The Space Congress® Proceedings

1969 (6th) Vol. 1 Space, Technology, and Society

Apr 1st, 8:00 AM

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Scholarly Commons Citation

Ledbetter, D. L.; Eaton, D. C.; and Habas, L. A., "NERVA -Contributing Today and Tomorrow" (1969). *The Space Congress® Proceedings*. 1.
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NERVA - CONTRIBUTING TODAY AND TOMORROW

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SUMMARY

The year 1968 has seen accomplishment of important goals in the technology development phase of the NERVA* program, including demonstration of the capability of the nuclear reactor to operate for 60 minutes at full-rated power, proving the ability of the system and components to meet specifications.

Based on the success of the technology development program, conceptual studies and designs leading to selection of the configuration for flight application were initiated.

From this complex R&D program a promise has come of many new and important technological developments. As various areas of research were opened to prove the feasibility of nuclear rocket propulsion, many conventional techniques required modification, due to the unique environment of the nuclear rocket.

Some of the significant technology now in use by the nonspace community that was originally developed by the engine contractor for the NERVA program will be described. Further, an extrapolation of some other technology areas currently being investigated and a suggestion of potential applications beyond those obvious in the earlier discussion will be presented.

INTRODUCTION

With each step of space exploration, technology is developed in support of the particular tasks of that step. This technology, based on the effort expended on earlier missions, e.g., MERCURY, GEMINI, APOLLO, results in new and important discoveries made through additional research, that extends the applicability of technology beyond its original purpose. Like these earlier programs, the past three years have seen many new technological developments in the NERVA program, that have found application with the industrial community at large.

NERVA consists of two phases: the technology phase, which is nearing completion, and the flight engine program. The flight engine phase will extend the work of the development phase to achieve flight of the nuclear rocket.

While many of the problems encountered in the NERVA program are common to nearly all new space research and development programs, the significant difference is in the long time span of the program and the involvement with the unique problems encountered within the nuclear science disciplines.

The technology phase of the program required that research and development, in many areas, be carried on in parallel because of the requirements for special considerations in design, testing, and evaluation incurred due to the nuclear environment; to the long lead times for material acquisition, test facility readiness, and the extensive posttest evaluations required for each test assembly. In addition, many of the more highly specialized areas required extensive additional research to support and prove the overall system feasibility. As a result, many new technological developments were made in several of the scientific disciplines which serve this sophisticated system.

To recognize the importance of these developments and their impact on the nonspace community, it is necessary to briefly describe the engine system and its operation, and to give a brief history of the NERVA program, and current status, in order to focus on the complexity of the research and development involved and its importance for a variety of industrial applications. The balance of the paper will discuss the technology of interest to the nonspace community, with several specific examples.

HISTORY

Although discussed during the Manhattan project, the practical beginnings of nuclear powered rockets grew out of a series of informal lectures on rocket propulsion organized in 1954 by the late Tom Gittings, then a member of the Reactor Division at the Los Alamos Scientific Laboratory (LASL). From these lectures there evolved a formal group called the Condor Committee, whose studies resulted in the formation of the nuclear division at LASL in April of 1955. The initial progress achieved by LASL in the conceptual reactor design and the fuel-element development was rapid, and, by 1960, the Kiwi A series of reactor tests had demonstrated the feasibility of a solid-core nuclear rocket. In 1961, Aerojet-General Corporation was selected as NERVA engine contractor, with Westinghouse Electric Corporation as reactor subcontractor, to develop a flight-type engine.

