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The Rover Nuclear Rocket Program

Thirteen years of work have produced a reliable reactor ready for development into a flyable engine.

Roderick W. Spence

Nuclear energy and space exploration have arrived at very nearly the same time, and it is not surprising that man would try to utilize a new-found energy source for a new and exciting field of adventure. Speculations (*1*) as to how fission energy could be used for space propulsion were current shortly after World War II; by 1955 well-defined proposals had been advanced and a nuclear rocket program (Project Rover) began. The only approach seriously considered was that of heating a propellant in a reactor to a very high temperature and expanding the heated gas through a nozzle to obtain directional thrust. Even in the early days it was recognized that this approach was not likely to lead to realization of the full potential of nuclear energy for space propulsion. But it did have the immediate advantage that the concept was clear and that a program of research and development could be described and started. This article is concerned primarily with the experience gained at the Los Alamos Scientific Laboratory in pursuing that simple concept.

The article first outlines the advantage of nuclear rockets and gives a general description of their basic features. Next, the main areas of work necessary to develop the reactor are briefly discussed, and a more or less chronological résumé is given of the achievements to date. Finally, there is a very brief discussion of more advanced methods of nuclear space propulsion.

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Advantage of Nuclear Rockets

The figure of merit often used to express rocket engine performance is the nozzle exhaust velocity. The importance of exhaust velocity stems from the (here somewhat simplified) fundamental rocket equation:

$$\Delta V = V_e \ln \frac{M_o}{M} = V_e \ln \frac{M + M_p}{M}.$$

In this equation ΔV represents the velocity changes required for any particular mission, including takeoff accelerations, mid-course directional changes, slowing-down at destination, and other changes, and thus characterizes the difficulty of the mission; M_o represents the initial mass of the space vehicle; M represents the vehicle mass after propellant M_p has been exhausted; and V_e is the exhaust velocity. Difficult missions (characterized by high values of ΔV) might be accomplished by making the propellant mass M_p very large as compared to the vehicle mass M, thus increasing ln (M_o/M). Because of the logarithmic function this is a very limited way of achieving high values of ΔV. A good space propulsion engine, therefore, should produce a high exhaust velocity (*2*).

The 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. For nuclear rockets of the type under discussion, in which heat is transferred from solid fuel elements to a gas, the gas temperature, T, is not likely to be any higher than that obtained when two chemicals, say hydrogen and oxygen, burn in the chamber of a conventional chemical rocket. The chief advantage of the nuclear rocket is that we may choose the propellant so as to obtain the lowest possible molecular weight. We naturally choose hydrogen. By so doing we can obtain exhaust velocities near 8 kilometers per second, as compared to about 4 kilometers per second for the best velocity obtained from chemical rockets. Nuclear rockets do, however, have some disadvantages. They are heavier than chemical engines, the liquid hydrogen they use has a low density which results in a requirement for large tanks, and shielding is required to reduce the radiation from the operating reactor. All three factors result in a performance penalty in the form of increased vehicle weight. The net gain resulting from replacing a chemical stage with a nuclear stage depends somewhat on the mission, but one can say, as a rough approximation, that the payload will be doubled.

Engine Description

The basic idea of a nuclear rocket engine is very simple (Fig. 1). Such an engine consists of a nuclear reactor whose purpose is to heat hydrogen to as high a temperature as possible; a nozzle through which the hot hydrogen expands; and a turbopump to force the hydrogen through the system. The actual engine, of course, has a number of complicating features. One obvious complication is the need for control systems for the reactor power and reactor temperature and for the hydrogen flow. Another is the scheme by which some of the hydrogen flow is tapped to drive the turbine. The entire nuclear stage must include the tanks in which the hydrogen is stored. The only practical way to store the hydrogen is as a liquid at a temperature near 20°K.

