THE DEVELOPMENT OF NUCLEAR ROCKET PROPULSION IN THE UNITED STATES*

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ABSTRACT

It is the purpose of this paper to present the overall history and status of nuclear rocket developments in the United States, to indicate the goals and objectives of the present development activities, and to illustrate some possible mission applications for engines of the class under development.

Historical milestones in this new field are presented and discussed, starting with the first published mention of the nuclear rocket concept in 1944, with particular emphasis devoted to events since 1957, the year the Kiwi reactor development programme was initiated—the reactor destined for ultimate use in the nuclear rocket engine system.

The Kiwi programme is described, the test dates and objectives indicated, and the test results presented, in a general sense, to provide an understanding of the background and development status of the reactor for the nuclear rocket application. The Kiwi reactor test procedures and facilities are described and the test site selection is reviewed.

The NERVA engine development programme is discussed. Guidelines and objectives that were established at the initiation of the programme in mid-1961 are outlined and descriptions are given of the engine and its subsystems and components; the unique test facility requirements (together with the facilities that are now under construction), and the special remote handling, transport, and assembly/disassembly equipment required for the engine development test programme. The Government organization that has been established for the management of the entire nuclear rocket propulsion and vehicle stage programmes is outlined.

Finally, the application of the in-development class engine to some initial missions of interest is explored, assuming that the nuclear-propelled stage is the third stage of the Saturn V launch vehicle. Some comparisons are made with the all-chemical counterpart vehicle. Lunar landing and planetary fly-by missions are considered, and solar system escape capability is indicated.

I. INTRODUCTION

THE purpose of this paper is to present the overall history and status of nuclear rocket developments in the United States, to explain the goals and objectives of the present development activities, and to indicate some possible mission applications for engines of the class under development.

To place this discussion in its chronological context, some history in this vital new field must be reviewed. Some of the significant nuclear rocket historical milestones are tabulated in Fig. 1. The first recorded mention of American nuclear rocket propulsion was made in 1944, when some Los Alamos Scientific Laboratory (LASL) personnel speculated about a broad range of potential applications of nuclear energy to propulsion. In 1946, a report was published concerning the application of a heat exchanger reactor to rocket propulsion. At that time, there was considerable scientific interest in the possibility of combining the tremendous potential of nuclear energy with the then-newly-exploited propulsion system concept of rocketry. Analysis and conceptual design studies were conducted by several organizations, as indicated in Fig. 1. Despite this first postwar interest and activity, no specific hardware developments were ordered, and the application of nuclear energy to propulsion was confined to the NEPA (Nuclear Energy for the Propulsion of Aircraft) project, the forerunner of the ANP (Aircraft Nuclear Propulsion) programme. It was not until the early 1950's that interest was again evidenced in the nuclear rocket concept. This interest

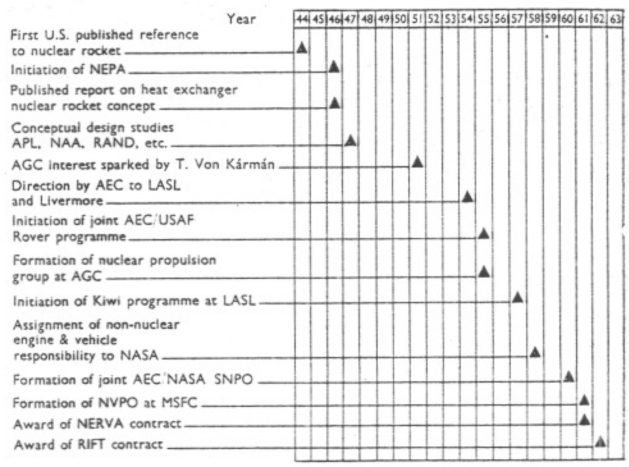

FIG. 1. Historical milestones.

developed in several locations almost simultaneously, with enthusiasm kindled at Aerojet-General Corporation and elsewhere by the late Dr. Theodore Von Kármán, Aerojet's founder and Chairman of its Technical Advisory Board for many years. Largely because of this renewed impetus, the Atomic Energy Commission (AEC) directed LASL and the University of California Radiation Laboratory (UCRL, Livermore, California) to study the problem of applying nuclear power to rocket propulsion. At that time, the UCRL group followed an approach which centered around the use of solid graphite reactors, with hydrogen as a propellent,

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while the LASL programme included consideration of ammonia or methane as propellents. In 1955, the United States Air Force became vitally interested in the propulsion potential that was offered by nuclear rocketry. The joint Atomic Energy Commission–United States Air Force ROVER programme was formally initiated, with the AEC having its traditional cognizance over reactor development and testing and the Air Force having responsibility for non-nuclear engine component and subsystem development and launch vehicle applications. In 1957, a specific ROVER reactor development approach was selected, marking the beginning of the Kiwi reactor development programme. The AEC decided to proceed with the fabrication and testing of research reactors using uranium-loaded graphite fuel elements to heat hydrogen to a temperature useful for rocket propulsion. The development responsibility was assigned to LASL, and the UCRL group was directed to devote their propulsion reactor efforts to the ramjet application. In 1958, responsibility for developing the non-nuclear engine and vehicles was transferred to the newly-formed National Aeronautics and Space Administration (NASA). In 1960, the joint AEC–NASA Space Nuclear Propulsion Office (SNPO) was organized, with its manager, Mr. Harold B. Finger, reporting to both AEC and NASA for the national nuclear rocket programme.

In the fall of 1960, the Kiwi programme results were so encouraging and the forecasts were so positive and confident that SNPO believed that an industrial engine contractor should be selected to direct and control, under SNPO guidance, the development of a flight reactor (based on the LASL-Kiwi technology and configuration) and the non-nuclear engine components and subsystems, and to integrate these into a useful and reliable flight propulsion system. Competitive proposals were prepared and evaluated in the Spring of 1961. In July, 1961, the NERVA (Nuclear Engine for Rocket Vehicle Application) contract was awarded to Aerojet-General Corporation. At the same time, the Government selected the Westinghouse Astronuclear Laboratory as a principal subcontractor for developing the flight reactor and certain other nuclear aspects of the engine development programme. Also in 1961, the Nuclear Vehicle Projects Office (NVPO) was organized within NASA at the Marshall Space Flight Center in Huntsville, Alabama, to provide technical direction for the development of the RIFT (Reactor-In-Flight-Test) stage, which would serve as the flight test vehicle for the nuclear engine. The Lockheed Missiles and Space Company was the successful bidder for this programme, and the RIFT contract was signed in May, 1962. Although the milestones in Fig. 1 and this discussion indicate a surprisingly long history of speculation and analysis and conceptual design concerning nuclear rocket propulsion, it should be emphasized that the first concerted effort was initiated in 1957 with the AEC decision to proceed with the Kiwi reactor development programme.

The NERVA engine development is based on the solid-core, heat-exchanger reactor concept, selected by LASL for the Kiwi reactor development programme. While other reactor concepts have been suggested and analysed, the AEC believed that the first propulsion system development should be based on the significant body of thought and technical data that was available regarding this concept. Although there are some obvious limitations to the solid-core concept, its selection was judged the most logical approach to the early demonstration of the feasibility of nuclear rocket propulsion. The propellent or working fluid chosen to extract the energy from the reactor exerts a significant influence upon reactor and engine design. Because rocket specific impulse is a direct function of the square root of (gas temperature divided by molecular weight), other things being equal, high gas temperature and low molecular weight are desirable. The data presented in Fig. 2 reflect this conclusion. Fig. 2 indicates the

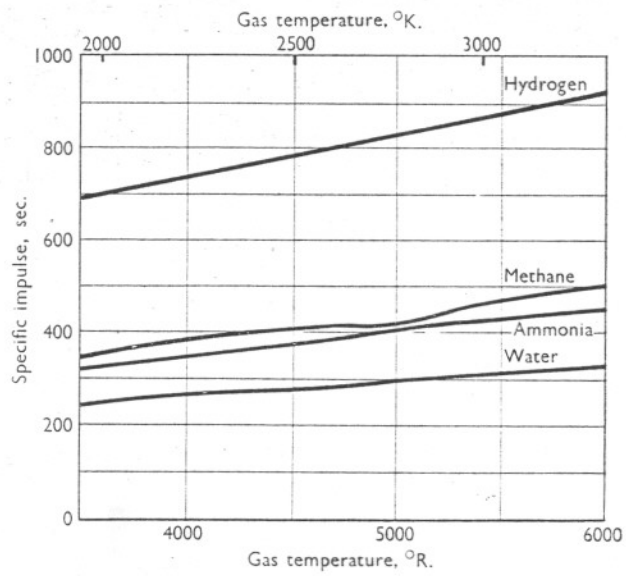


FIG. 2. Specific impulse as a function of temperature for several nuclear rocket propellents.

trend of specific impulse with gas temperature for four possible nuclear rocket propellents and clearly shows the superiority of hydrogen, which would have been expected because of its low molecular weight and resulting high specific impulse at any given gas temperature. To achieve these performance capabilities, the reactor must operate at as high a temperature as possible.

