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Left: This wintertime view of a section of the steel superstructure for the Westinghouse Transit Expressway in South Park, Pittsburgh, was taken in February, shortly before our copy went to the printer. Bethlehem Steel Company had just completed the fabrication and erection of the steel superstructure for the 9340-foot roadway loop. The concrete roadway runners on which the rubber-tired vehicles will operate are now being poured.

The three lightweight automated vehicles that will operate on the roadway are scheduled for delivery to South Park this month. Once the vehicles are installed, Westinghouse engineers will spend several months gathering engineering data on the new transit system and evaluating its performance.

The purpose of the $5-million project is to determine whether the Transit Expressway can meet the mass transportation needs of urban areas with medium population density throughout the United States. It is being financed by grants of $2,872,000 from the Federal Housing and Home Finance Agency, $886,000 from the Port Authority of Allegheny County, $200,000 from the Pennsylvania State Department of Commerce, and $1,042,000 from Westinghouse and other companies in the area.

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Cover Design: Nuclear propulsion in space is the message conveyed by artist Thomas Ruddy on this month's cover, using the now familiar rocket nozzle and a symbolic representation of a uranium atom.

The NERVA Nuclear Rocket Reactor Program

by W. H. Esselman

With nuclear rockets, man will have the capability of much longer range space exploration, because of their inherent superiority over chemical rockets. The NERVA program has demonstrated the feasibility of such nuclear rockets.

While the attention of the nation is now focused on the Apollo first manned lunar landing program, this mission should be envisioned as only the first step in the exploration of space. As the next round of space exploration crystallizes, the high performance of the nuclear rocket engine will assure its application in the advanced missions of the coming decade. Its first use will undoubtedly be as an upper stage of a chemical rocket. A nuclear rocket engine achieves twice as efficient use of each pound of propellant as can be attained with chemical combustion processes. Therefore, if it is substituted for a final stage chemical rocket, it can substantially increase the payloads that can be landed on the moon. In addition, a nuclear rocket engine using existing or planned boosters will permit planetary exploration that would be possible only with very much larger rockets if they were all-chemical. The development of the technology for the first of these nuclear rocket engines is making significant and rapid progress in both the Rover and the NERVA programs. Some of this progress is outlined here.

The unfolding of the U. S. nuclear rocket program, Project Rover, is charted at left from its beginnings at the Los Alamos Scientific Laboratory in 1955, through the entry of industry, to the present successful hot firing phase. Rapid progress was achieved by Los Alamos on the conceptual reactor design and fuel-element development. By 1959, the Kiwi[1] series of reactor tests demonstrated the significant performance and potential of the nuclear rockets and stimulated interest in the development of a flight-type engine. The NERVA (Nuclear Engine for Rocket Vehicle Applications) program was initiated in 1961. This effort, under the direction of the Space Nuclear Propulsion Office of NASA and the AEC, is being performed by the Aerojet-General Corporation as the prime contractor and Westinghouse Electric Corporation as the principal subcontractor with responsibility for the development of the nuclear subsystem, which includes the reactor, shielding, and reactor controls. The Kiwi program was intended to demonstrate feasibility and proof-of-principle of the nuclear rocket reactor. This it has successfully accomplished. Over the past several years, the Kiwi and NERVA reactor programs have been closely coordinated to provide a continuing, logical development program.

In November 1962, progress was interrupted by a vibration problem in the Kiwi B4A test, which required a detailed analysis and component test program to overcome. Recent successes in 1964 have, however, surpassed all objectives, and the understanding of nuclear-rocket technology is now increasing at an accelerated rate.

The present status of the development is amply summarized in the following statement by Harold B. Finger, Manager of the NASA Space Nuclear Propulsion Office, following the successful NRX-A2 test:

"Combined with the Kiwi B4E test run earlier this year by the Los Alamos Scientific Laboratory, this NERVA reactor test is further clear proof that this country has achieved a major advance in rocket propulsion—nuclear rocketry. These tests prove that the nuclear reactor concept is sound and that nuclear rockets can achieve the previously predicted high performance that will be required for future space missions."

The task assigned by the Space Nuclear Propulsion Office (SNPO) to the Westinghouse Astronuclear Laboratory was the development of a reactor system capable of flight operation. These efforts began with a review of the various Los Alamos designs to select the concept most adaptable to the flight environments. A design based on the Kiwi B4A was chosen. The development then proceeded, aimed at achieving a high-performance reactor capable of meeting the high reliability requirements of a flight engine. To accomplish this purpose, concentrated effort was required on the:

1) Structural design of a reactor capable of operating at near liquid hydrogen inlet temperatures and with outlet temperatures of several thousand degrees, coupled with the capa-

Project Rover Reactor Development Chronology

1955 to 1959: Research phase of the program conducted by the Los Alamos Scientific Laboratory.

1959 to 1961: Period of full reactor exploratory testing by Los Alamos during which general design methods were established, controls data and materials information were accumulated, fuel element fabrication methods were developed and initial reactor operation was conducted.

June 1961: NERVA development team of Aerojet-General Corporation and Westinghouse Electric Corporation selected.

1962: Kiwi power test series demonstrated successful reactor startup with liquid hydrogen. In November, tests of the Kiwi B4A, which was the favored design for the NERVA engine, led to the identification of fuel element vibration and structural problems.

1963: Year of redesign, analysis, component and subsystem testing, and cold flow tests of Kiwi B4A and Kiwi B4B reactors that demonstrated cause of the vibration and indicated that revised design approaches of Los Alamos and Westinghouse would lead to a stable design.

Early 1964: Cold flow tests conducted by Los Alamos on Kiwi B4D and Westinghouse on NRX-A1 indicated that the redesigns avoided the vibration problems.

May to Sept. 1964: Major milestones achieved by Los Alamos by the successful power operation of Kiwi B4D and Kiwi B4E which included a restart.

Sept. to Oct. 1964: Major milestone achieved in NERVA program by operation of the Westinghouse NRX-A2 reactor at full power and temperature conditions. Restart tests were also conducted.

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bility of withstanding booster type vibration and shock environments;

2) Fuel-element development to meet the high-temperature corrosion resistance and structural needs of the reactor;

3) Development of a reactor and fuel-element design capable of multiple restarts;

4) Development of nuclear and thermal design procedures that can precisely predict the flow and temperature conditions over this range of conditions;

5) Development of a control system and suitable instrumentation for controlling the reactor;

6) Development of a flight-type engine shield to reduce radiation dosage and heating in the key engine and stage components;

7) Development of facilities and capabilities required to produce fuel elements, assemble reactors, and test both component and full-scale reactors.

Some of these problems were part of the Kiwi development, but special attention was needed for the flight reactor. Before discussing the program aimed at these problems, consider the general operation of a nuclear rocket engine.

1—Operating cycle of a typical nuclear rocket engine is shown in this schematic diagram. Thrust is achieved by heating hydrogen to temperatures in the 3000 to 4000 degree F range and expanding this gas through a nozzle.