The Kiwi B test series, was initiated in December of 1961. A core vibration problem was highlighted by failure of the sixth test in the series, Kiwi B4A, in November of 1962. Extensive component and cold-flow tests indicated the cause of the failure, and corrective measures were taken. Successful tests of the Kiwi B4D and Kiwi B4E by LASL and of the NRX reactors, NRX A2 and NRX A3, proved that satisfactory design changes had been made. After solution of this problem, progress was again rapid with the testing of Phoebus 1A, NRX/EST, NRX A5, Phoebus 1B, and NRX A6. The Phoebus 2A reactor, originally planned to demonstrate high power reactor performance for direct application to the 200,000 lb thrust NERVA II engine, (dropped in favor of the 75,000 lb thrust version in 1968) demonstrated the ability to scale up the reactor design to higher power density and to obtain performance data under these

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* The Nuclear Engine for Rocket Vehicle Application (NERVA) program is administered by the Space Nuclear Propulsion Office, a joint agency of the U. S. Atomic Energy Commission and the National Aeronautics and Space Administration. Aerojet-General Corporation, as prime contractor for the engine system, and Westinghouse Electric Corporation, as principle subcontractor responsible for the nuclear subsystem, are developing a nuclear propulsion system.

operating conditions. Because of its large size, much of the hardware needed for the Phoebus 2A required significant extensions of the state-of-the-art in design and fabrication. The Pewee 1 reactor proved the feasibility of a small sized reactor (containing only about one-fourth as many fuel elements as the NRX reactors) as a test bed to support fuel element research and development. This reactor provides an environment that can simulate a variety of reactor operating conditions for evaluation of fuel developments at lower cost and with a shorter turnaround time than possible through use of the NRX size reactors.

The ground experimental engine (XE), under test at this time, is planned to (1) obtain data on engine operating characteristics under conditions that partially simulate altitude atmospheric pressure, (2) to test control concepts that are candidates for the NERVA flight engine control system and, (3) to gain experience in the operating characteristics of the downward firing engine test stand necessary to conduct the NERVA engine development program.

A summary of the reactor and engine system tests to date is given in Table 1.

TEST	OPERATIONAL CHARACTERISTICS			
REACTOR DESIGNATION (DATE)	POWER IN MEGAWATTS	FLOW IN LB/SEC	FULL-POWER DURATION IN MINUTES	NO. OF CYCLES
Kiwi A July 1959	78	7	5	1
Kiwi A' July 1960	85	7	6	1
Kiwi A-3 October 1960	100	7	5	1
Kiwi B-1A December 1961	300	21	1/2	1
Kiwi B-1B September 1962	900	65	1/2	1
Kiwi B-4A November 1962	600	—	—	—
Kiwi B-4D May 1964	1000	65	1	1
Kiwi B-4E August 1964	1000	65	10.5	2
NRX-A2 September 1964	1100	71	2.5	2
Kiwi TNT January 1965	—	—	—	—
NRX-A3 May 1965	1100	71	16.5	3
Phoebus 1A June 1965	1000	66	10.5	1
NRX/EST February 1966	1100	71	30	10
NRX-A5 June 1966	1100	71	30	2
Phoebus 1B February 1967	1500	94	30	1
NRX-A6 December 1967	1150	72	60	1
Phoebus 2A June 1968	4000	285	15	2
Pewee 1 November 1968	520	25	40	3
XE	1100	71	*	*

* Now in test

TABLE 1 - SUMMARY OF REACTOR TECHNOLOGY TESTS

Based on the results of the technology program, the decision was made in 1968 to proceed with the development of a flight engine (Table 2).

Figure 1 shows an artists concept of this engine without propellant tank. A comprehensive discussion of potential applications of the nuclear rocket is contained in recent literature.(1,2)

Thrust, lb	75,000 approx.
Specific Impulse, sec	825
Chamber Temperature, °R	4500
Propellant flow rate, lb/sec	90