The reactor has at least three distinguishing characteristics. First, it operates at a very high temperature; second, it operates at a high power density (to reduce reactor weight). This combination of high temperature and high power density presents a great challenge to reactor designers. On the other hand, things are considerably simplified for the designer by the third characteristic: the reactor operates on an open cycle (that is, the hydrogen passes through the reactor just once and there is no recycling), so complicated fluid-loops are not required.

The reactor can be considered to consist of two parts, the core and the surrounding reflector (see Fig. 2). The core is an assembly of graphite fuel elements containing U^{235}; the fuel elements contain passages through which the hydrogen flows and is heated. (The detailed design is classified information.) The reflector serves primarily to return escaping neutrons to the core, but it also serves as a convenient place to put control rods. These control the fission rate by moving a strong neutron absorber either closer to, or farther from, the core as desired. Hydrogen enters the system at the nozzle, where it cools the nozzle structure, and from there it proceeds through the reflector (cooling it and the pressure vessel) to the core inlet. At this point it is still quite cold, about 100°K, but as it travels through the fuel elements it is heated rapidly and emerges from the core at a temperature of at least 2500°K.

The work involved in bringing this simple concept to complicated reality can be conveniently divided into materials development, reactor design and analysis, neutronics, instrumentation and controls, and reactor testing. Some of the highlights of each of these fields are now discussed.

Materials Development

There are only a few high-melting materials suitable for use in reactors designed to run at very high temperatures. Two such materials are quite familiar, graphite and tungsten metal. Less familiar candidates are some metallic carbides: TaC, HfC, NbC, and ZrC. The choice of basic reactor material determines to a large extent the type of reactor design. Thus, tantalum, hafnium, niobium, and tungsten are all strong neutron absorbers, particularly for slowed-down (moderated) neutrons. The use of any of these elements in large quantities in a nuclear reactor practically dictates that the reactor design be such that neutrons are not allowed to slow down much (that is, dictates design of a fast reactor). Graphite and ZrC are not strong neutron absorbers and their use imposes no such constraint on the reactor design. Graphite has long been used as a high-temperature material in various industrial applications, and it has many attractive properties as a reactor fuel matrix material. It does have, however, one outstanding defect for use in a nuclear rocket reactor: it reacts very vigorously with hot hydrogen. Despite this drawback, graphite was chosen very early in the nuclear rocket program as the basic reactor material. The hope was that a suitable carbide cladding could be developed which would effectively slow down hydrogen corrosion. This hope has been largely realized and, to date, reactors have been run for as long as 1 hour, heating hydrogen to temperatures near 2500°K. A full discussion of the work now in progress on fuel-element materials cannot be undertaken because much of this information is classified; it can be said that further improvements in performance are likely, and that hydrogen temperatures in excess of 2800°K may be a possibility. As operating temperatures rise it can be expected that the life of the reactor will be shortened; for most space missions, however, running times of more than 45 minutes are not needed.

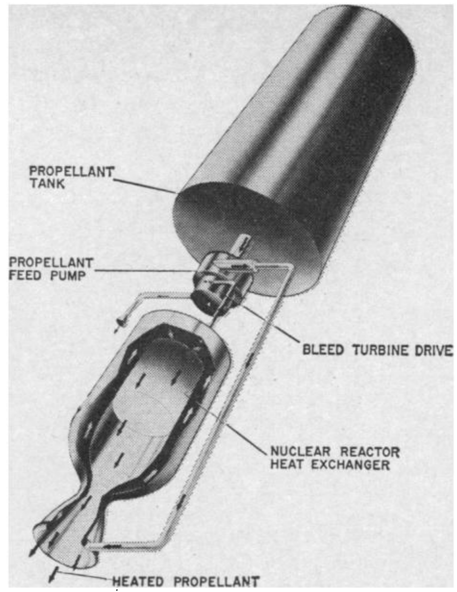

Fig. 1. Schematic drawing of a nuclear rocket engine.