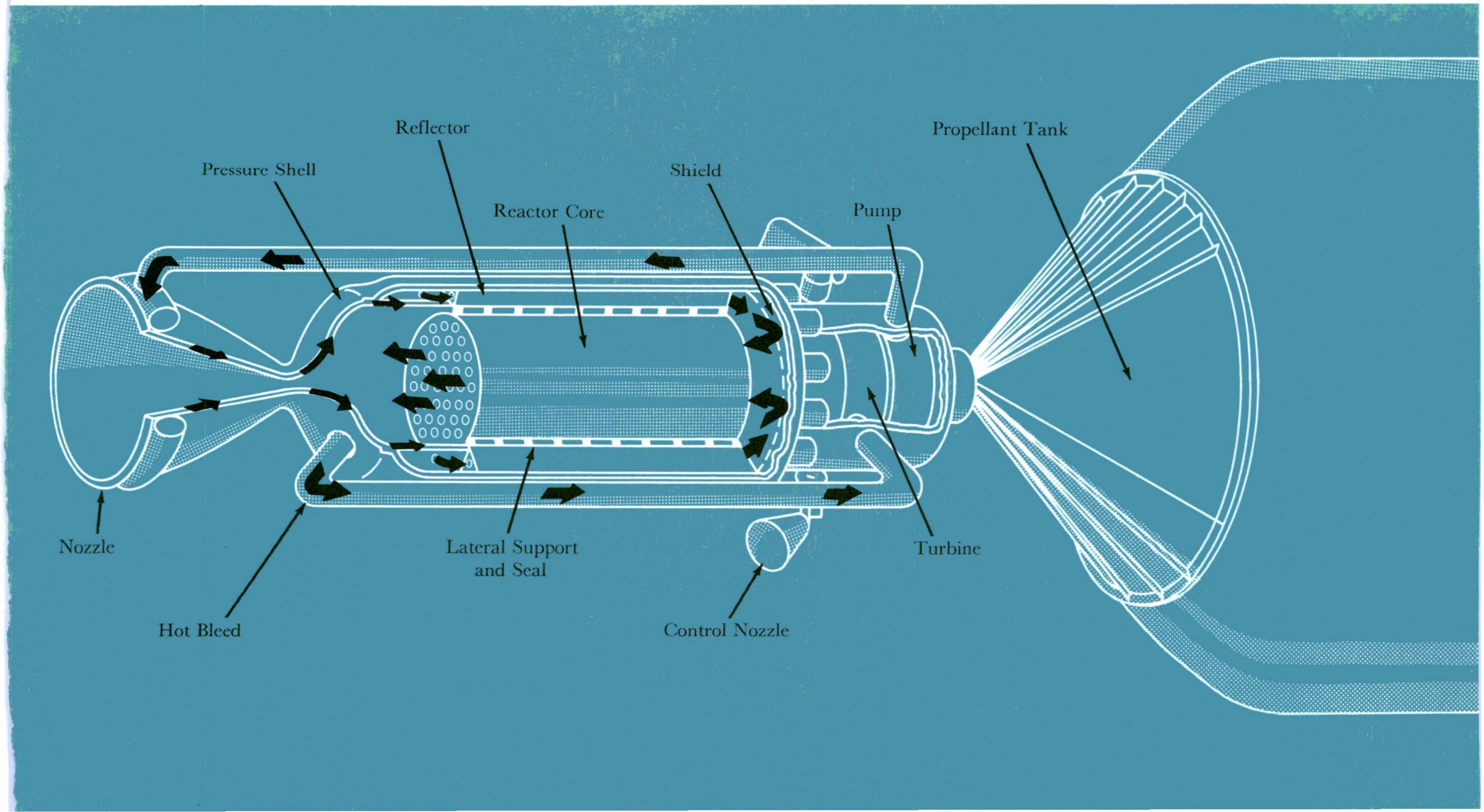
How It Works

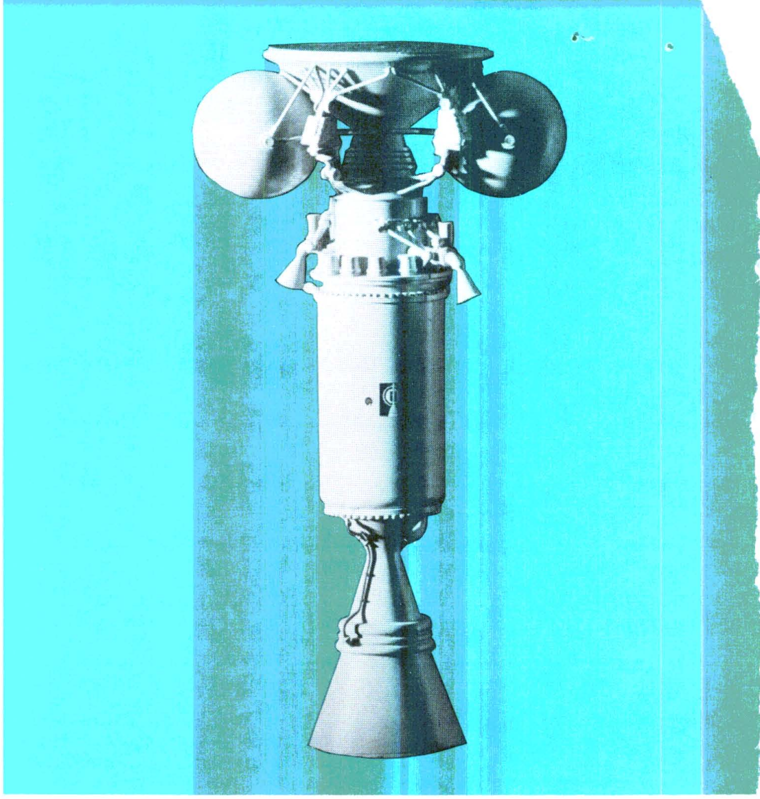
A nuclear rocket engine achieves its thrust by heating hydrogen to temperatures in the 3000 to 4000 degree F range and expanding this gas through a nozzle. The operating cycle of a typical nuclear rocket engine is shown in the schematic diagram (Fig. 1).

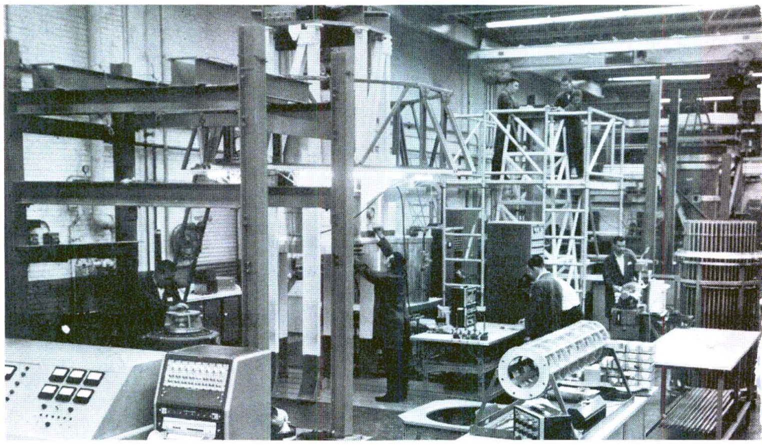
Liquid hydrogen in the vehicle tank stored at −420 degrees F is pumped to engine operating pressures by a turbopump. The hydrogen then passes through the tubes of a regeneratively cooled nozzle into the core, where it is heated to outlet temperatures. Passing through the nozzle, the hydrogen expands and accelerates to supply the engine thrust needed to push the rocket into space.