TABLE 2 - NERVA ENGINE SPECIFICATION

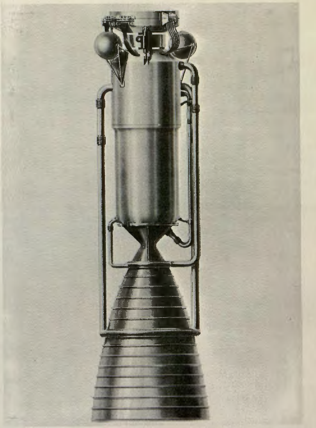

FIGURE 1 - NERVA FLIGHT ENGINE, 75,000 LB THRUST

NERVA ENGINE SYSTEM DESCRIPTION

Rocket engine performance is often expressed as a function of nozzle exhaust velocity. This exhaust velocity can be shown to be approximately proportional to $(T/M)^{1/2}$ where T is the temperature of the gas before expansion through the nozzle and M is the molecular weight of the gas. Since, in a nuclear rocket the temperature T is not likely to be higher than that obtained in a chemical rocket such as oxygen, and hydrogen, we attain our velocity advantage by choosing a propellant with the lowest possible molecular weight, hydrogen.

The nuclear rocket engine, Figure 2, consists of a nuclear reactor whose purpose is to heat hydrogen to as high a temperature as possible; a nozzle for expansion of the hot hydrogen, a hot bleed gas system from the nozzle to the turbopump, and a turbopump to force the hydrogen through the system. Control systems, including sensing elements and feedback loops are provided for the reactor power, reactor temperature and hydrogen flow. The entire nuclear stage includes the tanks in which liquid hydrogen is stored.

Three characteristics differentiate the nuclear rocket engine from other systems and lead to the requirement for development of new technology and unique systems and hardware.

1. The reactor operates at very high temperature and power density, complicating reactor design and problems in materials.

2. The system operates open loop, simplifying the engine cycle but greatly complicating the ground test facility problems.

3. The system is restartable and operates for a total time in excess of one hour. These criteria place severe requirements on all elements of the system particularly on the pumps and the reactor materials.

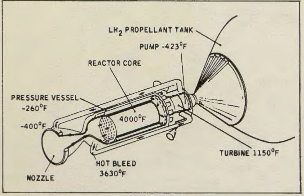

FIGURE 2 - NERVA ENGINE TEMPERATURE REGIMES

CURRENT STATUS OF NERVA DEVELOPMENT

With the Pewee 1 there have now been eleven consecutive reactors operated without a single instance of reactor failure.

A total of over nine hours of power operation has been accumulated, of which, more that four hours has been at, or near, design power. In the course of these tests, the high specific impulse that nuclear rockets have promised has been demonstrated with temperatures which would sustain a specific impulse approaching 800 seconds. Reactor characteristics are thoroughly understood and are predictable. Additional engine system information is now being developed through the current series of tests on the XE engine. These engine system tests are also proving the test facilities required for tests of the flight engine series.

The year 1968 saw initiation of work on the 75,000-lb thrust engine concepts with selection of the concept to be used scheduled for mid 1969. Detailed planning is underway for all phases of the program leading to testing of the first reactor for a flight engine in 1970 and completion of preflight mating tests for the engine about 1975. Basic specifications for the flight engine were previously shown in Table 2. The thrust of approximately 75,000 lb will be at a specific impulse of approximately 825 seconds. This performance compares to a specific impulse of approximately 450 seconds for advanced chemical rocket engines.

TECHNOLOGY OF INTEREST TO THE NONSPACE COMMUNITY

During the past several years, hundreds of technical papers have been published describing new techniques developed in support of the technology phase of the NERVA program.

Many of these developments have been adapted to and are now in use in industrial applications outside the NERVA program. This discussion will center on examples of recent significant developments. Details of these developments, as well as many others disclosed in the course of the NERVA program are available through the NASA Technology Utilization Program(3,4) and in the technical literature.

NERVA technology spin-off encompasses the entire range of research, development and provision activities in a complex program. Involved are work in materials properties, components and systems development, instrumentation, manufacturing, support equipment, testing and management systems. To illustrate the range of information developed, we will discuss examples of spin-off in each of these areas in brief detail and mention others on which information is available.