There are several possible reactor concepts that can be considered for this propulsion application. The first is the solid-core design, in which the fissionable material is contained in a solid core and provides a direct transfer of heat energy to the propellent. The second is the liquid-core design, in which fissionable material is contained in a liquid medium. The third is a design in which the critical mass is in the gaseous state. The liquid or gaseous reactor designs offer some significant potential mass and performance advantages, but an inherent requirement in any fluid-core design is the development of a successful method of containing the fissionable material. The state-of-the-art of these advanced reactor core designs does not approach the extensive body of thought and information available for the solid-core configuration. The advanced reactor concepts are shown schematically in Fig. 3. These

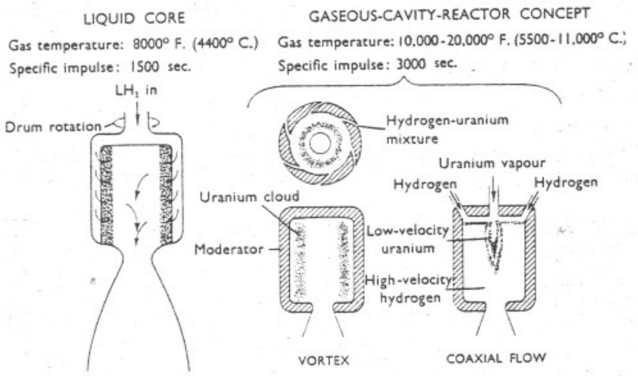


FIG. 3. Typical advanced engine concepts.

designs offer different gas temperature operating conditions, as governed by the materials which can be used for their construction, and they differ materially in the complexity of the reactor design itself. The solid-core reactor which was selected by LASL for the Kiwi programme, and which will serve as a basis for the NERVA engine, has a temperature limit that is governed by the physical properties and nuclear characteristics of the materials in the core. The solid-core reactor is relatively heavy and complex compared with the fluid-core reactors, and the power density of the reactor and pressure of the propellent within the core are two significant criteria influencing the success of the design. The mass and the dimensions of the core vary inversely with both power density and pressure, so that reactor mass can be reduced by increasing both power density and propellent pressure. For a given power level, the heaviest reactor will be that which operates in the thermal spectrum. Reactor mass decreases when the design is based on operation in the epithermal spectrum, with minimum mass achieved for a so-called fast reactor design. The fast reactor design, however, requires a relatively large quantity of fissionable material and presents some control problems that are not inherent in the thermal design. Operation in the thermal spectrum is the basis for the Kiwi and NERVA reactor designs.

II. THE KIWI PROGRAMME

As a result of the renewed interest in nuclear rocket propulsion in the early 1950's, the AEC selected a specific reactor development approach in 1957 and ordered LASL to proceed with the fabrication and testing of research reactors. Before this, LASL had investigated graphite materials because these materials were very high temperature structural materials for reactor fuel elements. With the responsibility for the reactor assigned to it, LASL selected a development approach for early demonstration of feasibility. The LASL approach was also strongly influenced by the difficulty of simulating some of the reactor environmental conditions without actually operating a reactor at a high power level. Hence, in the Kiwi development programme, there was considerable component testing followed quite early by tests of complete reactors.

Two series of Kiwi tests were scheduled at the beginning of the development, in accordance with the guideline for establishing overall feasibility as soon as practicable. The first series, the Kiwi-A series, was conducted using gaseous hydrogen and was planned principally as a fuel element development test. The Kiwi-A configurations had somewhat of a "battleship" nature and incorporated many features for facilitating and expediting the test programme, but these features would subsequently have to be modified or eliminated before a flight configuration could be established. Further, the decision to proceed with the Kiwi-A series using gaseous hydrogen postponed the necessity of developing and procuring liquid hydrogen pumping equipment. The first Kiwi (Kiwi-A) reactor test was conducted at Jackass Flats, Nevada, in July, 1959, and was operated at rated power and temperature for several minutes. The Kiwi-A′ was tested in July, 1960. The Kiwi-A′ had the same general external configuration as the Kiwi-A but had a revised core design. The third test in the Kiwi-A series (Kiwi-A3) was conducted during October, 1960, with the core instrumented to provide data to verify some discrepancies observed between predicted and actual operation during the Kiwi-A′ test. These three tests completed the Kiwi-A programme. A typical Kiwi test configuration is shown in Fig. 4. The overall Kiwi-A results were very encouraging. Some problems were discovered in the experiments but many of these were well understood and had been predicted in advance. Personnel at LASL believed that the remaining problems could be solved satisfactorily in the subsequent Kiwi-B liquid hydrogen series. Largely because of the successful Kiwi-A series and the enthusiastic forecasts made for the Kiwi-B series, the Government believed that it was timely to select an industrial engine contractor to be responsible for the development of the nuclear rocket engine system. At this time, the Kiwi-B series of reactors was being designed, and parallel approaches were being used in some areas to solve some of the problems. For example, more than one type of core

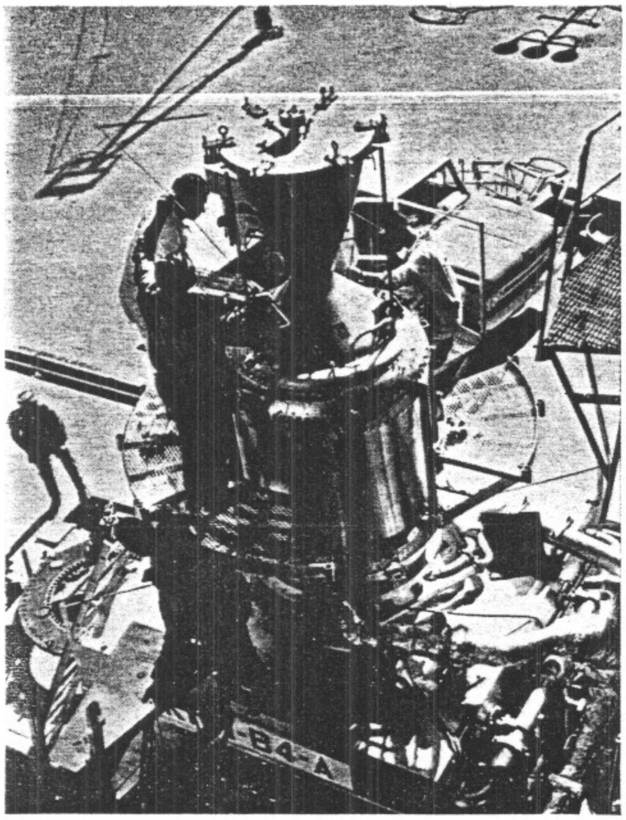


FIG. 4. Kiwi-B4-A reactor on test cart.

support was planned for this series of reactors. The Kiwi-B tests were scheduled to begin in the autumn of 1961, as shown in Fig. 5, and to extend through the following year. This Kiwi-B programme actually got under way late in 1961 and eventually required more time than had been scheduled. Some of the initial delay was caused by problems associated with the conversion of the test cell to handle liquid hydrogen. The first Kiwi-B test was conducted in December, 1961, and gaseous hydrogen was employed as the propellent to