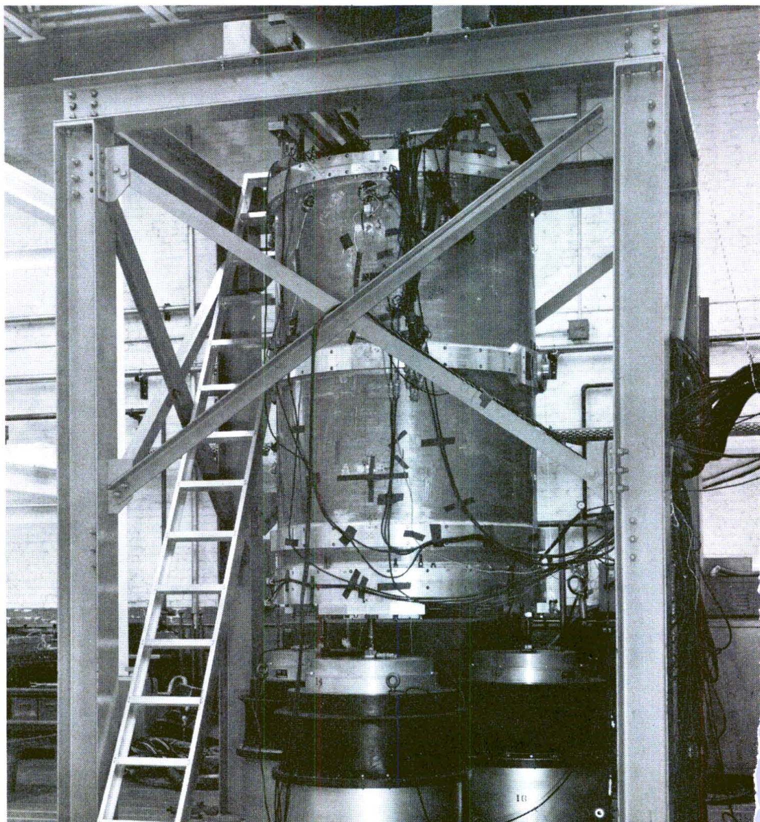
The "hot bleed" cycle shown is one in which hot gas from the nozzle is mixed with cold hydrogen, bringing the mixture to a temperature suitable for the turbine drive.

A mockup of the NERVA engine is shown in Fig. 2. The engine, which is 22 feet high from the top flange to the exhaust exit of the nozzle, has a performance goal to provide 50,000 pounds of thrust. The reactor, which is a right circular cylinder approximately 3 feet in diameter by 4 feet high enclosed within the pressure vessel, produces a thermal power of about 1000 mw. The annulus between the reactor core and the pressure vessel is occupied by a beryllium neutron reflector, which contains the reactor control drums. Directly above the inlet end of the reactor is a radiation shield that shadows the engine









components, vehicle, and payload, and protects them from excessive radiation doses and heat deposition. Liquid hydrogen passes through the turbopump into the propellant piping and into the regenerative cooling tubes of the nozzle. The spherical tanks supply actuator gas for engine startup.

The hydrogen extracts the heat generated in the reflector by neutron and gamma absorption and attenuation and cools the various parts of the reflector, so that the hydrogen is gaseous when it enters the shield region. After passing through the shield, the hydrogen enters the core. In the core, uranium fuel is dispersed in graphite elements that are pierced by circular propellant channels. The flow through the channels is controlled by orifices to obtain uniform temperature rise across the reactor. The heat generated by the fissioning of the uranium heats the hydrogen to an exit temperature significantly in excess of 3000 degrees F.

A primary measure of the performance of a rocket engine is given by its specific impulse (I_{SP}). Specific impulse is defined as the pounds of thrust delivered per pound per second of propellant flow. Greater specific impulse reduces the amount of propellant required for a given mission and makes possible heavier payloads. The big advantage of the nuclear rocket is in its ability to produce a higher specific impulse.

Most of today's chemical engines have a specific impulse of about 300 seconds while advanced engines burning hydrogen and oxygen will provide a specific impulse of 425 seconds. Specific impulse (I_{SP}) is related to exhaust temperature (T) and propellant molecular weight (M) by the proportionality:

$$I_{SP} \sim \sqrt{\frac{T}{M}}.$$

Since the specific impulse of an engine is inversely proportional to the square root of the molecular weight of the propellant gas, the nuclear rocket engine using hydrogen has a distinct advantage. Specific impulses in the range of 800 to 900 are attainable.

The evident potential performance of the nuclear rocket engine introduces the question of why they are not in use today. The answer lies in the status and unusual requirements of the development program. To illustrate this point, consider some difficult problems of the NERVA reactor program.

Difficult Problems in the NERVA Reactor Design

While the Westinghouse background in reactor development was a solid base for the NERVA development, it was immediately evident that many new technological problems required solution. High operating temperatures in a potentially

2—This mockup of the NERVA engine, *(top)* which would contain the nuclear reactor, is about 22 feet high from the top flange to the exhaust exit of the nozzle.
3—Component tests *(center)* were conducted in this laboratory. Included were tests on core parts and the complete core.
4—Reactor was vibrated *(bottom)* in an axial position in this test arrangement. Extensive vibration tests were conducted under anticipated conditions of operation.

corrosive atmosphere, extreme variations in temperature across the reactor, and rapid temperature transients make this reactor design a formidable task. The interplay of fuel-material temperature capabilities and nuclear and thermal design taxed the capabilities of metallurgists and reactor designers.

The nominal values of power density and heat fluxes in nuclear rocket reactors are in the range of ten times higher than in conventional nuclear reactors. These factors, coupled with the closeness of the fuel-material operating temperature to its physical limits, require much attention to the detailed thermal and nuclear design.

Effects that would be relatively insignificant in other designs have a major influence in the NERVA reactor. For example, a five-percent difference in fission density results in at least a 200 degree F change in coolant temperature leaving the channel. The effect of this small change in power generation on the hot-spot temperature is even further accentuated by the higher resulting film and material temperature drops.

To ease the fuel-element and reactor-design requirements, a highly sophisticated nuclear and thermal analysis was developed to obtain the precision required for the NERVA core design. This procedure supplies a three-dimensional heat generation prediction throughout the core. Statistical variation in fuel-element dimensions and fabrication variables are then introduced into the calculation of the hot-spot temperature. To reduce the maximum temperatures, each channel is carefully orificed to compensate for the variations in radial power generation and actual coolant channel impedance.

While the thermal and nuclear design problems were solvable by the extension and careful application of known analytical techniques, two problems were not so easily resolved. The high-temperature fuel-element development and the reactor mechanical design problems required proceeding with a reactor design based on a paucity of experimental information and much judgment in the selection of the proper design approaches. Imagine, for example, the problem of supporting a bundle of white-hot fuel elements in a stream of flowing hydrogen with the cold hydrogen that enters the reactor passing within inches of these hot elements! Clearly, the fuel-element development and the mechanical design are intricately related. A material with excellent high-temperature properties could greatly ease the structural design. Conversely, the invention of an ingenious reactor design can reduce the need for high fuel strength at the operating temperatures. As with all designs, the NERVA is a compromise based on the best material properties available today.