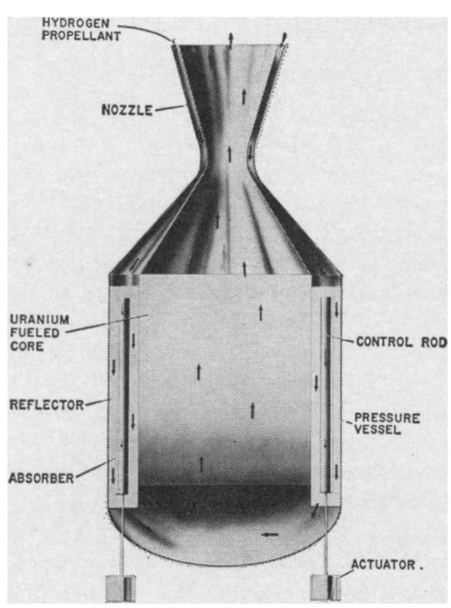

Fig. 2. Schematic drawing of a nuclear rocket reactor.

Reactor Design and Analysis

The primary objective in reactor design is to provide a device that will heat the propellant uniformly to the maximum temperature that the core materials will allow in the smallest and lightest-weight configuration possible. The design begins with a core-support concept and with selection of the fuel-element geometry, where power density, heat transfer, pressure drop, and both mechanical and thermal stresses are important considerations. Once the basic fuel element is selected, the design effort progresses toward satisfying the neutronic and core-support requirements. A complete discussion of the many steps involved in arriving at a final design would be too long for this article, but a few of the main problems can be mentioned. One of the most prominent has been the necessity of dealing with rather large expansion effects. It is not that graphite has a particularly large coefficient of thermal expansion but, rather, that the span of operating temperatures (> 2300°K) is so large. A core 1 meter in diameter would increase in diameter by about 1 centimeter with a temperature rise from room temperature to 2600°K. A gap between the core and the reflector to accommodate this expansion is therefore necessary. This expansion gap complicates further an already complicated region, because it is at this interface that a lateral support for the core is provided, and it is here that thermal insulation between the core and reflector is needed As an aside it might be mentioned that the commercial development of pyrographite has been a great boon to designers of nuclear rocket reactors. This material provides extremely effective thermal insulation combined with good structural integrity, and it is hard to imagine what we would have done without it.

It is not only the very high temperatures that can create problems but also the very low ones. Perhaps the most vexing of all our design difficulties have been leaks in cryogenic lines. Joints that test perfectly at room temperature may spring sizable leaks when cooled to 20°K. Such leaks are always awkward when one is dealing with hydrogen because it burns so readily in air, but they are doubly awkward when the radioactivity level prohibits close approach.

One area where considerable effort has been needed is that of radiation heating. Neutrons and gamma rays from the fission process are absorbed in all parts of the engine structure. The contribution to the total thermal load from this absorption is by no means small, and must be estimated fairly accurately. Thickening a part to enable it to better withstand the combined mechanical and thermal stress load is not always effective; the strength may be increased thereby, but so is the thermal stress arising from absorption of radiation.

For best performance the fuel elements should all be operating at the same temperature, because any hot spot will, to some degree, become the limiting factor in any attempt to raise core temperature, and any cold spot lowers the average temperature. Temperatures can be regulated locally by varying the uranium content of the elements or by using inlet-orifice jets to meter the hydrogen flow through fuel-element passages. The largest adjustments are needed near the core edge, because neutrons returning from the reflector give rise to an increased fission rate there. The shape of the curve obtained when fission rate is plotted against core radius is very sensitive to details of the interface design and to the position of the control rods. The accurate prediction of fission rates near the core periphery is one of the most difficult problems the reactor designer faces.