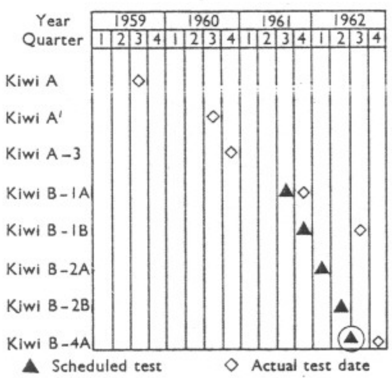


FIG. 5. Kiwi reactor test programme.

provide a checkout of the new Kiwi-B basic design. In September, 1962, the second Kiwi-B reactor test was conducted, and in November, 1962, the third. During these tests, the reactor core and its support failed. The tests could hardly be considered to be successful or to serve as a basis for committing a complete engine development effort. The mechanism of failure was not understood, and after the third Kiwi reactor test, there were several, apparently equally valid, postulations of the reason for failure. It was decided that, before the next power test, extensive reactor component development testing and complete reactor core cold flow and vibration testing would be completed. The first of the cold flow experiments was conducted in May, 1963. As a result of this test, the mechanism of core failure was at least tentatively identified as being associated with vibrational dynamics. Hence, it was possible to incorporate certain design changes into the reactor configuration to ensure that subsequent power tests would be successful. More cold flow tests and an extensive series of vibration tests will be started in autumn of 1963. As a result of the reactor tests to date, much has been learned, and problems identified as serious development obstacles at the outset of the programme have been solved satisfactorily. The physical properties of graphite are reasonably well understood and have been verified by testing. Methods have evolved for satisfactorily fabricating the graphite fuel elements, and techniques have been developed for their operation in a hydrogen environment. The problems of control during start-up and operation have apparently been solved. In fact, during the last Kiwi power test, when there were extreme variations in reactivity and other parameters, the controls performed satisfactorily under much more severe conditions than would ever be expected in the engine during development test or flight. The structural integrity of the reactor core is the principal remaining reactor development objective to be achieved.

The choice of an appropriate test site for the reactors was a significant consideration because of the dangers of a possible excursion within the reactor and because the facility should be kept reasonably simple by releasing the exhaust plume into the open atmosphere. The AEC and LASL had used two principal test sites for many years—one in the Pacific, and the second at Jackass Flats, Nevada, approximately 90 miles north and west of Las Vegas. Early estimates that the release of the exhaust plume in the Nevada sky was permissible were confirmed by testing. Testing of the Kiwi reactors had been particularly successful as regards the release of radioactivity at the test site. Fig. 6 is a site plan of the Nuclear Rocket Development Station (NRDS). This plan shows that the reactor maintenance, assembly, and disassembly building is far from the test stands. which are in turn removed from each other and are a considerable distance from the control point. The special facilities for testing the nuclear rocket engine will also be located at this site and are discussed later.

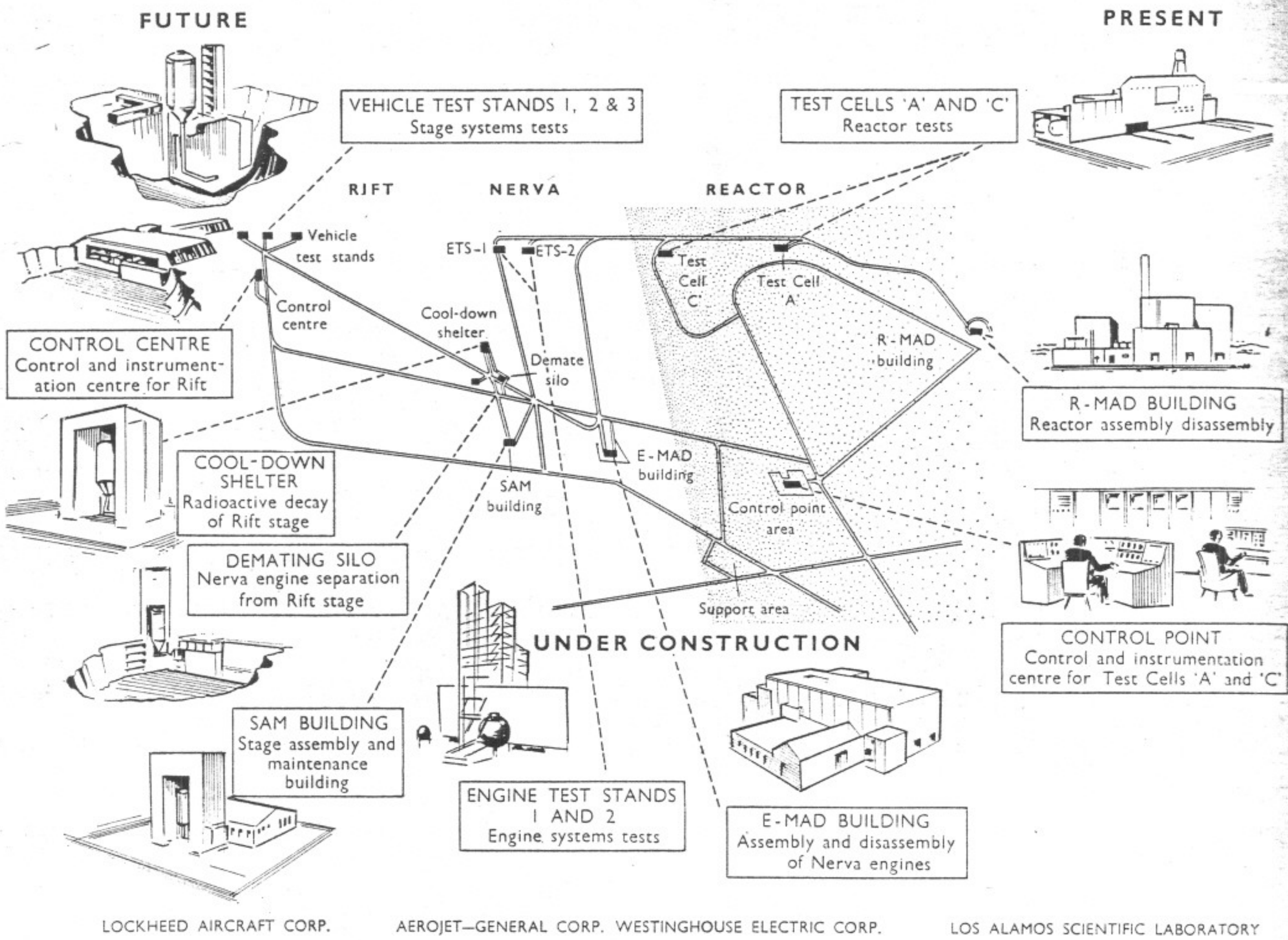


FIG. 6. Nuclear Rocket Development Station.

III. THE NERVA PROGRAMME

As indicated, the results of the Kiwi-A series of reactor tests were so encouraging and the forecasts for the Kiwi-B series of tests were so enthusiastic that the contract for the engine development was awarded to Aerojet-General Corporation in July, 1961. Westinghouse Astronuclear Laboratory was selected as principal subcontractor with responsibility for developing the flight reactor based on the LASL/Kiwi technology and configuration. Many guidelines were established at the outset of the programme, and three of these are worth mentioning to provide a better understanding of some of the developments and events that have occurred since the initiation of this programme.

The flight reactor design was to be based on LASL/Kiwi technology and configuration, and the industrial team was to make only those changes in the mechanical design that were necessary to ensure that the reactor could perform in the space environment.

The second significant ground rule concerned the development of the non-nuclear engine components and subsystems and required that no large-scale procurement or development of these components or subsystems be effected until a reactor configuration was tested successfully and approved for incorporation in the engine. Permitted development had to be related to components with long lead times or that have critical or unknown characteristics from the standpoint of engine or reactor operation or testing. An example of this approach is the development of the turbopump for use in the engine propellent feed system, which is proceeding, while only cursory attention is being devoted to such items as the thrust structures, the gimbal, and roll control. Because of the continuing reactor mechanical design problem, this ground rule remains in force.

