for perfect gas flows which would allow simple and relatively accurate performance predictions to be made by a designer from one-dimensional calculations without the necessity of performing a complete nozzle analysis. It was believed that the existence of such a simplified method of analysis would greatly increase the utility of the performance manual.

A short 9th meeting of the Theoretical Methods Committee was held Monday afternoon, 17th of July, 1967 in Washington, D. C., in conjunction with the AIAA Joint Propulsion Specialists' Conference. The three current work packages, (1) the Effect of Nozzle Flow Striations on Engine Performance, (2) the Screening of Reaction Rates, and (3) the Effect of Nozzle Combustion on Engine Performance, were reviewed by their program managers. The results of these studies (which were essentially complete) indicated much larger performance effects than had been originally anticipated. The implication of these effects on the engine performance were discussed at some length. It was agreed that the next meeting of the Theoretical Methods Committee should be devoted mainly to a review of the analytical engine model adopted by the Overall Concepts Committee in light of the new information available from these work packages.

The 10th meeting of the Theoretical Methods Committee was held on the 12th and 13th of September 1967 at the Jet Propulsion Laboratory, Pasadena, California. A. W. Ratliff of Lockheed, Huntsville, the principal investigator of the contract to study the Effects of Nozzle Flow Striations on Engine Performance, reported on the effects of various mixture ratio distributions as they affected the specific impulse of four propellant systems. As anticipated, the losses were sufficiently great relative to the performance of the same propellant system operating at the average overall mixture ratio and it was confirmed that these effects must be considered in nozzle analysis. It was asked how accurately the effects of a mixture ratio maldistribution might be approximated if one made the assumption that a constant percent of ideal performance (vacuum specific impulse) were lost from mixture ratio maldistribution irrespective of area ratio. A. W. Ratliff said that he regarded this as a reasonable assumption and subsequently computed the percent loss in specific impulse for the parabolic mixture ratio distributions at the nozzle throat to test his hypothesis. The results suggested that the approximation was reasonable except for the F_2/H_2 propellant system.

S. S. Cherry of TRW Systems, the principal investigator of the study contract to Screen Reaction Rates, reported that except for the continuing investigation of the OF_2/diborane propellant system the subject contract work was completed. The purpose of the study was to identify those chemical reactions where the estimated current uncertainty in the reaction rate constants contribute to a significant uncertainty in nozzle specific impulse and to determine which chemical reactions must be included in the kinetic chemistry nozzle analysis to insure accurate results. In this regard, it was noted that there were some reactions where a large perturbation in the reaction rate constant had little effect on computed nozzle specific impulse, but which were essential to a kinetic chemistry nozzle analysis because they furnished important intermediaries for other more critical reactions. Phase 1 of this study was concerned with the development of a table of kinetic reaction rates and associated uncertainties for the propellant systems considered. These "best-value" reaction rate constants were developed from a critical review of the available rate screening literature, and are available in Cherry, S. S., "Screening of Reaction Rates," Phase 1, Final Report, TRW Systems Report No. 08832-6001-T0000, 22 May 1967. It was reported that for most reactions the computed kinetic specific impulse was not affected by as much as ± 0.5 seconds in impulse by perturbing individual reaction rate constants over their respective uncertainty ranges. This discovery should make it possible to eliminate some of the many chemical species which are currently considered in the kinetic nozzle analysis with a resulting time saving in the computational sequence. At the time of this meeting, S. S. Cherry stated that there were only 12 to 15 primary reactions where existing uncertainty in the reaction rate constants could effect nozzle performance by more than ± 0.5 seconds. (For example, for the N_2O_4/A50 propellant system, there are only 5 such reactions). However, it was emphasized that some of the other reactions would have to be included in the kinetic nozzle analysis because they lead to the formation of important intermediaries required for the primary reactions. It was noted that one of the worst reactions from a standpoint of the uncertainty in the reaction rate leading to a large uncertainty in specific impulse, was the molecular hydrogen dissociation reaction, that is, $H_2 + M \rightleftarrows 2H + M$. S. S. Cherry said that his study indicated that a 5% uncertainty in this reaction rate constant could lead to an uncertainty of 0.5 seconds in specific impulse for some propellant systems. One of the surprises of this study was the nonlinearity of the effect of a reaction rate perturbation on specific impulse. It demonstrated that a maximum specific impulse could be reached with a certain reaction rate and that a further increase in the reaction rate constant (while maintaining all other reaction rates constant) would actually decrease the overall performance.