Materials Properties

Materials used in NERVA may be exposed to single and combined environments not experienced in other systems. The nozzle tubes, for example, are cooled on one side with liquid hydrogen at an entering temperature of 40°R (-420°F) while being in contact with the hot gas stream in the nozzle chamber more that 4000°R (3640°F) on the other side of the thin wall. Radiation from the nuclear reactor combines with the temperature extreme to further complicate the materials problems.

To ensure successful operation of the nuclear engine under these extreme conditions, it was necessary to devote a substantial effort to determining additional engineering properties of many materials. Needs of the program required extension of basic design information into operating regimes not covered by prior property data.(5) Figure 3 shows some of the areas where knowledge was extended under irradiated and unirradiated conditions in the cryogenic and high temperature regimes.

To better utilize this information, a Materials Properties Data Book was compiled to standardize allowable material properties of special interest to the nuclear rocket program. This handbook includes physical, mechanical, nuclear chemical and fabrication characteristics of materials and provides the allowable stress for design use. Design properties are established on one of three criteria in the following order of preference: (1) statistically established - 3σ; (2) specification guaranteed values; and (3) 80% of the average of experimental data. This data book has not yet been released for public distribution.

Components

Combined extreme temperature and nuclear environments, coupled with other conditions, such as high speeds for rotating parts and guaranteed reliability over the required operating life greatly complicate design of many NERVA components. Bearing races capable of operating under high loading and radiation for three hours in liquid hydrogen at speeds up to 24,000 rpm have been developed for the turbopump.(6) The bearing retainer (fabricated from S-glass reinforced polybenzimidozole (PBI)) is shown in Figure 4. This development can be a significant contribution in bearing technology and will find widespread usage both in cryogenic and high temperature applications. Many areas of component development are resulting in a variety of innova-

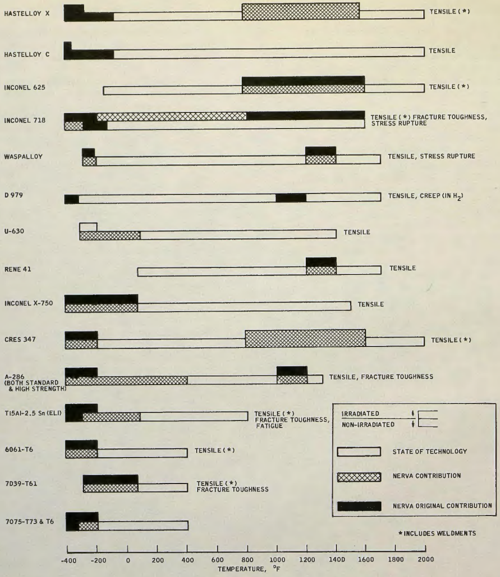

FIGURE 3 - NERVA PROGRAM EXTENSION OF MECHANICAL PROPERTIES DATA AS INFLUENCED BY TEMPERATURE AND NUCLEAR ENVIRONMENT

tions useful to industries involved with control of high pressure fluids; e.g., valve seals, high pressure pumps, etc. These are being made available as they are proved.

Systems

Evaluation of the effect of each of the complex variables in the nuclear rocket at the startup, transient, and steady state operating conditions required development of many computer analysis techniques. These range from programs for iterative solution of basic equations at each state point to those for analysis of sophisticated problems in heat transfer, structural stress analysis, thermal flow, vibration, shielding, etc. Costs for generation and implementation of any particular code can be thousands of dollars. Frequently, the programs are of such a fundamental nature that they can be applied to many fields within the industrial and educational community. These programs are collated and made available by NASA and the AEC through the University of Georgia Computer Management and Information Center, COSMIC.(7,8) To date, over 25 NERVA related computer code programs have been made

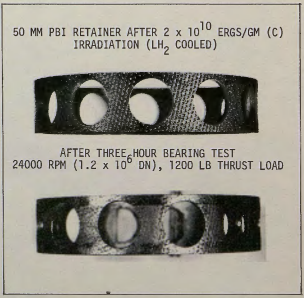

FIGURE 4 - IRRADIATED BEARING RETAINER

available to industry for application.