The third significant ground rule concerned the overall goals and objectives of the NERVA development. The ultimate goal of this programme is the demonstration that a nuclear rocket propulsion system will perform safely and reliably in the space environment. While directed studies of the application of NERVA class engines to specific missions of interest are being conducted, this initial NERVA programme goal remains as stated.

The Government organization for the management of the nuclear rocket programme is shown in Fig. 7. The

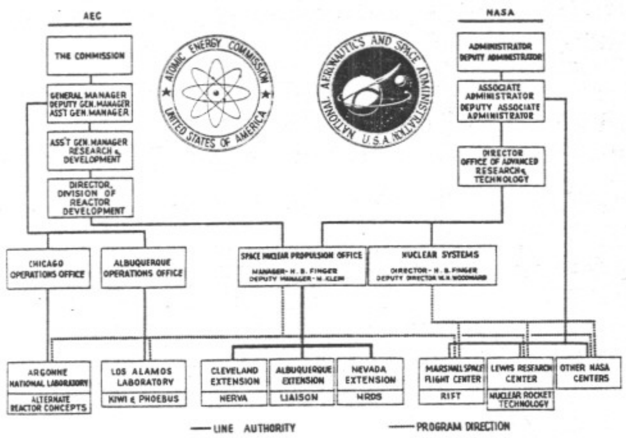


FIG. 7. Nuclear rocket programme organization.

Manager of SNPO, Mr. Harold B. Finger, reports to both the AEC and NASA for the national nuclear rocket effort. Within the AEC, the channel is through the Director, Division of Reactor Development, and within NASA, it is through the Director, Office of Advanced Research and Technology. The Space Nuclear Propulsion Office Headquarters has three field extensions: The Cleveland extension, located at the Lewis Research Center of NASA, is responsible for the technical direction of the engine development programme; the Albuquerque extension provides certain liaison functions with LASL; and the Nevada extension has cognizance of the development test activities at the Nuclear Rocket Development Station. As shown, Mr. Finger also has additional responsibilities within NASA as Director of Nuclear Systems in the Office of Advanced Research and Technology. In this capacity, he provides programme direction to the Nuclear Vehicle Projects Office at the Marshall Space Flight Center. The NVPO is responsible for the technical direction of the RIFT (Reactor-In-Flight-Test) vehicle, the stage that will be used for the engine feasibility demonstration programme. The Lockheed Missiles and Space Company of Sunnyvale, California, was selected in the Spring of 1962 to be responsible for stage development.

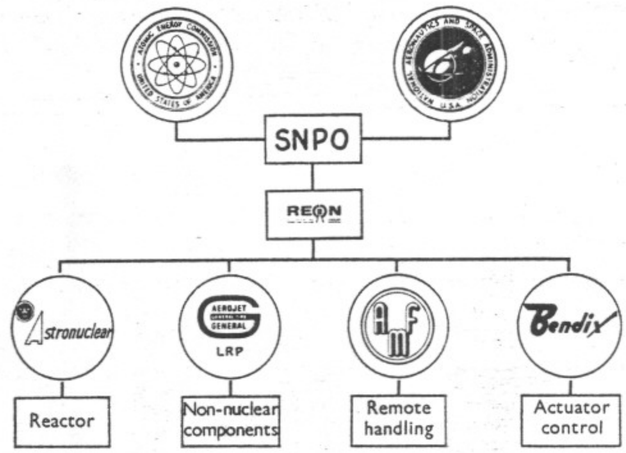


FIG. 8. NERVA development team.

The NERVA engine development team is shown in Fig. 8. With prime contractor responsibility, Aerojet-General Corporation established a special programme management office at its Azusa, California, plant to exercise overall control and direction of the complete development effort. This organization is named REON (for Rocket Engine Operations—Nuclear) and includes personnel qualified by experience in the technical, administrative, and managerial skills required for this complex effort. The Westinghouse Astronuclear Laboratory is a principal subcontractor and is responsible for developing the flight reactor and associated nuclear aspects of the programme. This organization is located in Pittsburgh, Pennsylvania. Aerojet's Liquid Rocket Plant at Sacramento, California, is responsible for developing most of the non-nuclear engine components and subsystems. Also, AMF Atomics, a division of the American Machine and Foundry Company, is responsible for designing, developing, fabricating, and installing the unique remotely-controlled equipment for assembling, disassembling, and transporting the engine during its development tests in Nevada. The fourth principal participant is the Bendix Corporation, which is responsible for developing certain radiation-resistant control system components.

The first 6 months of the NERVA programme, Phase I, lasted from July, 1961, up to January, 1962. This initial effort was devoted largely to two principal activities. The first major effort concerned the preliminary design of the NERVA flight-test engine. The second effort concerned the complete engine development programme plan. During this period, some non-nuclear engine components were built and tested and certain other activities were conducted, but the preliminary design and the programme plan were the chief results. During Phase I, a full-scale mockup of the NERVA flight-test engine was constructed. A photograph of this mockup is shown in Fig. 9. The flight test engine is approximately 22½ ft. long from the engine–vehicle interface to the exit plane of the exhaust nozzle. Its diameter at the pressure vessel is approximately 56 in., and the maximum envelope is approximately 8 ft. across the pressurization spheres. The NERVA engine consists of several major subsystems: the propellent feed system (including the turbopump and required valves and lines); the nuclear subsystem (including the reactor, the reflector, and the shield); the thrust chamber assembly (including thrust structures, pressure vessel, gimbal for thrust vector control, and the main engine exhaust nozzle); the engine control system; and the pneumatic system. The NERVA engine operates on the so-called hot-bleed cycle principle, which derives its name from the position along the propellent feed system flow path, and hence temperature, at which hydrogen is extracted to provide turbopump working fluid. A flow schematic is shown in Fig. 10. Liquid hydrogen propellent from the vehicle tank enters the engine through the main tank shut-off valve, flows through the pump, is ducted to the cooling passages of the main thrust nozzle where it regeneratively cools the nozzle, passes up inside the pressure vessel through the reflector and shield, passes through the reactor core where it is heated to a very high temperature, and is finally discharged through the main exhaust nozzle producing the engine thrust. The hot-bleed cycle extracts $\sim$3% of the propellent flow at the reactor exit. This bleed flow is diluted and cooled by some relatively cool hydrogen from the reactor core inlet plenum. The mixture then enters the turbine as working fluid and the turbine exhaust is discharged overboard through suitable nozzles to provide residual thrust recovery and vehicle roll control.

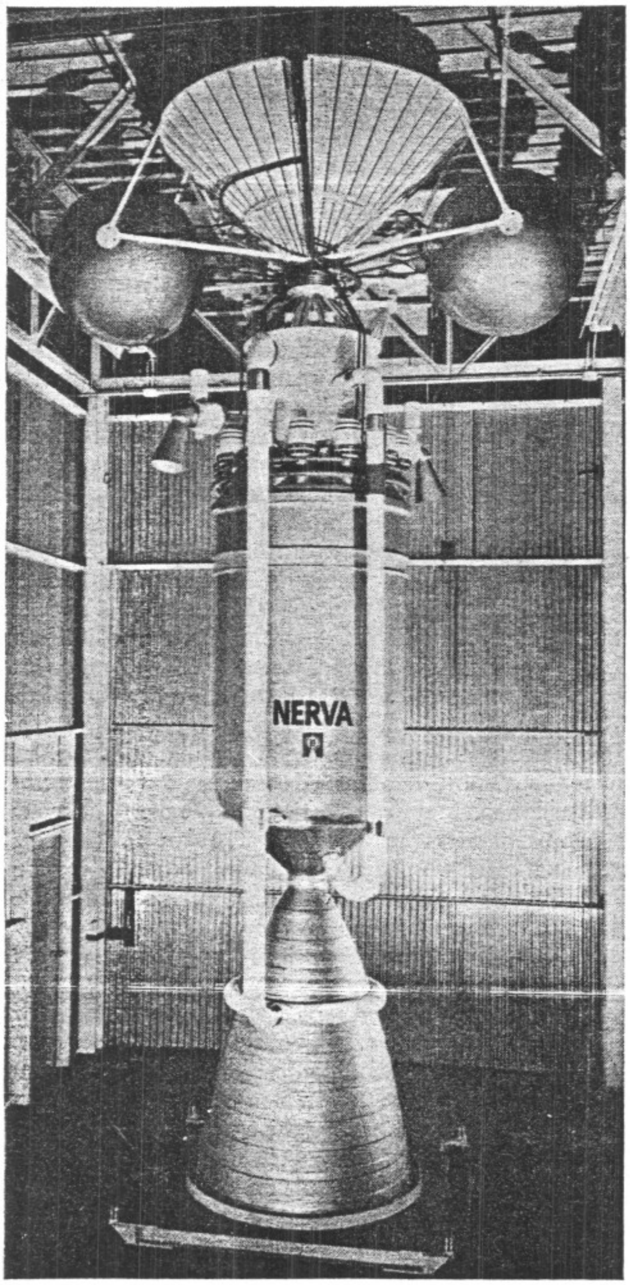


FIG. 9. NERVA flight test engine mockup.