Neutronics

The first objective in reactor neutronics design is to make sure that the reactor will go critical—that is, to make sure that a self-sustaining fission chain reaction can be initiated and that it can be sustained at all stages of reactor operation. The experimental work begins with relatively crude mock-ups in general-purpose critical assemblies. As experimental and calculational results are obtained, the mock-ups become more realistic and the reactivity effects of various design options can be measured. This part of the effort culminates in a recipe for loading the fuel elements with uranium. As implied above, the uranium content of fuel elements near the core edge has to be less than the content of elements near the core center. It is not sufficient, however, just to achieve a flat radial fission distribution for a reactor at room temperature. In addition, the various reactivity changes which occur as the reactor rises to full power must be calculated. For example, as the temperature rises and the core expands there is a loss in reactivity. On the other hand, as hydrogen flow begins, the hydrogen in the core moderates the neutrons, and this results in a gain in reactivity. Fortunately, in our graphite-based reactors these two effects largely cancel each other, so that reactor start-ups can be programmed which call for relatively little control-rod motion once criticality is achieved. It is important that the control-rod settings at the reactor design point be estimated with good accuracy, because the position of the control rods affects the fission rate and hence the temperature near the core edge.

Instrumentation and Controls

Accompanying the testing of developmental reactors are many measurements of temperatures, pressures, power, hydrogen flow rate, strains, accelerations, noise level, and so on. Most of these measurements (often more than 1000) are recorded for later analysis; some of them are used to help control the reactor-run variables, while others are displayed to monitors in the control room. As would be expected for reactors running at high temperature, temperature measurements are by far the most numerous. Generally they are of two kinds: temperature measurements for materials and for hydrogen. For both, temperatures can be measured with good accuracy up to about 2000°K; above that temperature great care has to be exercised in the construction of the thermocouples used. We have used tungsten/tungsten-rhenium thermocouples exclusively for measurements above 2000°K. So far we have been successful in measuring gas temperatures near 2500°K with an accuracy of a few percent, but material-temperature measurements have given us trouble above 2300°K. A valuable check on operating temperatures can be obtained by calculating the nozzle-chamber temperature from the measured chamber pressure and the rate of hydrogen flow. It is thus possible to obtain the desired average temperature to within about ± 100°K. It is not possible to obtain and display fine-grained temperature measurements throughout the core, so we have to be content with sampling the temperatures in a relatively small number of places.

For reactor control the most important operating variables are temperature, power, and hydrogen flow rate. All can be controlled by the technique of comparing the measured with the desired values and adjusting the variable until the difference is zero. This continuous zeroing of the error by a feedback technique is called closed-loop operation, and it has proved to be remarkably successful for our reactors. At one time both reactor power and reactor temperature were controlled by closed-loop operation, but lately it has been the practice to use this method of control only for reactor temperature and hydrogen flow rate. In passing it might be mentioned that fairly rapid changes in power are common for nuclear rocket reactors during the start-up phase. Power can be increased from essentially zero to a few megawatts in half a minute or less.

In the early days one possible control problem gave us a good deal of worry. It was postulated that during reactor start-up (before critical pressure or critical temperature had been reached and while the hydrogen was in the two-phase flow regime) surges of dense hydrogen would enter the reactor core, moderating the neutron flux and resulting in uncontrollable excursions of power and temperature. In fact, this did not happen at all, and reactor start-ups can be made smoothly and reliably.

Very early in the program we began planning for reactor tests. We were aided from the beginning by the Albuquerque division of American Car and Foundry, Inc., for reactor assembly and disassembly, and by Edgerton, Germeshausen and Grier, Inc., for data transmission and recording. Our first concern was to find a suitable site, far enough from populated areas so that the radioactivity from a reactor accident would not endanger anyone. We naturally thought of the Nevada Test Site, where the Los Alamos Scientific Laboratory (LASL) had been conducting nuclear weapons tests for some years. We chose Jackass Flats (named probably by some long-forgotten prospector) in the Amargosa desert some 20 miles (30 kilometers) from Mercury, the base camp for weapons activities.