One example is a program for solving one or two dimensional, transient, or steady-state conduction heat transfer problems that are subject to convection, radiation or adiabatic boundary conditions, and provides for heating from internal heat generation.

This program is used to generate a network mesh and produce a temperature distribution for one or two dimensional transient or steady-state conductive heat transfer problems. These problems are subject to convection, radiation, or adiabatic boundary conditions with provisions for heating from internal heat generation. The program eliminates both the tedious calculations and the detail of constructing the finite difference network associated with general heat transfer problems. The user divides the geometric figure of the problem into a series of approximate rectangles. A rectangle is composed on one homogeneous material and all four of its sides may be skew lines.

The program will divide each of the rectangles into smaller subdivisions (subcells) of approximate rectangles. These subcells will form the grid for the finite difference method of solution. The mass of each subcell will be represented by a point mass which is the temperature node. The program is limited to 350 nodal points.

Another example is a computer program to determine the dynamic actuation response characteristics of a pneumatic spring-mass system as applied to a linear actuated valve.

To predict the dynamic response characteristics of valves utilizing a linear pneumatic actuator, this program uses an equivalent spring-mass system whose response can be thoroughly investigated.

The program takes into account all parameters of the system during motion such as: position, time, velocity, acceleration, gas flow rates from subsonic to sonic, changes in pressure and volume with respect to time, temperature, moving mass, spring rates, function, controlling orifice diameters, and external forcing function exciting the system. The method of iteration is used. All variables are assumed constant for small increments of time and dependent variables are calculated from the data at the preceding time increment.

Instrumentation

Instrumentation systems for NERVA encounter unique problems due to several conditions. Wide extremes of temperature are encountered with thermocouples penetrating the structure in an area cooled with liquid hydrogen at 40°R (-420°F) to measure gas temperatures of 4500°R (4170°F). The radiation environment causes internal heating and signal error in transducers and cables. Cables are flame sprayed to the cooled pressure vessel in order to provide the necessary cooling. The hot hydrogen gas carries carbon particles from the reactor and these particles migrate through ordinary thermocouple sheath materials. Tungsten-rhenium thermocouples, insulated with beryllium oxide beads and sprayed with a coating of 90% tantalum-10% tungsten have been developed to operate in the hot gas stream.

One of the concepts for high temperature thermocouples may have application with steel manufacturers to more accurately control the temperature of molten metals. Where temperature must be rigidly maintained to protect the integrity of the metals being made, this type of thermocouple may be useful in monitoring the fabrication processes. The flame spraying technique, developed to provide a heat sink for cables, has further valuable potential in the metals industry and the petroleum refining industry in those areas where cables are exposed to radiant heat.(9,10)

Manufacturing

The complex shapes, close tolerances and high integrity required in components for the nuclear engine program have led to many significant innovations in manufacturing. Adaptation of many of these techniques to other industries may result in significant savings in manufacturing costs as indicated by the following examples.

Multi-Head Electro-Discharge Machining (EDM)

On NERVA, EDM has been improved to reduce fabricating time and costs by simultaneously machining contoured longitudinal grooves, feed holes and slots in high strength alloy units, to very close tolerances. Figure 5 shows the setup of the complex structure in the index fixture for EDM machining. Note that the longitudinal grooves follow the internal convergent-divergent contour of the structure.

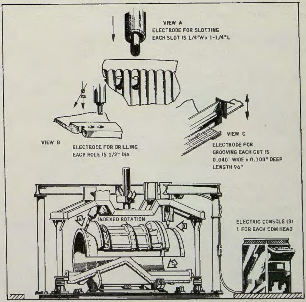

FIGURE 5 - MULTI-HEAD ELECTRIC DISCHARGE MACHING

Application of this technique in high production situations could result in cost savings in production manhours alone, of millions of dollars. Specific application of the multi-head EDM process to the automotive industry's high production techniques in fabrication and machining engine blocks could offset their initial investment which approaches 100 million dollars and could decrease downtime due to the breakage of the many drills used in the operation.