R. C. Mitchell of Rocketdyne, the principal investigator on the study contract to examine the Effect of Nozzle Combustion on Engine Performance, reported that there were two significant discoveries made during this study. First, there was a pronounced recovery in nozzle performance losses caused by incomplete chamber combustion if there is any continued combustion downstream of the nozzle throat, and second, there appears to be no limiting area ratio beyond which there is no benefit from additional combustion.

The subject of transonic flow was put on the agenda because it had been known for some time that the Hall type power series transonic flow solutions for a perfect gas did not accurately predict wall pressures or the location of the sonic surface for nozzles having relative radiuses of curvature of less than 2, and many of the Theoretical Methods Committee members were uncertain as to what effect this limitation had on the best current nozzle performance prediction capabilities. It was agreed that the best check between different transonic analytical methods was provided by a check of predicted wall pressures, centerline pressures and the relative location of the sonic line. In this regard, it was noted that the planned ICRPG reference axisymmetric computer programs would generate their own start line. It was recommended that the transonic analytical methods being considered be adapted to the analysis of two-dimensional nozzles (rather than axisymmetric) and results be computed and compared with exact transonic solutions which were available for this geometry. No further action was planned for the Theoretical Methods Committee on this subject at this time, but it was recommended as a likely area for future work.

At previous meetings some disagreement had been noted regarding which of two possible integration schemes was best for evaluating the boundary layer loss. Also, at issue was the relative magnitude of the error incurred by not considering the displacement effect of the boundary layer on the main stream in computing the boundary layer loss. Calculations were presented which indicated that the wall pressure correction could amount to 1/3 of the correction for wall shear. This is the correction which is introduced when the mainstream (considered inviscid for the supersonic nozzle analysis) is displaced a distance corresponding to the displacement thickness, δ^*, of the boundary layer. Other members felt that the error incurred by neglecting the displacement of the boundary layer in an inviscid analysis of flow through a nozzle would be negligible in most cases and remained unconvinced that the displacement caused by the boundary layer would lead to significant (greater than 0.25%) correction to nozzle specific impulse. An ad hoc subcommittee consisting of members of the Overall Concepts and Theoretical Methods Committees had been attempting to resolve these questions to their mutual satisfaction. This subcommittee's choice of the best method of computing the boundary layer loss would be incorporated into the ICRPG reference program and could necessitate the inclusion of a third standard method of analysis into the "ICRPG Performance Evaluation Calculation Manual for Liquid Rocket Engines." This eventually could come about if it was determined that a significant improvement in the prediction of nozzle performance could be obtained if the axisymmetric kinetic nozzle analysis is rerun with a nozzle whose dimensions had been displaced from those of the real nozzle by a distance equal to the boundary layer displacement thickness.

On 25 September 1967, a subcommittee appointed by D. R. Bartz to represent the contracting agencies of the ICRPG selected Aerojet-General Corporation to write the "ICRPG Performance Evaluation Calculation Manual for Liquid Rocket Engines." Their proposal was considered the best received from the standpoints of their technical approach and understanding of the objective RFP, experience of personnel, corporate facilities, man-hours and bonus work offered. The subcommittee to monitor this contract was selected at this time and consisted of members of the Overall Concepts and the Theoretical Methods Committees from JPL, AFRPL, Pratt & Whitney Aircraft, Rocketdyne, and Dynamic Science.

The 11th meeting of the Theoretical Methods Committee was conducted as a joint meeting with the Overall Concepts Committee on December 12 and 13, 1967, at TRW Systems, Redondo Beach, California. A short presentation on the status of recent projects undertaken by the Theoretical Methods Committee was given. Preliminary reports on the following work packages had been received by Dynamic Science and the members of the monitoring subcommittees:

1. The Effect of Nozzle Flow Striations on Nozzle Performance - Lockheed Missiles and Space Company
2. The Effect of Nozzle Combustion on Engine Performance - Rocketdyne
3. Screening of Reaction Rates - TRW Systems

The necessary changes to convert 1 into a final report had been sent to the contractor by Dynamic Science and the other preliminary drafts were still in the process of review.