By 1958 the construction of the first facilities was under way. They consisted of a test cell, a control building, and an assembly-disassembly building located approximately 3 kilometers from each other in a triangular array. The test cell and assembly building were linked by a railroad, which soon acquired the name Jackass and Western. The assembled reactor was to be transported by way of this railroad to the test cell, where the necessary propellant and electrical connections would be made. The tests themselves were to be conducted from the control building, and all data were to be recorded there by means of the many wires running from the test cell. After completion of the tests, a remotely controlled engine would move to the test cell, engage the radioactive reactor, and transport it to the disassembly bay for disassembly and postmortem.

The first reactor to be tested was Kiwi-A, on 1 July 1959. The test was a great success, not only for the reactor but for the test site facilities as well. Kiwi-A, with its thick graphite reflector, its water-cooled nozzle, its modest operating power of 100 megawatts, and its rate of gaseous hydrogen flow of 3 kilograms per second, was hardly a prototype of a useful reactor for space vehicles, but we had learned a great deal in designing, building, and testing it. Now we were eager to push on to the next step, testing of a 1000-megawatt reactor called Kiwi-B. The original test cell was not adequate for testing a 1000-megawatt reactor, so a new test cell was designed; among the new facilities provided were two storage dewars, each holding 15,000 kilograms of liquid hydrogen. The responsibility for designing and fabricating a turbopump capable of delivering 30 kilograms of liquid hydrogen per second to the reactor was given to Rocketdyne, a division of North American Aviation; Rocketdyne was also given the task of supplying the liquid-hydrogen-cooled nozzle. The reactor design itself was quite different from that of Kiwi-A. One major change was the use of a beryllium reflector in which were located the control rods. The reactor core was completely redesigned. It was clearly going to take time to build the new reactor, the new test cell, and the new turbopump and nozzle. It was therefore decided to test certain of the new reactor-core features in the Kiwi-A geometry. This was done in 1960. Two noteworthy results were obtained, one good and one bad. The good result was the finding that NbC worked well in inhibiting graphite corrosion; the bad result was a warning that the Kiwi-B core design might have a serious weakness.

Meanwhile the National Aeronautics and Space Agency had been created in the fall of 1958, and in August 1960 a joint AEC–NASA office called the Space Nuclear Propulsion Office (SNPO) was formed, with Harold B. Finger as manager. This office took over, from the original AEC-Air Force partnership, the management of the nuclear rocket program. The success of the Los Alamos Scientific Laboratory efforts encouraged SNPO to initiate industrial participation in the program, and, in July 1961, Aerojet-General Corporation was selected to develop a flyable nuclear rocket engine (called NERVA for Nuclear Engine for Rocket Vehicle Application) with Westinghouse Electric Corporation's newly founded Astronuclear Laboratory (WANL) named as the chief subcontractor to supply the reactors. It was planned that the NERVA reactor would be based on whichever Kiwi-B design (there were three at that time—B-1, B-2, and B-4) performed best in actual test. In May 1962 the Marshall Space Flight Center engaged the Lockheed Missiles and Space Company to design and build a flight test vehicle for a nuclear rocket