Vibrator Improves Spark Erosion Cutting

Deep holes of a metal cross-section, other than circular, are ordinarily formed using a spark erosion technique. Considerable machine cutting time is lost due to the time required to repeatedly retract and clean the cutting electrode of residue buildup. The application of a variable frequency mechanical vibrator, attached to the head of the spark erosion cutting machine, prevents residue buildup on the electrode and permits continuous cutting. Excess residue is flushed away with nonconductive electrical transformer oil. As a result of the adaptation of the vibrator cutting production on aluminum material has been increased in specific instances to more than 300%.(11)

Welding Standards

A welding manual recently developed for use in training at the Nuclear Rocket Development Station, found immediate acceptance and application throughout private industry. Examples of different types of welding are given, and pictorial representation of both acceptable and nonacceptable weldments are illustrated. This manual is now in use and is helping to establish and maintain specifications and standards for in-the-field welding that are needed for a variety of government and commercial applications.(12)

Another concept recently developed is a High-Speed Brazing Furnace that uses Infrared radiation for controlled brazing of metals (100°F to 1100°F). Potential of this device includes use in the electronic equipment manufacture, in development of components, and in a variety of other laboratory orientated applications.(13)

A technique has also been developed to calibrate ultrasonic test equipment used in detecting minute laminar discontinuities in thin metal strip stock. This technique permits calibration to sensitivity that senses laminar defects down to 0.0022-sq-in., in 0.012-in. strip stock. Previous methods were not only time consuming and difficult to apply, but usually destroyed the strip stock.(14)

Support Equipment

The nuclear environment created by development testing the engine/reactor, necessitated the establishment of a method to assemble and disassemble the system entirely with remote handling equipment. In addition to the sophisticated design of this equipment, special tools and machines were needed for some of the more complex phases of posttest disassembly. Deburring mills, and cross-sectioning saws were adapted to fit a variety of manipulators as well as pneumatic socket wrenches, special component stands, etc. Figures 6, 7, and 8 are photographs of remotely operated devices in the assembly/disassembly area, the posttest examination area and the remotely operated train used for transfer of the nuclear engine between the assembly/disassembly area and the test stand, and for remote installation of the engine into the test stand.

The remote handling technology developed for this task is now beginning to find application outside the nuclear engine program in central power stations. To meet the increasingly stringent fuel handling and fuel servicing requirements for future power stations, more advanced remote handling techniques will be required. Figure 9 shows a model of a handling system for remote removal, servicing and replacement of steam generator equipment in a nuclear power plant. The manipulators and removal tools disconnect the steam generator which is to be serviced and place it on an elevator which lowers it out of the plenum into a transfer cart for removal to the maintenance shop. This system permits essential maintenance operations without requiring personnel access to the plenum area where a radiation hazard might exist.

Further application of remote handling system technology to the field of oceanographic research may significantly increase the versitility of deep sea research devices and vehicles. One device,

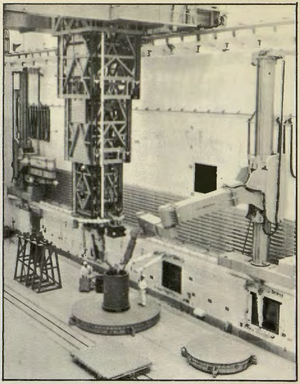

FIGURE 6 - MAINTENANCE ASSEMBLY/DISASSEMBLY AREA

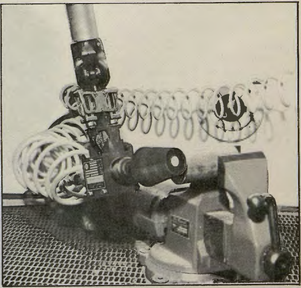

FIGURE 7 - REMOTELY OPERATED DEBURRING TOOL

FIGURE 8 - RAILROAD TRANSPORT SYSTEM

FIGURE 9 - REACTOR PLENUM SERVICING SYSTEM

a zero reaction space tool developed for assembly operations in space was tested underwater to simulate the full effect of reactive force on the operator while floating in space. (Figure 10) Adaptation of this tool to undersea operation may facilitate many submersible repair operations.