The selection of the hot-bleed cycle principle and an outline of some of the alternates that are available and were considered warrant discussion. The propellent feed systems are divided into two basic classes: direct tank pressurization and pumped cycles. The use of either class of system is feasible, and both classes can be developed, but each has its advantages and disadvantages. In the gas-pressurized system, direct gas pressure is used for expelling liquid hydrogen from the propellent tank through the flow control system to the reactor. The advantages of this system are simplicity, reliability, and high performance, whereas the principal disadvantage is the relatively heavy tank requirement or conversely a low chamber pressure, which compromises reactor design. In the various pumped cycles, the heavy tank problem is alleviated but the engine obviously becomes somewhat more complex. Several possible pump cycle concepts are shown in Fig. 11. The topping cycle is characterized by series flow of the propellent through the major engine subsystems. All of the propellent in the tank flows through the pump, through the coolant passages of the nozzle and the reactor reflector, into the low-pressure-ratio turbine, and finally into the reactor core. With this configuration, highest specific impulse can be achieved for any given reactor core exit temperature. A complication exists, however, because special reactor design features must be included to raise the temperature of the turbine working fluid to a level at which the pump power requirements can be met. The special reactor design features required to accommodate the topping cycle have not been incorporated in the Kiwi configuration and, therefore, this cycle could not be selected for NERVA without major reactor development effort. The various bleed cycles are so called

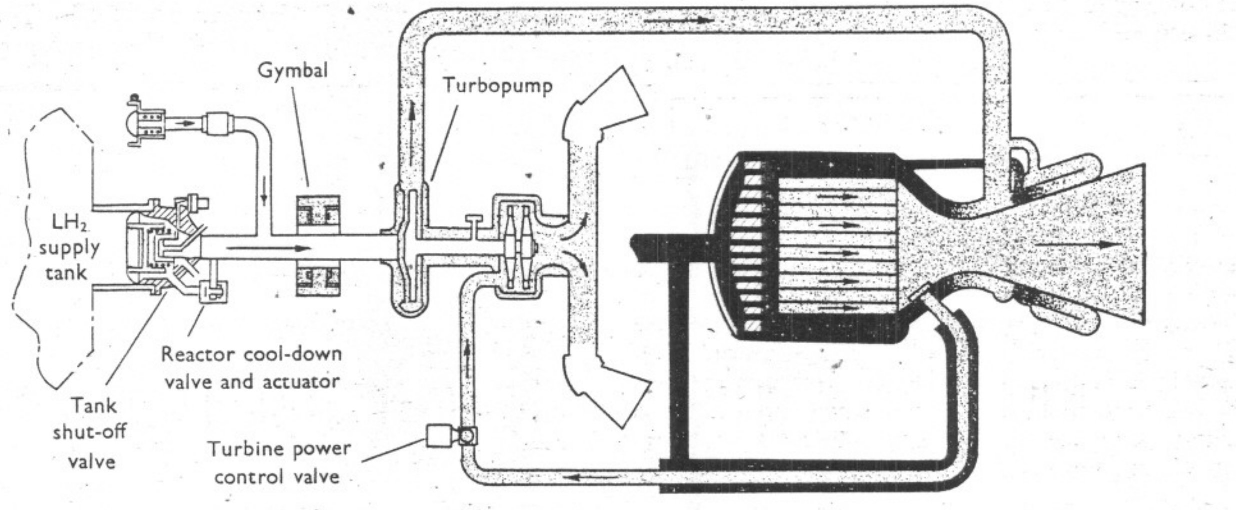
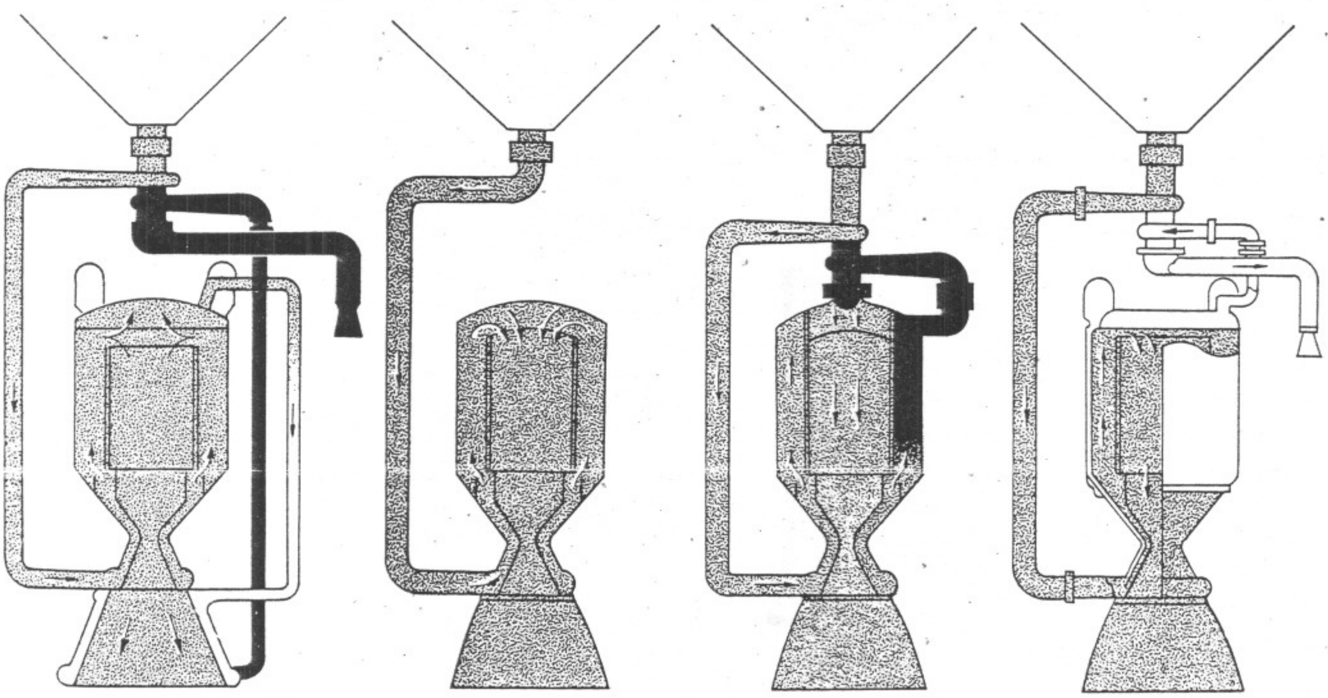


FIG. 10. Hot bleed cycle flow schematic.

because pumping power for the cycle is obtained by bleeding off a small portion of the hydrogen propellent and using it as the turbine working fluid. The location of this bleed determines the temperature of the working fluid and, hence, the performance of the turbine. This process ultimately affects the specific impulse of the overall engine. Of the various bleed cycles shown, the hot bleed cycle offers the greatest engine specific impulse and, therefore, was selected as the cycle for NERVA.

Although the potential of nuclear rocket propulsion in terms of vehicle performance is certainly vast, these gains are not achieved without certain complications that have not been previously encountered in rocket development and operation. One of the most significant of these unique environments is radiation, which creates a long list of effects and influences ranging from the behaviour of materials in the combined radiation–cryogenic environment to the requirements for the



(a) (b) (c) (d)

FIG. 11. Alternate engine cycle flow schematics.