The subject of the anticipated ICRPG reference programs which would be made available through Dynamic Science when completed were reviewed.

1. ICRPG Reference One-Dimensional Isentropic Equilibrium Expansion Nozzle Program, ODE
2. ICRPG Reference One-Dimensional Kinetic Expansion Nozzle Program, ODK
3. ICRPG Reference Axisymmetric Kinetic Expansion Nozzle Program, TDK
4. ICRPG Reference Axisymmetric Equilibrium Expansion Nozzle Program, TDE
5. ICRPG Reference Nozzle Boundary Layer Program, TDL

The first three of these ICRPG reference nozzle programs were under modification by or through Dynamic Science, and the last two were being modified by Pratt & Whitney under contract to Dynamic Science. It was anticipated that these computer programs would be made available to the rocket industry at the cost of transcribing them on computer tape (tape would be supplied by the organization requesting the ICRPG reference computer program). Versions will be available for IBM model 7090, IBM model 7094, CDC model 6600, and the UNIVAC 1108 computer systems. Relative to its future involvement with the problems of the liquid propellant rocket engine industry, the Overall Concepts and Theoretical Methods Committees jointly discussed expanding the scope of their activities beyond the problems associated with the consideration of a simple pressure fed liquid propellant rocket engine operating under steady-state conditions. The question of whether to reconstitute the existing committee was considered in order to insure that the representatives to the ICRPG committees were technically expert in the subject areas being considered. This question arose in conjunction with the great interest in air-augmentation exhibited by some of the members present which was a new field to other members. It was recommended that serious consideration be given to the advisability of formally reconstituting the three working committees in the event that the Performance Standardization Working Group elects to become heavily involved in an area which is not familiar to a majority of the existing membership. It was suggested that if this were done the retention of part of the existing membership would be desirable to stay in-phase with the work currently nearing completion. In conjunction with the consideration of air-augmentation as a future work area, the Theoretical Methods Committee resolved that any official committee action on this subject should be preceded by the appointment of one or two members from each of the three working committees to a subcommittee which would investigate this area. This subcommittee would have authorization to select the framework from which experimental and theoretical models could be derived for presentation to the three working committees. A list of new subject work areas was compiled and 18 subcommittees were created to investigate these areas.

1. Energy Release
2. Boundary Layer Analysis
3. Metallized Propellant Systems
4. Two-Phase Flow
5. Film Cooling
6. Secondary Injection
7. Nonconventional Nozzles
8. Ablating nozzles
9. Computer Program Improvement
10. Transonic
11. Reaction Rate Data
12. Effect of Shocks in Nozzles
13. Flow Separation
14. Air-Augmentation
15. Small Engines
16. Dynamic Performance/Throttleable Engines
17. Pump Fed Engines
18. Vehicle Performance

These subcommittees were held responsible for delivery of preliminary written reports to Dynamic Science. The five essential elements which were to be covered in the written briefs on these subjects were:

1. Identification of the problem relative to the magnitude of its effect on measured or computed performance
2. The nature of the problem - more specific
3. Recommended approaches:
   a. analytical
   b. experimental
4. Approximate level of effort (anticipated level of funding required)
5. Recommendations:
   a. As committee action items/funded within committee
   b. Funded by outside agency

J. L. Piper of Aerojet outlined the contents of the anticipated ICRPG Performance Evaluation Calculation Manual for Liquid Propellant Rocket Engines, and discussed some of the details at greater length. Schematic flow charts illustrating the order and nature of the computations required for the ICRPG standard performance evaluation procedure and the ICRPG simplified performance evaluation procedure were presented. It was recommended that the manual should specify a standard procedure for developing the mixture ratio maldistribution at the injector face. This suggestion was accepted.