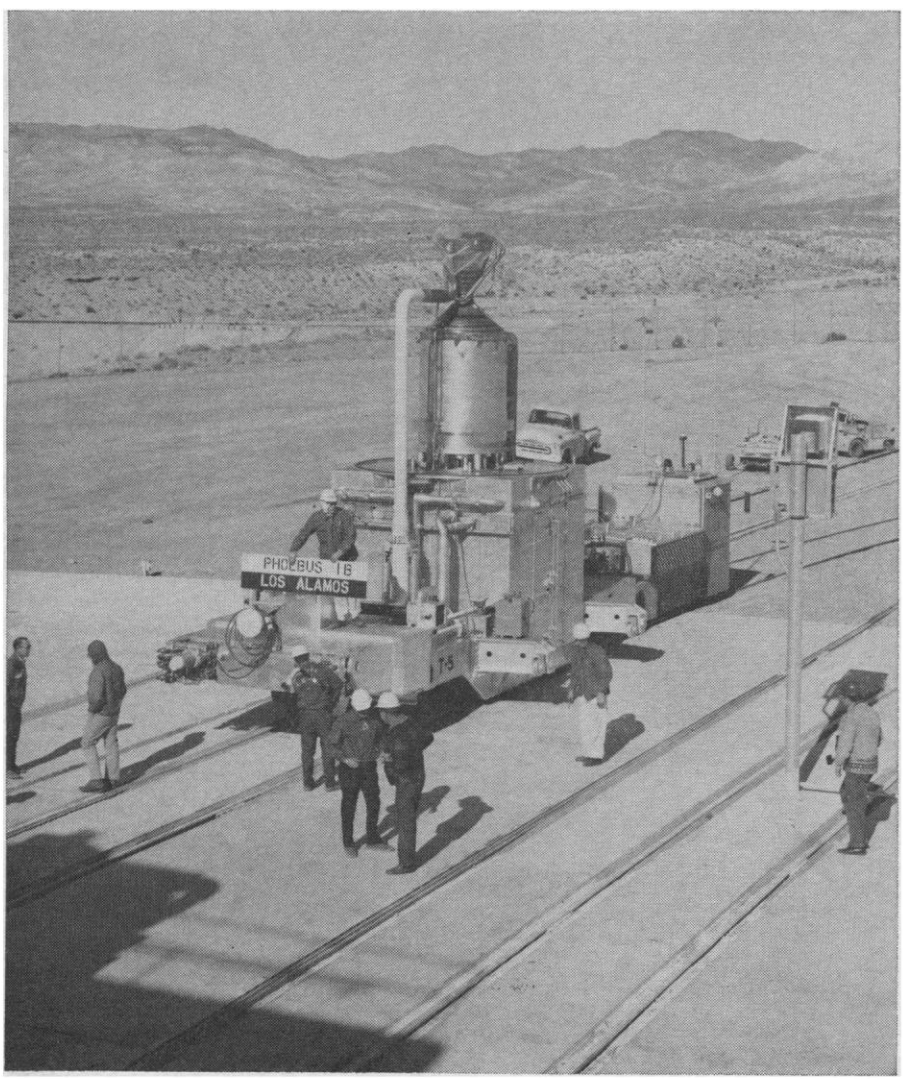

Fig. 3. Reactor Phoebus 1B approaching the test cell.

engine. This latter development had to be canceled later because of funding difficulties.

The first test of the 1000-megawatt Kiwi-B-1 design was performed in December 1961 at reduced power with gaseous hydrogen. All the new reactor features worked well. The first test with liquid hydrogen, in September 1962, was an important one. It laid to rest, once and for all, apprehensions concerning the difficulties associated with two-phase flow. The turbopump and nozzle performed admirably. The reactor core, however, behaved in a way that confirmed our previous suspicions: it wouldn't do, and it proved it wouldn't do in a series of spectacular ejections of white-hot material from the nozzle. Fortunately we had ready for testing another—and, we thought, better—reactor design called Kiwi-B-4, which we favored for NERVA development. This reactor was tested on 30 November 1962. Although test operations were smooth, tell-tale flashes of light in the nozzle exhaust warned us that there was trouble in the reactor core. On disassembly it was discovered that most of the fuel elements had been broken. It looked as though the entire core had experienced severe vibrations—a kind of "flapping." The trouble was soon diagnosed as a faulty design feature which allowed flow-induced fluctuations in pressure. There followed a redesign period in which several cold-flow reactors (reactors containing no uranium in the fuel elements) were tested in Nevada to make sure that our redesign had solved the problem. The final proof came with the Kiwi-B-4D test in May 1964, which was curtailed due to a nozzle failure, and with the tests of Kiwi-B-4E the following August and September. These latter tests were completely successful and demonstrated beyond any doubt that nuclear rocket reactors were feasible. The first WANL reactor, NRX-A2, which was based on the Kiwi-B-4 design, was successfully tested later in the same year. Since that time improvements in fuel elements and changes in details of reactor design have been tested by both LASL (reactors Phoebus 1A and Phoebus 1B) and the NERVA contractors (reactors NRX-A3 through NRX-A6). Of special interest was NRX-A4 (also called EST for Engine System Test), in which for the first time all major engine components were assembled and tested together, although not in flight configuration. The most recent reactor test, that of NRX-A6 last December, established a new record operating time of 60 minutes. Figure 3 shows a typical Phoebus 1/NRX-A reactor mounted on its test cart.