(a) Heated bleed cycle. (b) Gas-pressurized cycle. (c) Topping cycle. (d) Cold bleed cycle.

remote engine assembly and disassembly techniques and the general hazards problem. Also, the residual radiation that exists after engine shut-down creates the many problems associated with the cool-down requirement. The long durations of operation that can be expected with this new propulsion system place new and unusual requirements on rocket rotating machinery characteristics as well as the lifetime of the reactor core in its unique environment. A few examples of the impact on non-nuclear engine components and subsystems will illustrate some of the typical problems that are being encountered or envisioned. Because of anticipated radiation damage to all organic-based materials, some of the traditional techniques and materials must be avoided in the design of many components. Turbopump bearings, for example, have been traditionally lubricated by organic-based components. For this application, however, some other means must be found. With the large amounts of liquid hydrogen that are available, the least complicated scheme appears to be cooling the bearings with the propellent. Several different bearing configurations have been fabricated and tested in a specially designed bearing test fixture. Test results to date indicate that a satisfactory hydrogen-cooled bearing can be incorporated as a completely satisfactory component. Similar problems exist with the organic materials that are traditionally used for valve seats and packings. Instrumentation that performs in the radiation environment will require special treatment, and radiation effects testing of the instrumentation components is being conducted at the present time.

The basic nozzle concept for NERVA represents an extension of current techniques used in conventional regeneratively cooled liquid rocket nozzles. The principal difference results from the large contraction ratio that is required for the NERVA application. The longitudinal loads, which in conventional nozzles are transmitted through the tube bundle, cannot be accommodated by the high-contraction-ratio NERVA nozzle. Hence, a method had to be developed to carry these loads. Some fabrication difficulties were encountered with the selected scheme, but these fabrication difficulties can probably be overcome, and this nozzle concept can be successfully exploited. The turbopump configuration shown in Fig. 12 is based on a rather long development history at Aerojet that preceded award of the NERVA contract by several years. Various configurations have been built and tested, and the satisfactory development of the single-stage centrifugal pump coupled to the two-stage axial turbine can be forecast with confidence. Other components have been built and tested, but the programme ground rule regarding the large-scale procurement and development of non-nuclear components and subsystems precluded the accumulation of any appreciable amounts of development experience or test data.

The unique radiation environments present some new complications in conducting the development test

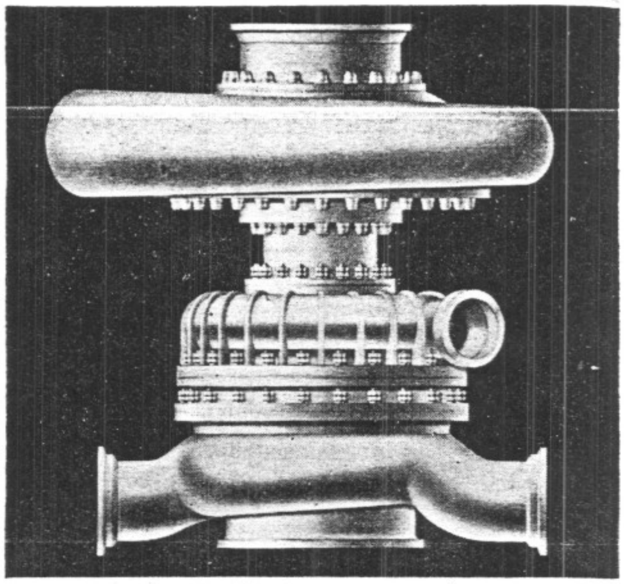


FIG. 12. Mark IV NERVA Turbopump.

programme. The reactor and the non-nuclear engine subsystems will be assembled into the complete test engine in the engine maintenance, assembly, and disassembly building (E-MAD) at NRDS (Fig. 6). A cutaway view of this building is shown in Fig. 13.

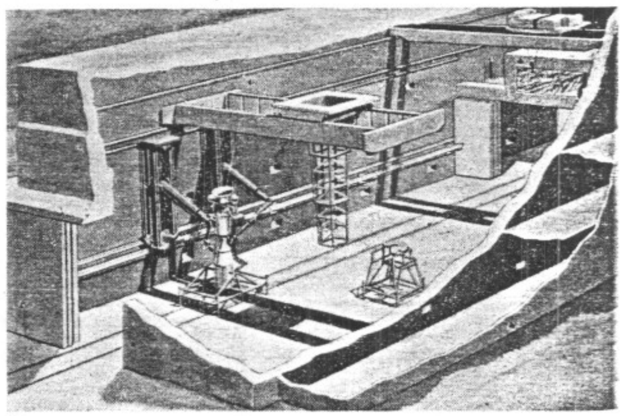


FIG. 13. E-MAD Building.

When assembled, the engine is placed on the engine installation vehicle for transportation and installation into the test stand, which is located approximately 2 miles from the E-MAD building. This transport-installation system is shown in Fig. 14. The engine installation vehicle (EIV) is essentially a railway flat car with appropriate superstructure to support and transport the engine. The shielded control car houses two men who will have control over the entire engine transport and test-stand installation sequence. Motive power is provided by the prime mover, also shown in the figure. Following the engine tests, the engine is remotely

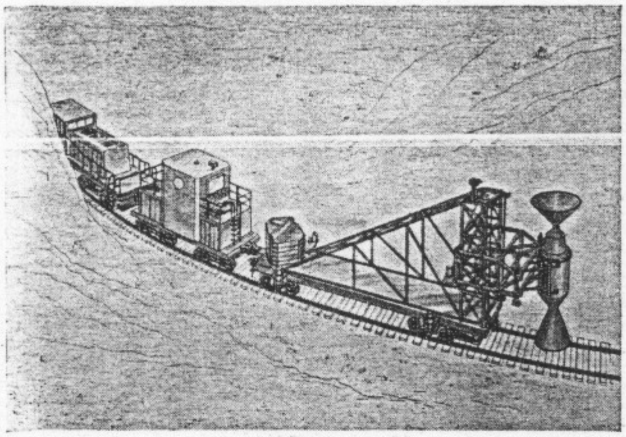


FIG. 14. Engine transport-installation system.

disengaged from the test stand, attached to the EIV, and returned to the E-MAD building, where it is remotely disassembled for post-mortem inspection.* The engine is disassembled into its major subsystems in the main bay of the E-MAD building, and small satellite cells located around the periphery of the main bay are used for the disassembly and post-mortem inspection of individual sub-systems and components. The overhead positioning system, the wall-mounted handling system, and the typical floor-mounted fixtures are shown in the cutaway view of the E-MAD building. Ground was broken for this facility at NRDS in August, 1962. About 2½ years will be required to complete the construction and activation of the facility.

Test Cells A and C were also built at NRDS to meet the requirements of the Kiwi reactor test programme. These two test cells are similar, and one is shown in Fig. 15. Test Cell A will also be used to accommodate the development test of the NERVA flight reactor. The reactor maintenance, assembly, and disassembly building (R-MAD) was also built for the Kiwi programme and will be used by NERVA during the flight reactor test series.