The many requirements of a satisfactory fuel element eliminate most of the known materials. In addition to being capable of containing the fissionable element, a satisfactory material must possess:

1) Suitable nuclear and radiation resistance properties;

2) Mechanical properties at operating temperatures to withstand the temperature gradients and pressure differences imposed by the energy production and fluid flow conditions;

3) Capability to withstand the rapid changes in temperatures required by the rapid startup requirements of a nuclear rocket engine;

4) Suitable low-temperature physical properties to withstand the shock and the vibration loads caused by the booster operation;

5) Sufficient corrosion resistance to hydrogen to maintain its structural integrity and contain the fissionable materials for the required engine operating times.

The temperature requirements eliminate all the elemental materials except graphite, tungsten, rhenium, tantalum, molybdenum, and niobium. The only temperature-compatible compounds are some of the metallic carbides, nitrates, and borides. While needed physical data is lacking on most of these materials, the choices rapidly narrow to a few possible materials.

Graphite was chosen for the NERVA fuel element. It has excellent high-temperature properties, with a sublimation temperature of 6700 degrees R, and relatively high tensile strengths at operating temperature (~2000 psi). While the mechanical design was simplified by the choice of graphite as the fuel element material, the design of the reactor remained a formidable task. The relatively good low-temperature characteristics of graphite with respect to vibrational and shock loadings eased the problem of mounting the core so that it can resist booster induced vibration damage.

Graphite's ability to withstand thermal shock has allowed a design which can be subjected to rapid thermal transients. The high operating temperatures cause a more subtle problem of accommodation for the expansion of the core and the sealing between the cryogenic regions of the reactor and the high operating temperature regions. The design of this seal is one of the more formidable tasks of the NERVA program.

In the fall of 1962, extensive damage occurred to the Kiwi-B4A reactor during a power test. The cause of this damage was not immediately evident, and considerable concern developed over the adequacy of the basic reactor principle. Critical evaluation of the evidence, however, identified the most probable cause of the reactor damage as a severe hydrodynamic vibration. A concentrated analytical and test program confirmed the vibration premise and guided design changes to prevent the condition.

The overall result is a rugged reactor design shown schematically in Fig. 1, capable of coping with all the postulated environmental conditions of booster and flight operation and maintaining its integrity during the severe high-temperature operation.

Experimental Program

Before a reactor could be committed to a full-scale test, an intensive experimental program was required to verify the adequacy of the key components. From an economical or schedular standpoint, it was impractical to test each of the components under all of its environmental conditions—in general, combined environmental testing (such as vibratory tests under high-temperature radiation conditions) could not be performed. Instead, several classes of component tests (Fig. 3) were conducted on core parts and the complete core. Some of these tests are still in progress to qualify the reactor for more strenuous operations or for flight service.

A few examples can indicate the scope of the component test program. In Fig. 4, for example, the reactor is shown being vibrated in an axial position. Extensive vibration tests were conducted under all of the anticipated booster vibrations, plus any vibrations expected from nozzle-induced or two-phase vibration-induced conditions.

Fluid flow tests on the many parts of this reactor were performed in a hydrogen flow facility constructed at the Westinghouse Waltz Mill Test Site. This facility was used primarily for checking the liquid and gaseous hydrogen flow-distribution conditions within the reflector and the core. In addition, experiments were performed to study the stability of the various parts under the many unusual operating conditions. This facility was designed to perform experiments with liquid hydrogen flow rates up to about four pounds per second.

At the other end of the temperature spectrum, many electrically heated furnaces were developed to test the fuel elements and other key parts at high-temperature operating conditions. Perhaps the most significant of these installations is the furnace used to check the quality and capabilities of the fuel elements. In this unit, single elements are electrically heated to reactor operating temperatures and are subjected to hydrogen flow rates simulating reactor operating conditions.

Reactor Control

In addition to the reactor developmental problems, the control of the reactor also encompasses many questions.

One problem is to achieve sufficient reactivity control to safely vary the reactor power level through all desired transients. Because control is obtained only from the reflector drums, the available reactivity adjustments are limited. This limited control span must be sufficient to compensate for the operating effects of hydrogen and temperature, and to allow adequate margins for shutdown and excess reactivity. Since information on the reactivity effects of temperature and hydrogen in the core and reflector can only be obtained by full-scale reactor tests, great emphasis (and dependence) was placed on the use of proper analytical approaches for predicting the nuclear characteristics of the reactor. This work has proceeded well, and initial results show close agreement between predictions and full-scale experiments.

The other control problem arises in the kinetics or dynamics of the system during startup and power operation. Particularly important are predictions of temperatures and pressures within the system and the reactor during the startup flow transient. The liquid-to-gas change in the hydrogen entering the engine introduces a two-phase flow problem—accompanied by all the uncertainties associated with this phenomenon. The two-phase flow condition first exists in the piping, then passes on to the nozzle. As pressure of the turbopump rises to 195 psia, the hydrogen becomes supercritical, thereby ending the two-phase flow condition. Effects of hydrogen on the system have been adequately predicted, and initial runs agree closely with the results obtained by analog computer analysis.

The stability of the reactor when subjected to flow conditions approaching liquid hydrogen entering the core is of major significance. Concern has been expressed during past years about postulated instability problems caused by the high positive reactivity worth of liquid hydrogen. Very low core inlet temperature conditions have been avoided to prevent this potential difficulty. Recent tests, however, have demonstrated stability.

Reactor Testing

The most significant experiments and the culmination of the foregoing efforts are the full-scale tests. Each of these tests is a major undertaking and, therefore, only a limited number can be included in the program. Since essential information must be learned from each full-scale test, the prime prerequisite for a successful program is the organization, planning, and training which precedes the actual run day. In the NERVA Project, the planning for a specific reactor experiment begins almost two years before the actual test date. After much discussion and compromise, precise objectives are established and the experimental plans are carefully designed. The experimental plan must incorporate the maximum amount of the reactor designer's desires without compromising the main objective.

The first specifications to be established following the design of the experiment are the measurements and instrumentation requirements. Six to nine months before a test, firm commitments are made on the 200 to 300 instruments to be mounted on the reactor. Detailed revisions are required to the basic reactor design to accommodate these thermocouples, pressure and differential pressure probes, accelerometers, displacement transducers, and strain gauges. Instrumentation external to the pressure vessel can be altered more easily, but it too must be established at least six months before the test. A total of 500 to 700 instruments are required.

These requirements highlight another basic development problem in that the majority of these instruments must function in a severe radiation environment. Besides being tolerant to the total radiation dosage, some of the instruments must be designed to operate with gamma heating rates as high as 30 watts per gram. This heating problem is the more difficult one, requiring that the internal instrument design be such that heat is conducted to surfaces that can be cooled by hydrogen.

In addition to the development and design required to properly instrument a reactor test, plans must be made to accumulate and rapidly prepare the data for analysis. The adequacy of the data acquisition system used in the NERVA program can be judged by the fact that a complete set of plotted data is issued three days following a test. This may present of the order of 100,000 bits of plotted information.

Other plans and analysis that must be prepared prior to a reactor test are: (1) Predictions report of each of the variables to be measured; (2) detailed test specification, operating procedures and check-off lists; (3) detailed handling assembly and disassembly procedures for the test article; and (4) safety analysis of the particular experiment. As these plans are completed, the reactor is being assembled for the tests.