Testing

Rocket coolant channel tubes plugged accidentially by inclusion of low density materials, such as: rubber, plastic, wood, wax, vinyl, etc., cannot be cleared effectively without knowing the position and shape of the plug. When X-Rays are made through the heavy Hastelloy X nozzle walls,

FIGURE 10 - ZERO REACTION SPACE TOOL

the low density materials do not show because they absorb little X-Ray relative to the amount absorbed by the metal.

Solution of this problem involved well-controlled thermal neutron radiography by a nuclear test reactor* which produces sharply defined film images of plastic, wood, etc., due to neutron absorption by hydrogen-containing materials.(15)

The reactor furnishes a uniform columinated beam having a divergence of approximately .004 in/ft. The beam diameter, at approximately 20 ft. from the reactor core center, is sufficient to image standard 14 x 17-in. X-Ray film. The film image is made by low energy gamma rays, produced from a gadolinium transfer screen placed in contact with the film.

Results through 1/2 in Hastelloy X nozzle wall can detect a small piece of dental floss of .009-in. thickness.

Management Systems

The usual problems of information identification and retrieval found in all complex programs are compounded in NERVA due to the relatively long time span of the program (1961-197x). Organizational structure changes, personnel who are promoted, transferred or leave the organization and technological advancements all tend to lead to dispersed storage centers for correspondence, reports, drawings and other forms of information transference media. Decentralized storage then encourages drift in record keeping and storage techniques. Unless a large, strong central control group is maintained, manual cross-correlation of data between the various groups of media types becomes difficult.

One management system to provide reliable, rapid location of all information related to any given subject area has been developed, utilizing computers for the cross-indexing routines, and provides a locating system for all information transfers with a minimum of change in usual file techniques. (This system is currently being checked out and evaluated.) The communication is marked upon receipt, with a sequential identification number and type code, a copy is also marked to indicate subject, key words, key phrases, task identification, etc.

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*The General Electric Nuclear Test Reactor at the Vallecitos Nuclear Center, Pleasanton, California.

The information is introduced to the computer for storage and subsequent retrieval. The communication is stored in the usual manner and location, i.e., drawings in drafting, correspondence in administrative area., etc.

Retrieval is accomplished simply by describing the communications desired in terms of content, author, organization, addressee, key words, key phrases or other identifier contained in the memory.

Another recent Management System has elicited wide interest with several hundred firms that have requested additional backup data.

It was desirable to develop a visual display, suitable for rapid and visual review by top management, to illustrate the impact and path of critical items, showing their net effect on program objectives.

The solution involved creation of a chart technique, PERTREE, that displays the essential status elements of a PERT system in a vertical array, of high graphic quality.(16)

Conclusions

In statements before Congress by top NASA and AEC officials in 1968, it was said that the nation would, in addition to space propulsion supremacy, receive many spin-off benefits from the nuclear rocket program. These statements have since been authenticated. Review of NERVA developed technology has already found extensive utilization by the non-space industry.(17)

Continued research and development in the NERVA program is expected to further enhance the knowledge gained during the technology phase of the program. Experience with materials, components and systems operating in the extreme temperature and nuclear regimes of the nuclear rocket will continue to provide innovations and knowledge with direct application to the problems and progress of the non-space community.

Many of the significant spin-off developments are applicable only to space or nuclear rocket propulsion system and cannot be adapted to other programs. However, future technological developments applicable to private and commercial interests, including a variety of inner-space undersea operations, may make other spin-off attractive. Usefullness of such technology can only be measured by applicability to other fields.

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