Ground was broken for the first nuclear rocket-engine test stand (ETS-1) in June, 1961, a month before the award of the NERVA contract. Design work had preceded the construction by approximately 10 months to a year. An artist's concept of the completed facility is shown in Fig. 16. The hydrogen storage facilities, the hydrogen run tank and its shielding, the rail-mounted side shields, and the engine exhaust duct are also shown in the figure. The facility is approximately 140 ft. high

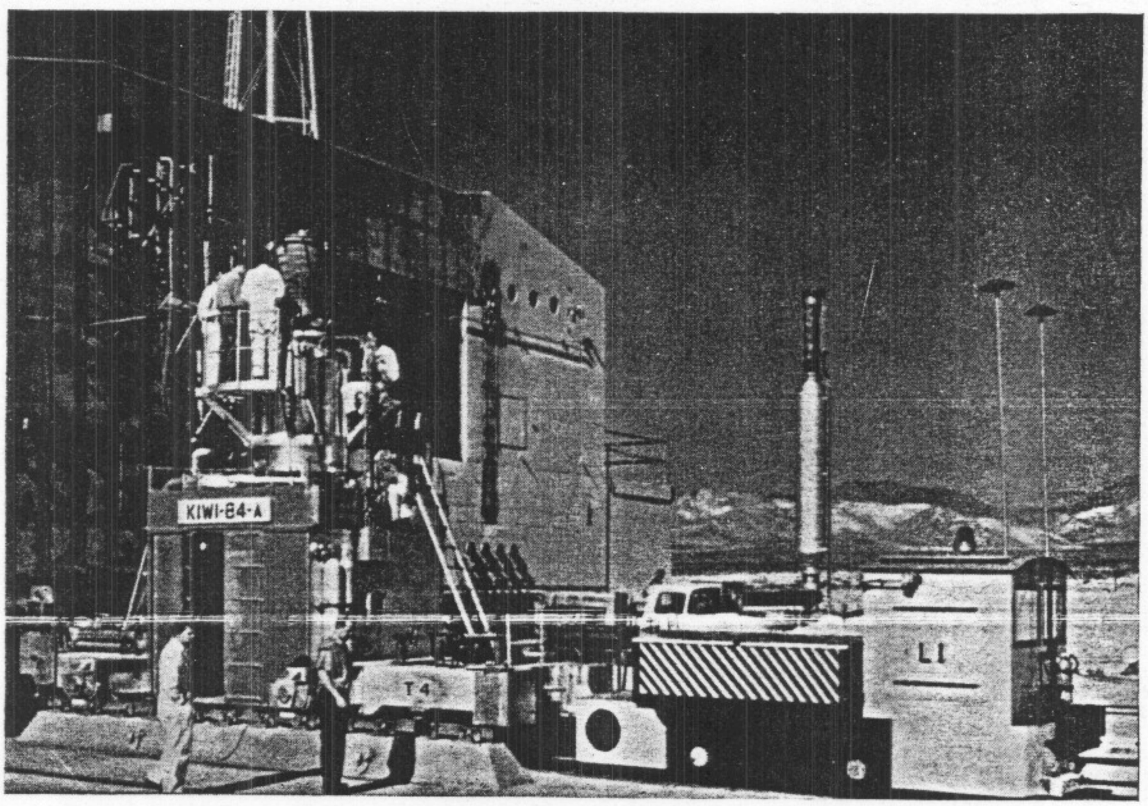


FIG. 15. Test Cell A.

* At this point, a short film depicting this sequence was shown at the presentation.

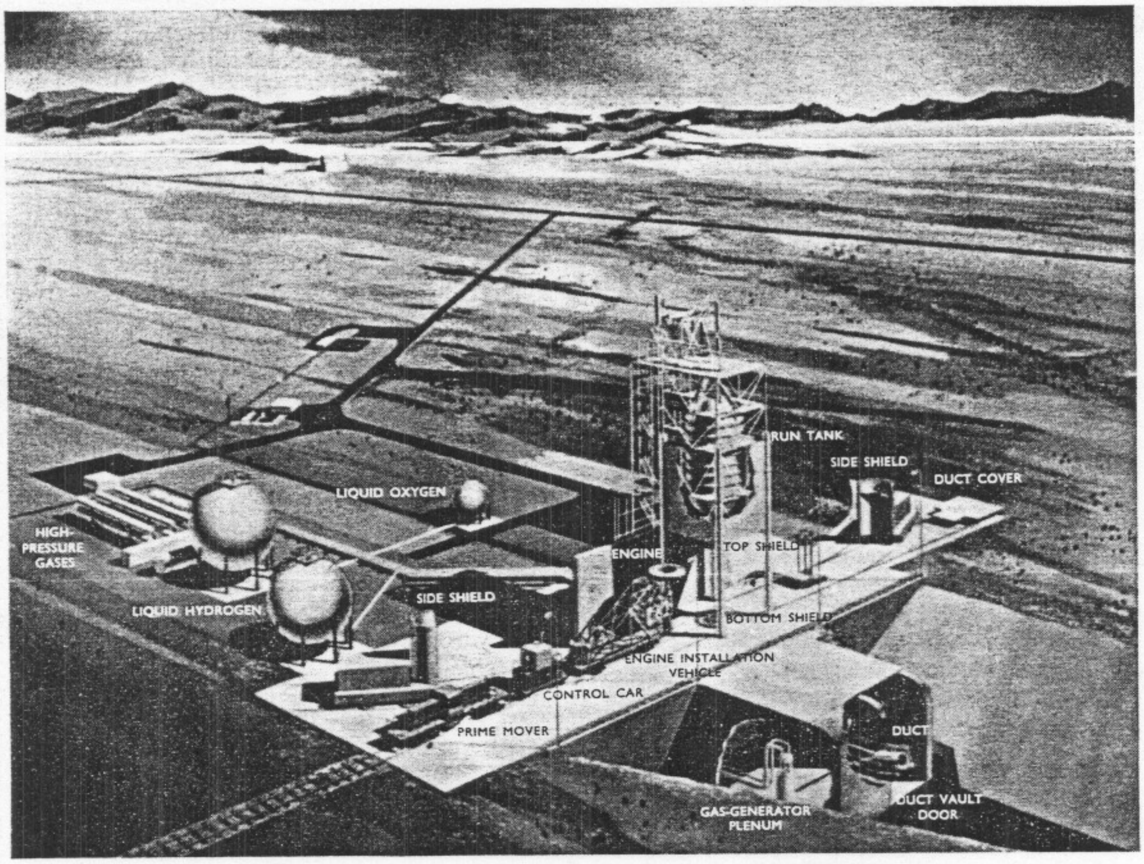


FIG. 16. Engine Test Stand No. 1.

from the deck surface to the top of the run tank superstructure, and the vault containing the exhaust duct is approximately 55 ft. deep. The test stand civil works are largely completed, as shown in Fig. 17, which is a construction progress photograph. However, the facility instrumentation, control, and nuclear rocket exhaust system must be installed and checked before the facility can be completely activated for the first engine development test.

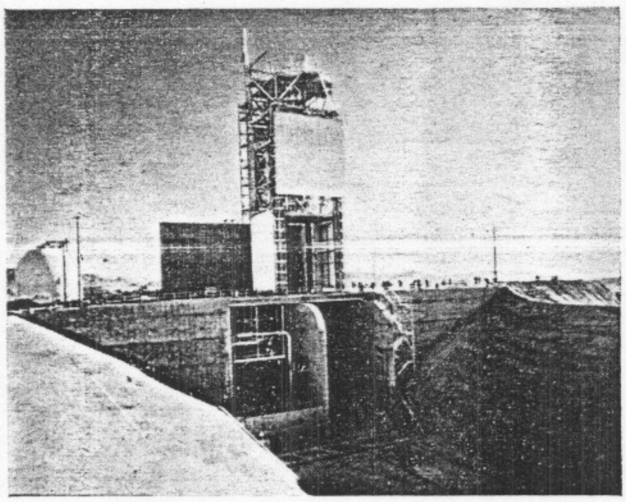


FIG. 17. Engine Test Stand No. 1 (Construction Progress).

The preceding discussion describes the general status of the nuclear rocket engine development. In summary, the nuclear rocket-engine development programme in the United States is presently paced by the structural design of the reactor. We are confident that this obstacle can be successfully overcome in the near future, but perhaps not as quickly as we might wish, because test reactors are expensive and long lead times are involved. With the successful demonstration of the structural integrity of the reactor core, we can proceed expeditiously to the engine development test programme, to flight testing, and ultimately to a variety of challenging space missions.