The reactor developmental program has been a clear success, and its success has brought into sharp focus the question of what size engine the Space Nuclear Propulsion Office and its contractors should develop for space application. Nuclear rocket engines can be useful for lunar logistics missions, for unmanned deep-space missions requiring heavy payloads, and for Earth orbital operations of various kinds, but they really come into their own for ambitious manned interplanetary journeys.

A study (*3*) of one such mission (a manned Mars landing expedition) was made which entailed assembly of the vehicle in low Earth orbit (see Fig. 4 for an artist's conception of this operation) and use of a cluster of three or four nuclear engines for the Earth departure phase, another nuclear engine for braking near Mars and placing the vehicle in a Mars orbit, and still another nuclear engine for the return to Earth. For this manned Mars mission, an engine of 200,000-pound (90,600-kilogram) thrust was found to be well suited. The studies did not show a tremendous advantage for any particular thrust; in fact even thrusts as low as 125,000 pounds were not greatly inferior for the Mars mission, particularly if reactor lifetimes could be increased somewhat over the 30 minutes assumed in this study. Nevertheless, the higher-thrust engine seemed a very reasonable choice, since such an engine could also be used for many types of lesser space missions with only a small weight penalty. Therefore a few years ago SNPO agreed that LASL should design and build a 5000-megawatt reactor which would serve as the prototype of the reactor in an engine of 230,000-pound thrust. This 5000-megawatt reactor is called Phoebus 2. When operating at full power it uses liquid hydrogen at the rate of 150 kilo-