The full-scale tests are performed at the Nuclear Rocket Development Station at Jackass Flats, Nevada. This 90,000-acre site about 90 miles northwest of Las Vegas was established in February 1962, by agreement between the AEC and NASA, and includes the part of the AEC's Nevada Test Site, which had been used for the ground tests of the Kiwi reactors. Operations at this site are controlled by the SNPO Nevada Office.

The principal facilities at NRDS are shown in Fig. 5. Test Cells A and C and the R-MAD (Reactor-Maintenance, Assembly, and Disassembly) building were developed and are being used for the Kiwi and NRX test programs. The R-MAD building is used for assembly and remote disassembly of the reactors. Other facilities shown on the map are the ETS-1 test stand and the E-MAD (Engine-Maintenance, Assembly, and Disassembly) buildings, which were developed as a part of the NERVA program. The NERVA engine will be assembled and disassembled in the E-MAD building and tested in the down-firing position in ETS-1. This test stand includes a cooled duct to direct the exhaust gas from the stand. The design of this duct represents a complex fluid flow and material cooling problem.

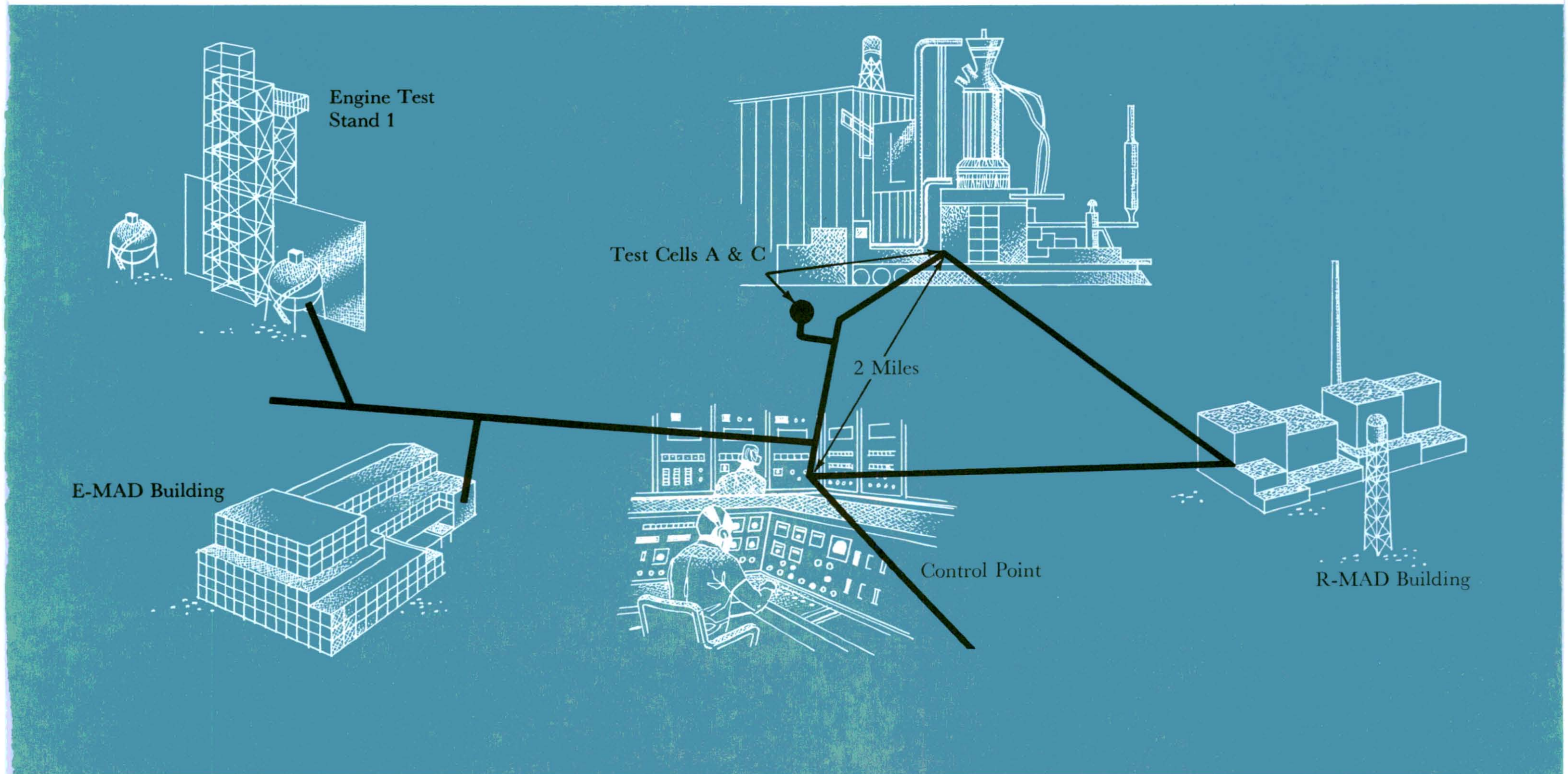
The NERVA reactor, which is shipped from the Astronuclear Laboratory in Pittsburgh, is assembled with a nozzle and pressure vessel on a test car (Fig. 7) in an assembly and disassembly building. The test car is a railroad car modified to provide a shielded region for the control actuators and electrical equipment. It also contains the coolant, purge and hydraulic lines and instrumentation leads required for the test. The nuclear reactor assembly is mounted with the nozzle pointing up. Subsequent to these operations, the test assembly is transported to the test cell, about two miles away.