IV. MISSION APPLICATIONS OF NERVA-CLASS OPERATIONAL NUCLEAR ROCKET ENGINES

The NERVA programme was defined at the outset as a programme for demonstrating the feasibility of using nuclear rockets. This definition naturally follows, since the feasibility of using nuclear rockets has never been demonstrated and the flight test of NERVA will be the

Free World's first known launching of a nuclear rocket. The demonstration programme will involve several ballistic flights from Cape Canaveral, boosted by the Saturn V launch vehicle. The nuclear stage vehicle, known as RIFT, is shown in Fig. 18 and is being developed for NASA by the Lockheed Missiles and Space

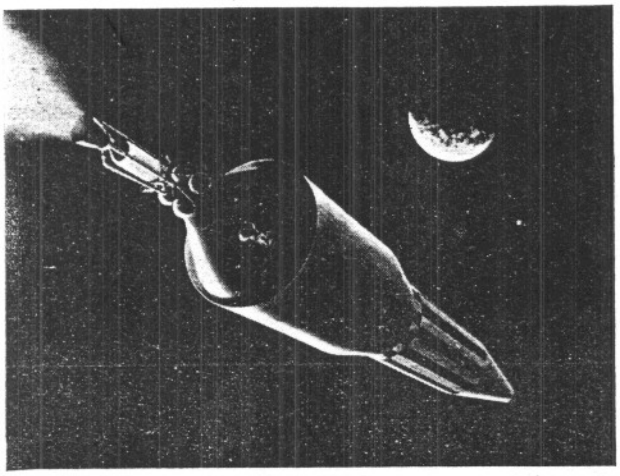
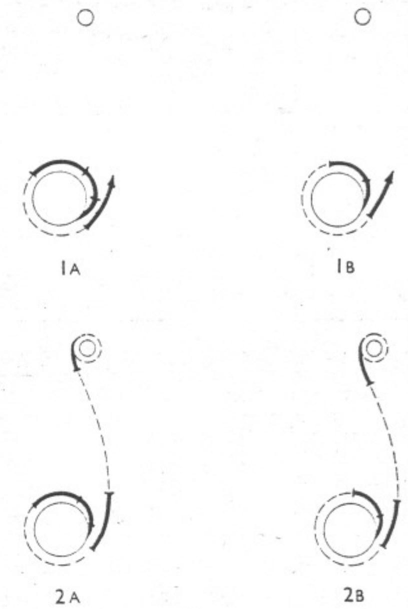


FIG. 18. RIFT stage.

Company. This vehicle will be 33 ft. in diameter and will weigh much more than 100,000 lb. when fully loaded. Sizes can be appreciated by noting that the diminutive engine, as it appears here, is over two storeys high.

The usefulness of NERVA is not planned to end with the ballistic feasibility demonstration. An underlying philosophy in the development of RIFT and NERVA is that they ultimately be capable of performing useful operational missions in space. Accordingly, numerous application studies are being made of the NERVA engine. These studies cover lunar operations of several forms and heliocentric transfer orbits for "deep space probes," manned exploration, and parabolic and hyperbolic solar system escape trajectories.

Fig. 19 presents one set of results for lunar operations using the Saturn V as the launch vehicle. Nuclear-powered Cases 1 and 2 use essentially the RIFT vehicle. For Case 1, the NERVA engine is used for injection into the lunar transfer trajectory only, with a hydrogen/oxygen chemical rocket providing "de-boost" into the lunar orbit. In all cases shown, a hydrogen/oxygen rocket is used to transfer from lunar orbit to the lunar surface. The payloads shown are reduced 25% if the storable UDMH/N_2O_4* propellent system is used for the lunar-orbit-to-surface transfer. The suborbital start, Case 1A, requires a shutdown and restart of the NERVA engine if an Earth parking orbit is used. If a direct shot with no parking orbit is to be used, then no restart is required although launch timing becomes very difficult. This case represents a better staging ratio than Case 1B. In



SINGLE SATURN V LAUNCH

	Paylod to lunar surface	
	Lb.	% of all-chemical
Nuclear engine used		
1. Outbound injection only:		
A. 3-stage suborbital start ..	40,600	150
B. 3-stage orbital start.. ..	36,000	133
2. Earth-to-lunar orbit:		
A. 3-stage suborbital start ..	44,000	163
B. 3-stage orbital start.. ..	40,000	148
Chemical rockets only used ..	27,000	100

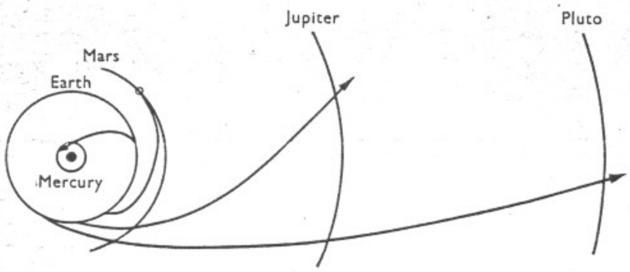
FIG. 19. Lunar missions and payloads.

this latter case only, an orbital start-up of the NERVA engine is used, giving a smaller payload on the Moon.

In Case 2, the nuclear engine is used for all extra-orbital velocity changes except midcourse correction. In this operation, manned egress from the lunar orbiting vehicle is complicated by the nuclear radiation from the engine. Leaving the engine in one orbit and dropping to another orbit by a chemical rocket is one solution to this problem. For Case 2A, the suborbital start is again used with the conditions for Case 1A. The chart shows that the 44,000-lb. payload on the lunar surface is the maximum payload for the considered operations. Case 2B again simplifies operations by first starting the NERVA in Earth orbit, with an attendant loss in payload of 4000 lb. due to the less favourable staging.

As a point of reference, the payload capability using the Saturn V plus hydrogen/oxygen space engines is approximately 27,000 lb. With this payload as a 100% reference, the proportionate increases in payload are shown for the four operational modes using NERVA.

* Unsymmetrical dimethylhydrazine/dinitrogen tetroxide.



SINGLE SATURN V LAUNCH

Mission	Useful payload, lb.
Mars orbit (nuclear for transfer injection only)	30,000
Mercury fly-by	55,000
Jupiter fly-by (2½-year transfer)	40,000
Hyperbolic solar escape (3 years to pass Pluto)	6000

FIG. 20. Escape missions and payloads.

Fig. 20 presents the payload capabilities using a NERVA engine for escape missions. An exhaustive list of possible space missions can be developed for the NERVA engine. However, for purposes of this presentation, only four are shown. The selected payload capabilities are broadly representative of all possible missions with the constraint that all flights use a single Saturn V vehicle, that is, no Earth orbit rendezvous. All operations shown are similar in that they use the NERVA engine to propel the vehicle from a low Earth orbit to the transfer orbit. The NERVA is then shut down and ejected, alleviating the need for a shutdown-cooldown transient control.

In the first case, which gives 30,000 lb. of useful payload in a Martian orbit, the use of storable UDMH/N_2O_4 propellents for the deboost into the Mars orbit is assumed. The mission must be performed during a favourable time period or severe reductions in payload will result.

The Mercury fly-by with 55,000 lb. of useful payload on board is generally equivalent to a solar probe. In this and the remaining cases, the payload passes the planet and is not captured as in the Mars case.

The Jupiter fly-by has a trajectory which takes 2½ years from the Earth to the Jovian near-miss. A 40,000-lb. payload would be greatly reduced if transfer times of from 1 to 2 years were required. A 2½-year flight poses interesting problems in equipment reliability and power supplies.

As a bracketing mission, the case of a solar system escape is included. An arbitrary ground rule is that the flight time from the Earth until the vehicle passes the mean radius of Pluto be 3 years. Again considering equipment reliability and power supply, this time period is long even though a severe payload penalty is being paid. The payload for this hyperbolic trajectory is 6000 lb., whereas the payload for a parabolic escape is more than 30,000 lb. with a greatly increased transit time to the Pluto orbit.

Although these missions have been restricted to single Saturn V flights, advanced boosters and Earth orbital rendezvous techniques could significantly increase the payload carrying capability of NERVA. For example, a manned Mars excursion could be mustered in Earth orbit using Saturn V boosters and rendezvous. A 1,500,000-lb. vehicle could thus be assembled and ejected towards Mars with a 75% increase in payload over an all-chemical system. This corresponds to a cost reduction of approximately 40% for a given payload.

V. CONCLUSIONS

This paper outlines some of the highlights of nuclear rocket developments in the United States. The major historical events have been outlined, and the programme has been described and its current status indicated. Some mission capabilities of the class of engine being developed have been presented. All the preceding material is intended to provide a general understanding of the developments in this challenging new field.