In regard to the boundary layer loss, the ad hoc subcommittee whose purpose was to resolve the differences encountered when the boundary layer loss was computed from (1) the integral of the wall shear (method incorporated in the Pratt & Whitney Boundary Layer Computer Program currently being modified to produce the ICRPG reference program, TBL) or (2) the momentum thickness, θ_e, and displacement thickness, δ_e^*, at the nozzle exit, (the method recommended by D. R. Bartz and W. B. Powell of JPL) identified that the source of these differences results from deletion of the term accounting for the effect of wall curvature in the momentum boundary layer equation. This factor was dismissed as a first order vanishing term from a Prandtl "order of magnitude reasoning" but it was shown that the cumulative effect of disregarding this term was not inconsequential. The ad hoc subcommittee accepted this oversight in the development of the boundary layer equation for a contoured wall as being responsible for the differences in the boundary layer loss as computed using the wall shear versus the momentum deficit approach, and appropriate corrections to the ICRPG Reference Boundary Layer Computer Program, TBL, would be made.

The 12th meeting of the Theoretical Methods Committee was held on 10 and 11 June 1968 at the Sheraton-Cleveland Hotel, Cleveland, Ohio. The Committee turned its attention to its future role, opening the discussion with some remarks on air-augmentation. The ICRPG Performance Standardization Steering Committee favored air-augmentation as a new area of system attention as opposed to technique advances, i.e., the emphasis would not at this time be on developing the pieces of the methodology as had been done with the liquid rocket system. For example, standard terminology needed to be developed for air-augmentation systems as a preliminary to any consideration of performance prediction methodology. It was felt to be premature to adopt any specific action with regard to the Committee's role with air-augmentation. Whether a new committee would be formed under the Performance Standardization Working Group devoted to air-augmentation was left open. The first order of business for the committee would be in following up and preparing for the implementation of what had been produced. Implementation in NASA and the services was being pushed internally by members of the Steering Committee.

A minimum operation mode was discussed in which the Committee would probably meet twice a year with the primary goal of implementing the various products, i.e., the machine programs, the Performance Evaluation Handbook, the Measurement Uncertainty Handbook, and the "Handbook of Recommended Practices for Measurement of Liquid Propellant Rocket Engine Parameters". If additional funding became available, then the Committee could consider improving some of the loose ends associated with the techniques already adopted. The subsequent discussion centered around this topic. An improved transonic flow analysis and further experimental work related to turbulent flow meters were mentioned as prime candidates for further funding; however, most of the discussion revolved around what could be done to improve the reaction rate picture if additional funds became available. The belief was expressed that the expertise did not exist in the present Committee that was required to properly investigate and evaluate the multitude of experiments that had been performed to obtain rate data and to ascertain from such a study what ha already been adequately done, what remained to be done, and how it should be done. The question as to whether a government laboratory might be persuaded to take on this kinetics job was raised. NBS was, with internal funds, assembling kinetics data but this was not the extent of critical review that needs to be done. The concensus of the Committee was that if funding became available the Committee felt that it had an obligation to implement a work package directed at establishing a reference set of reaction rate data for which the confidence level was substantially higher than that which existed at the present time.

The 13th meeting of the Theoretical Methods Committee was held on 3 and 4 December 1968 at LTV Aerospace Corporation, Missile and Space Division, Dallas, Texas. General comments on the attainment of the Theoretical Methods Committee's first phase goals of publishing and distributing the "ICRPG Liquid Propellant Thrust Chamber Performance Evaluation Manual" were made.

It was recommended that a user's group be established to deal with the problems that were bound to arise as the reference computer programs went into general use. Some procedure for the relating of problems encountered in using these programs, their possible solutions, and recommended program modifications were thought essential if the idea of reference computer programs were to be maintained. It was moved and approved that a reference computer program user's group be set up. Dynamic Science was to serve as the coordinating agency for the user's group and would perform the following duties:

1. Answer questions regarding the computer programs
2. Act on information provided by users of the programs regarding (a) errors (real or suspected), (b) desirable modifications, (c) complaints, (d) any item of information thought to be of value to other users.

3. Periodically issue numbered information bulletins. These bulletins would be sent to the same individuals to whom the computer programs were originally sent.