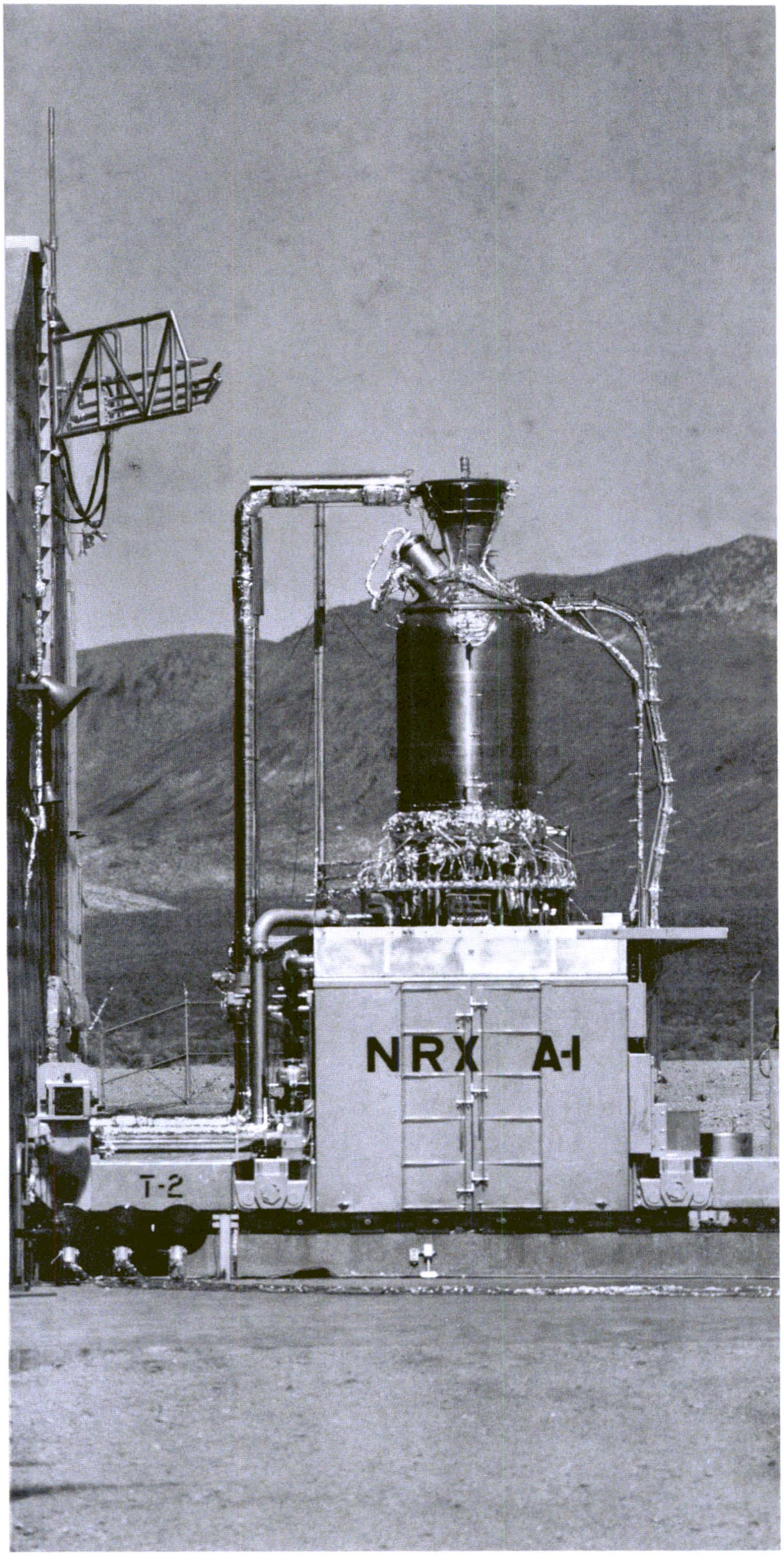
The NRX-A1 reactor mated to the test cell is shown in Fig. 6. Piping and electrical connections are made through the test cell wall, by means of a shielding plug carried on the end of the car. This plug is designed to allow remote disconnection following the reactor test.

The test cell used for the NRX testing is Test Cell A, which has one 100,000-gallon and two 28,000-gallon liquid hydrogen dewars and 700 instrument channels for data acquisition. The liquid hydrogen is pumped to the reactor by a facility turbopump, and the turbine is driven by high-pressure hydrogen gas from the gas storage farm. The test cell includes a gas manifolding room, a flow control room, and a reactor hook-up room. An aerial view of the test cell is shown in Fig. 8.

A room adjacent to the cell contains the data acquisition equipment, which collects instrumentation signals from the reactor. All reactor test operations are controlled from a Control Point about two miles from the test cell, thereby eliminat-

5—**Principal facilities** at the Nuclear Rocket Development Station are shown here in diagrammatic form. R-MAD and E-MAD buildings are for maintenance, assembly, and disassembly of the reactor and engine, respectively.





ing direct radiation hazards to control personnel during the test. Control signals are transmitted to the reactor through an underground cable. The data is transmitted to the Control Point by a hard wire FM multiplexing system.

The tests are performed by a joint test organization called NTO (Nevada Test Organization), composed of Aerojet-General Corporation and Westinghouse personnel. The tests are under the direction of a Test Director, who has full responsibility for the conduction of the test. A Test Review Board representing the technical disciplines, and SNPO, are present throughout the final days of the preparation for the run and during the testing to approve any last minute revisions to the test specification. Starting two days prior to the test, called R-2 day, each of the operations proceed according to a prescribed check-off list. Checks are made of the test piping and valving systems and the controls of each of the operational units. An end-to-end check is performed on each of the instrumentation channels. Inputs are introduced as close to each of the detectors as possible, and a calibration check is made at the Control Point two miles away.

These operations continue through R-1 day during which another set of check-offs must be accomplished. On run day, the final check-offs are accomplished and, at about 0600, the status of the check-off board at the cell is reviewed. When all local operations are completed, the cell is evacuated and road blocks are established about two miles from the cell. Following this time, no one can enter the evacuated area except the re-entry team, who must be instructed by the Test Director.

The Control Point check-off begins at about 0730. In addition to the instruments at the Control Point, complete television coverage of the test cell and test article is maintained.

The control room personnel consist of about twenty operators (shown in Fig. 9) under the direction of a Chief Test Operator (CTO), who receives his direction from the Test Director. Other key operating personnel present during the test include the data acquisition team, the television and photographic monitoring team, test-cell monitoring team, radiation and safety personnel, and sufficient personnel to repair any malfunction. During the test, a team of design personnel are observing some one hundred key variables that are being recorded on strip chart recorders. If any variable exceeds a red line value, they notify the Test Director.

A data review team is available to review the quick-look data immediately following the run. Final safety approval to

6—The NRX-A1 reactor mated to the test cell. Piping and electrical connections are made through the test cell wall.
7—NERVA reactor is assembled with a nozzle and pressure vessel on a test car, a railroad car modified to provide a shielded region for the control actuators and electrical equipment.
8—Aerial view of the test cell used for NRX testing. The cell has one 100,000-gallon and two 28,000-gallon liquid hydrogen dewars, and 700 instrument channels for data acquisition.
9—Control room personnel number about 20 operators. Other key operating personnel include a data acquisition team, television and photographic team, and other specialized groups.

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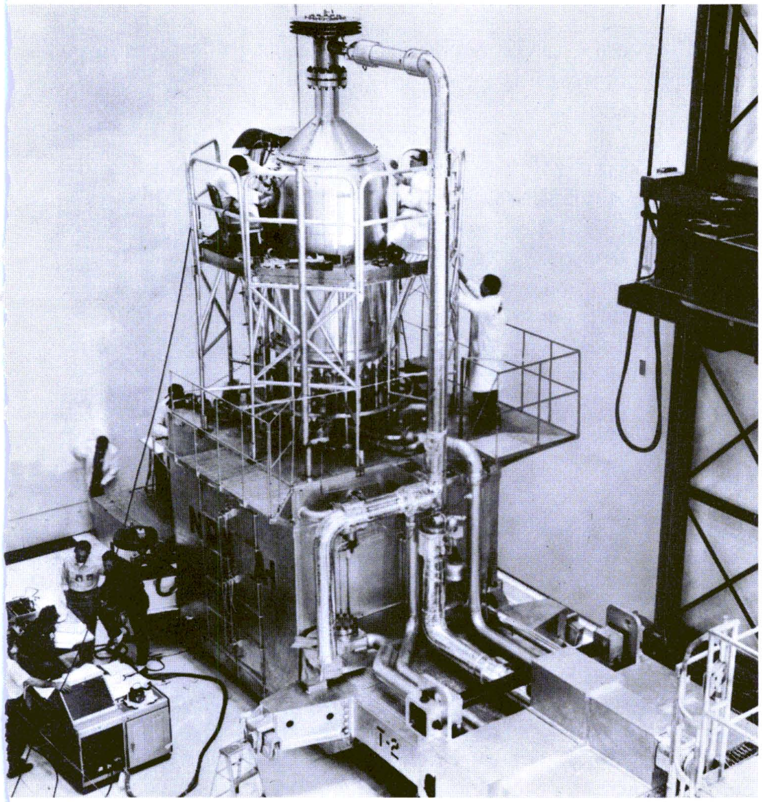