The question of the future activities of the Theoretical Methods Committee was an item of both practical and philosophical discussion for the major part of the meeting. The Committee had accomplished with some degree of success, those tasks for which it was originally organized to do. In order to achieve its goals, in a reasonable time, several compromises had been made, and other difficult problems such as energy release were forced to rely on empiricism. It was expected that new projects and goals would be established by the Working Group upon completion of this initial phase, but this was not the case. Other areas of future investigation were left up to the discretion of the Theoretical Methods Committee provided the Steering Committee could be convinced that the proposed work efforts were of measurable value. In this regard, any agreed upon work package would be funded by the Services and NASA on an individual need and interest basis through the JPL procurement department instead of through Dynamic Science as had been the general practice in the past. If the Committee felt that there was no justification for its continued existence, this recommendation would be acceptable to the Steering Committee.

After considerable discussion of possible new work areas, the Committee established an energy release subcommittee to evaluate the status of analytical techniques for energy release phenomena and make recommendations as to the desirability of doing further work in that area. The Committee also established a multiphase flow subcommittee to evaluate the status of analytical techniques for multiphase flow phenomena and make recommendations as to the desirability of doing further work in that area. In the realm of possible improvements to the present methodology, the following work areas were enumerated:

1. Revise TBL to permit calculation of ablating nozzles, and possibly revise the boundary layer analysis.

2. Modify TDK transonic analysis to allow multizone expansion and low $(\frac{r}{r^*})$ nozzles. Extend TDK calculations to give exit conditions.

3. Modify the chemistry in ODK and TDK to include expanded carbon chemistry.

4. Add VPP (variable properties program) to TBL.

5. Conduct a rate evaluation.

6. Develop a general gaseous chemistry package for ODK and TDK.

The Committee voted to recommend to the Steering Committee that items 2 and 3 listed above be undertaken. The remaining items would be enumerated as areas of technological weakness in which work should be done outside of the Theoretical Methods Committee. These recommendations were transmitted to the Steering Committee by Dynamic Science.

The 14th meeting of the Theoretical Methods Committee was a joint meeting with the Theoretical Methods Committee, the Experimental Measurements Committee and the Overall Concepts Committee and was held on the evening of 11 June 1969 in Colorado Springs, Colorado. W. Powell of JPL opened the meeting by discussing a proposed need to change the method of operation of the working group necessitated by limited funding and a possible reduction in individual company support. He stated that as there was only enough money available to maintain Dynamic Science's support function, the working group could only obtain action on items considered important by convincing an outside agency that the work in question was significant enough to be funded. In order to function in this manner, he suggested that the working group needed to formulate some means of remaining cognizant of what was and should be going on to enable it to resume the role of an overall coordinating group. He also felt the need to combine the three existing committees into one smaller active committee with a larger group of interested individuals who would remain informed of the working group's activities and be willing to both become an active participant when needed and disseminate the products of the working group to their own organization. Some discussion was held on future work areas for the working group and it was decided to accept the recommendations of both the Theoretical Methods Committee and the Experimental Measurements Committee as presented at their last meetings. In regard to the working group organization, a recommended reorganization of the Performance Standardization Working Group is shown in Figure A-3. Committee chairmen would be selected at the next Committee meeting or at the discretion of the Performance Standardization Working Group's Steering Committee.

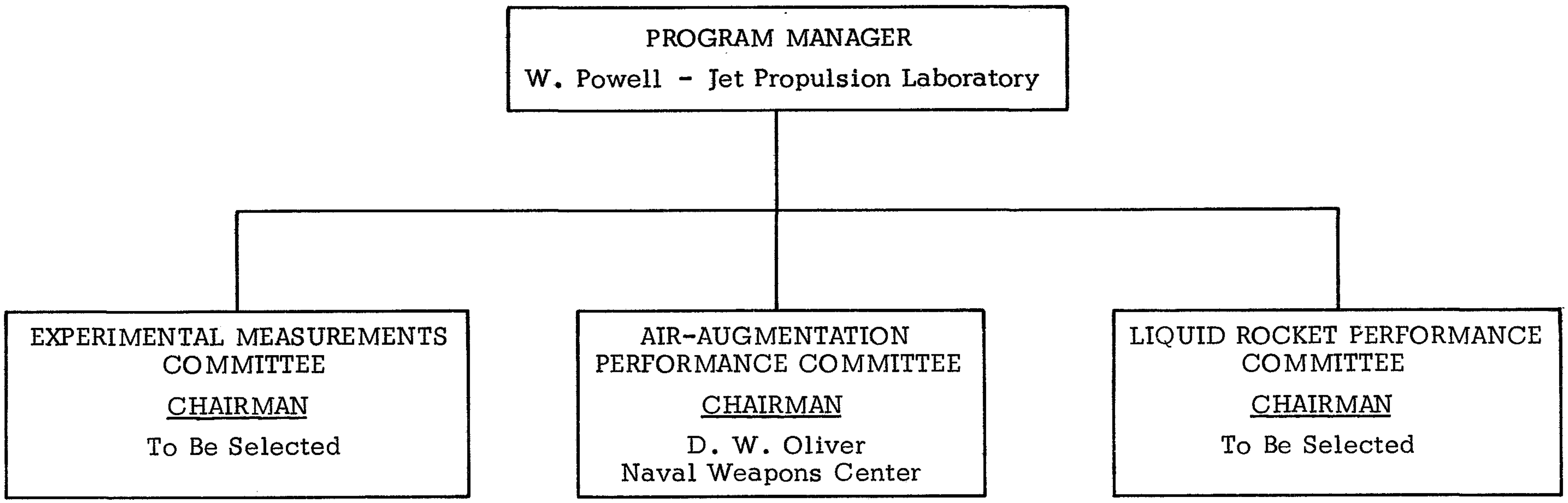
PROGRAM MANAGER
W. Powell - Jet Propulsion Laboratory
EXPERIMENTAL MEASUREMENTS COMMITTEE
CHAIRMAN
To Be Selected
AIR-AUGMENTATION PERFORMANCE COMMITTEE
CHAIRMAN
D. W. Oliver
Naval Weapons Center
LIQUID ROCKET PERFORMANCE COMMITTEE
CHAIRMAN
To Be Selected

Figure A-3

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ICRPG PERFORMANCE STANDARDIZATION WORKING GROUP

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APPENDIX A

DISTRIBUTION LIST

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Attn: Keith Chandler, R-P + VE-PA

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Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91103
Attn: W. B. Powell, Technical Manager

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Washington, D. C. 20546

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Research and Technology Division
Air Force Systems Command
Edwards, California 93523
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U. S. Army Missile Command
Redstone Arsenal
Alabama 35809
Attn: Technical Librarian

U. S. Naval Ordnance Test Station
China Lake
California 93557
Attn: Technical Librarian

CPIA

Chemical Propulsion Information Agency
Applied Physics Laboratory
8621 Georgia Avenue
Silver Spring, Maryland 20910
Attn: Technical Librarian

Army Materiel Command
Attn: Mr. Harold E. S. Jersin
Code AMCRD-MT
T-7, Gravelly Point, Rm. 2705
Washington, D. C. 20315

Defense Research and Engineering
Attn: Mr. G. R. Makepeace
Propulsion Technology Office
Pentagon, 3D1065
Washington, D. C. 20301

Naval Air Systems Command
Attn: Mr. Robert H. Heitkotter, AIR-330D
Munitions Bldg., Rm. 3810
Washington, D. C. 20360

B. F. Wilson
(AMSMI-RKL) Building 5452
Army Missile Command
Redstone Arsenal
Huntsville, Alabama 35809

J. W. Connaughton
(AMSMI-RKL) Building 5452
Army Missile Command
Redstone Arsenal
Huntsville, Alabama 35809

AFRPL (RPRE)
Attn: Mr. Walter A. Detjen
Edwards, California 93523

AFRPL (RPCL)
Attn: Forest S. Forbes
Edwards, California 93523

Captain Clyde McLaughlin
AFRPL (RPRRC)
Edwards Air Force Base
Edwards, California 93523

Dean Couch
Naval Weapons Center
Code 4584
China Lake, California 93555

Naval Air Systems Command
Attn: Mr. S. N. Block, AIR-53664
Room 2W21, W Bldg.
Washington, D. C. 20360

NASA, Lewis Research Center
Attn: Mr. Irving A. Johnsen
21000 Brookpark Road
Cleveland, Ohio 44135