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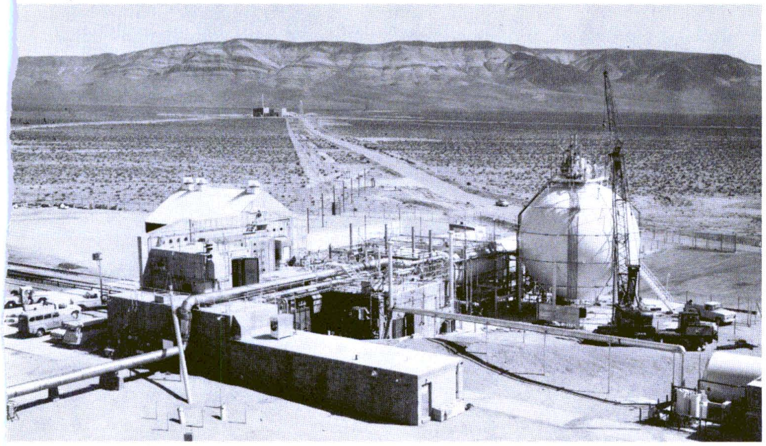

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run is obtained from SNPO-Nevada, who analyze weather conditions with relation to any possible malfunction.

When all the various checks are completed, the run phase of the test is started. The complete test profile, which includes power level, flow rate and temperature, is controlled by an automatic programmer. The Chief Test Operator has the ability to stop the test cycle and to override certain control parameters if unusual operating conditions exist. In practice, the operating sequences occur so rapidly that only a few trimming corrections on reactor power or temperature are possible during a run. No change in plan is possible at this time. The success achieved in the few minutes of testing is primarily the result of the months and years of planning that preceded the order to run.

The NRX-A1 test, run in the spring of 1964, was the first full-scale test conducted as a part of the NERVA Project. It was a nonnuclear test, used to prove out the structural and stability conditions within the reactor under the high-flow and vibratory conditions of engine operation.

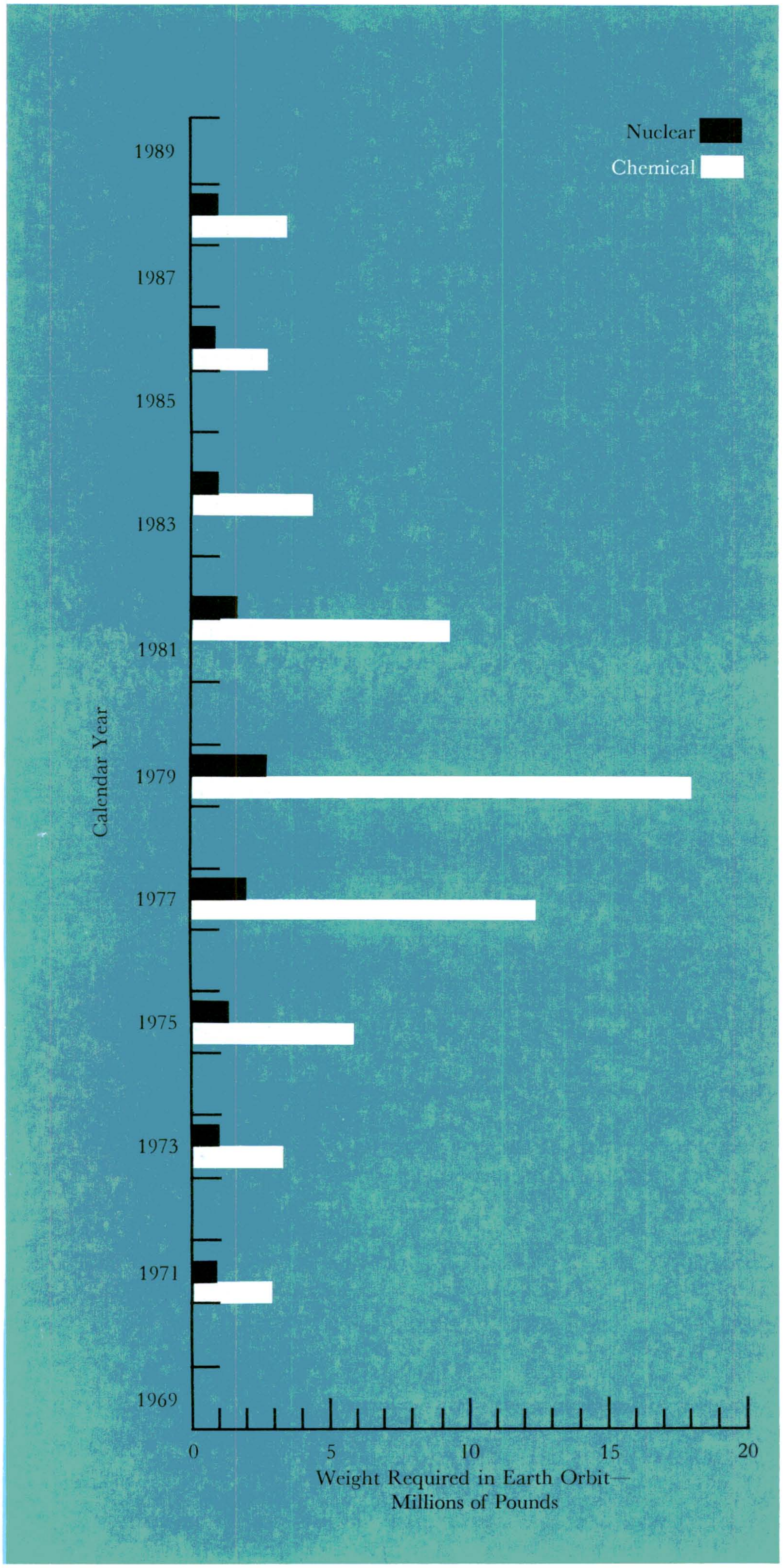
A series of tests were performed to check the integrity of the system, starting with nitrogen flows and followed by gaseous and liquid hydrogen.

Flow rates representing a substantial fraction of full-flow conditions were passed through the reactor, and observations were made for any structural damage or any vibratory condition. Approximately 525 channels of instrumentation were used during the test. No major damage or unusual condition was observed, and the test was rated an unqualified success.

Following a test, the test car is returned to the R-MAD building. For NRX-A1, which was not a nuclear test, disassembly was not performed by remote operation, but for the "hot" NRX-A2 test, the reactor has been brought into a large disassembly bay, and operations performed remotely.

In July 1964, the second NRX reactor (NRX-A2) was delivered to Nevada and was installed on the test car. It was mated to the test cell, and on August 12 the first criticality was achieved on the reactor. Tests continued through the month of August and early September in preparation for achieving the first powered run in the NERVA program.

On September 24, the hot test of the NRX-A2 reactor was conducted. All of the test objectives were achieved, and the operating time and power level exceeded expectations. The reactor operated for slightly over six minutes at power levels above 50 percent of the full power rating. During the latter part of the run, full power conditions were attained. A photograph of the NRX-A2 test assembly during the firing is shown on p. 75. The proper functioning of the majority of the experimental instrumentation allowed significant amounts of data to be accumulated. A second test run was conducted on October 15 when the reactor was operated at low powers for a period of 20 minutes. Significant information was obtained on reactor stability with dense hydrogen and two-phase hydrogen entering the core. At present, extensive efforts are underway to analyze all this information; also pending are observations to be made during the remote disassembly of the reactor.



The Future

The future course of the nuclear-rocket program involves testing more reactors, until the design is qualified for engine tests, and the simultaneous development of the other engine components such as the nozzle and turbopump. At that point, a complete engine will be mounted in an NRDS test stand, ETS-1. The stand includes a run tank containing 70,000 gallons of liquid hydrogen, installed in the superstructure above the engine firing positions. The engine will be tested with the jet firing downward into an altitude chamber approximating expected startup conditions of temperature and vacuum.

Following the series of NRX and engine system tests, the nuclear engine will be ready for flight operation. Its high specific impulse makes the nuclear rocket engine an attractive choice for deep solar system probes, for manned trips to nearby planets, or for ferrying substantial equipment to the moon and beyond.

For example, the substitution of a nuclear stage using the NERVA engine for the chemical third stage of the Saturn V configuration would result in 40 to 75 percent more payload landed on the moon than with the chemical Apollo mission.[2]

For planetary missions, the advantages of nuclear rocketry are even more impressive. For example, while the orbital relations for a Mars mission are favorable for a brief period every two years, the energy required varies greatly over a 17-year cycle. These energy requirements determine the total vehicle weight that must be launched into earth orbit. For these long-range manned Mars missions, Fig. 10 compares the launch weight of an all chemical vehicle to that for a nuclear-powered vehicle for beyond-orbital operation.[3] The comparison of the required launch weight is shown for each year up to 1987. The difference is noteworthy for the near optimum years, but is several factors for the nonoptimum ones.

With these performance capabilities, it is certain that the nuclear rocket engine will find a significant place in the spectrum of space propulsion power sources. For long-range space missions, there is no doubt that the nuclear rocket has an inherent superiority over any chemical rocket; in deep-space probes, nuclear-powered vehicles appear to be the only practical approach in the foreseeable future.

Westinghouse ENGINEER
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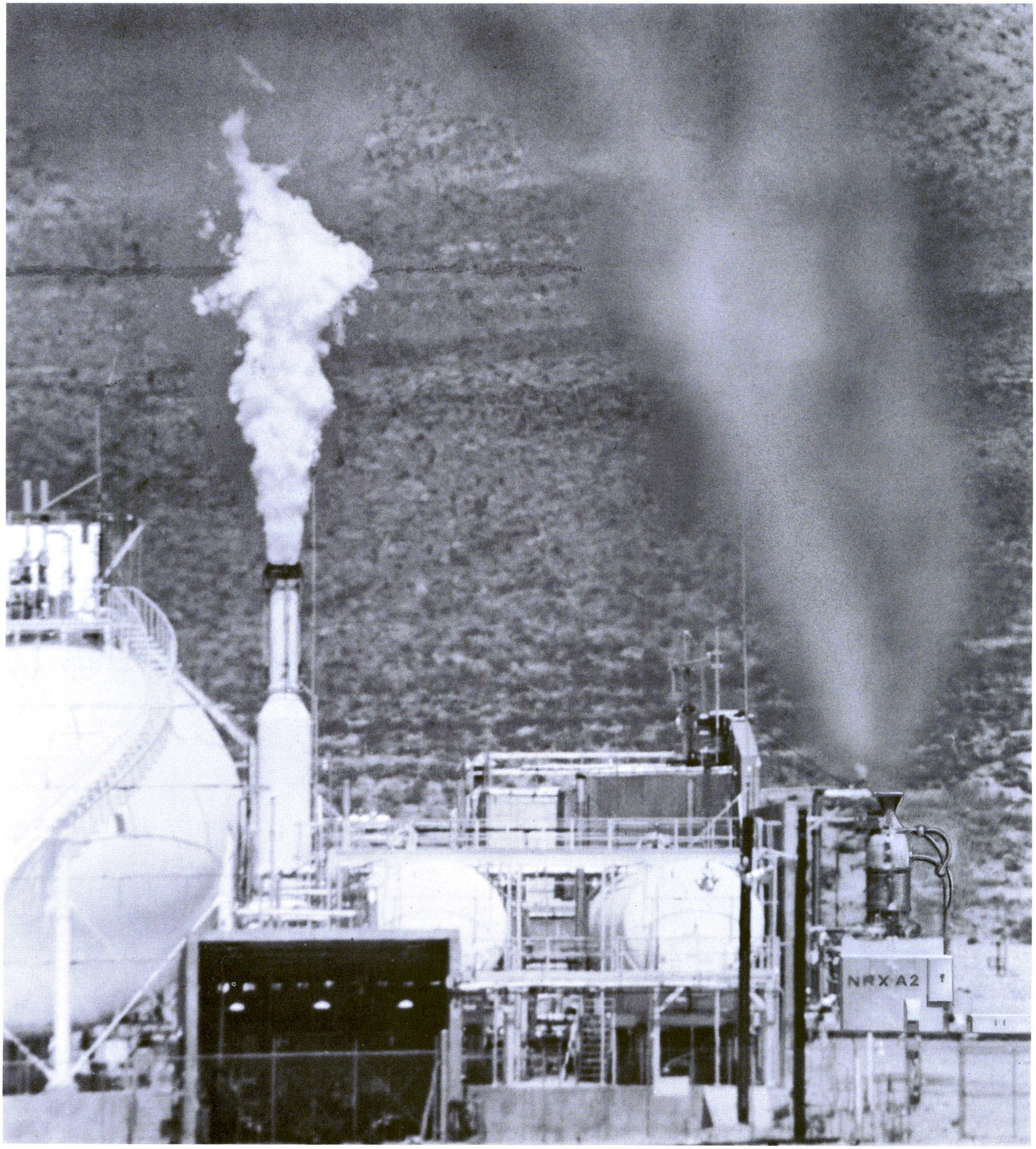
References:
[1]R. E. Schreiber, "Kiwi Tests Pave Way to Rover," *Nucleonics*, Vol. 19, No. 4, April 1961, 11.77-79.
[2]Harold B. Finger, "Space Nuclear Propulsion Mid-Decade," *Astronautics & Aeronautics*, January 1965.
[3]LMSC-A664211—"Nuclear Rockets for Long-Range National Space Objectives," Lockheed Missiles and Space Company.

10—A comparison of launch weights of an all-chemical vehicle and a nuclear-powered vehicle for beyond-orbital operation, in this case for a Mars mission.
11—Firing of the NRX-A2 is shown here. During these tests the reactor operated for slightly over six minutes at power levels above 50 percent of full-power ratings, and during the latter part of the run, full-power conditions were attained.


NRX A2