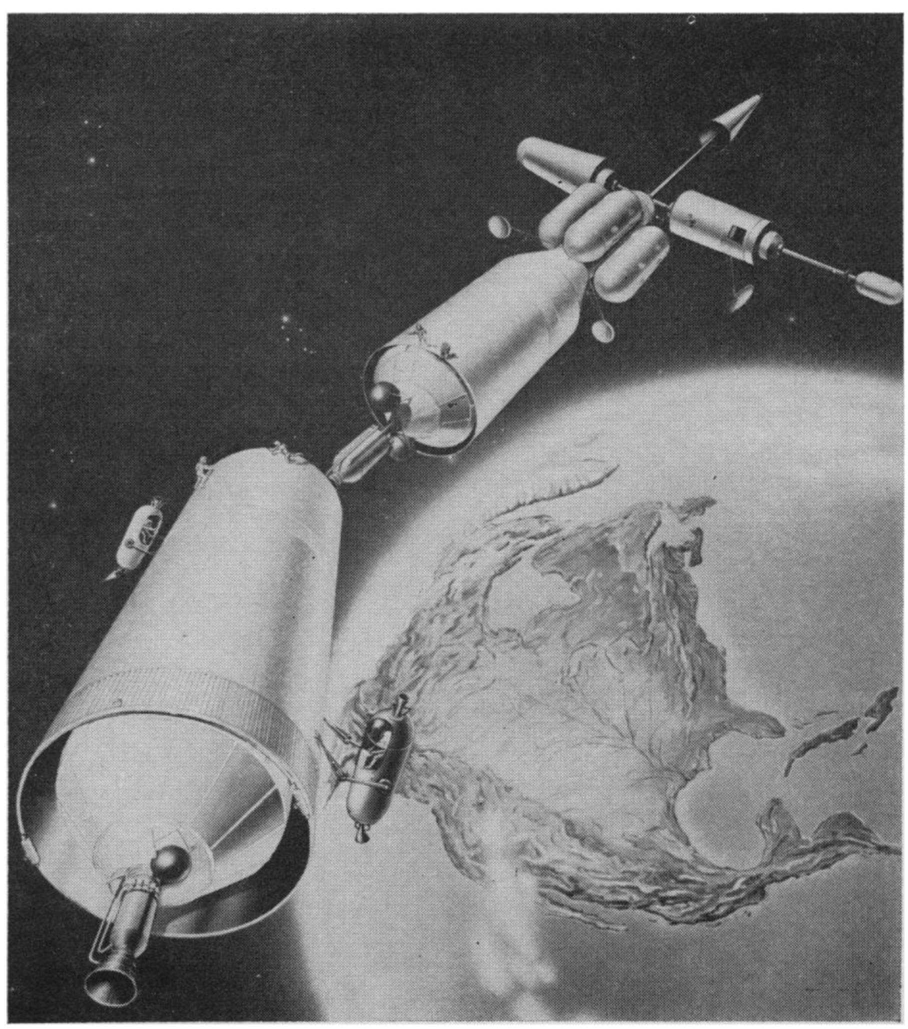

Fig. 4. Artist's conception of assembly, in orbit, of a manned Mars vehicle (*4*).

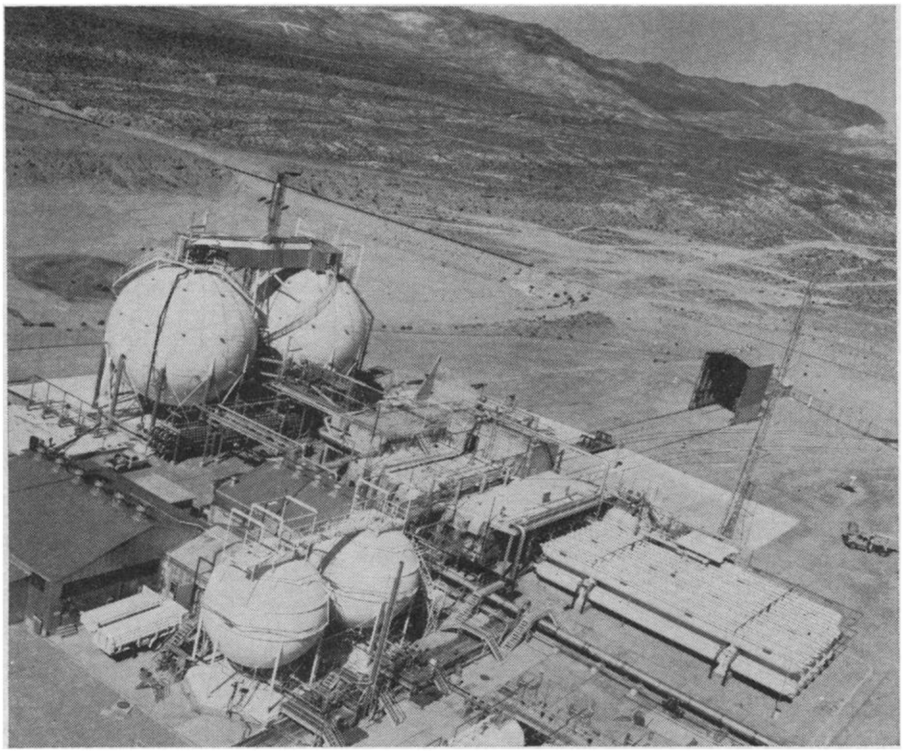

Fig. 5. Overall view of Test Cell C, Nuclear Rocket Development Station, Jackass Flats, Nevada.

grams per second. At the time we decided to go ahead with Phoebus 2 we realized that our test cell facilities at the Nuclear Rocket Development Station (as the site at Jackass Flats was now called) were not capable of testing a 5000-megawatt reactor. For one thing, the dewars at Test Cell C held only 30,000 kilograms of liquid hydrogen, so they could not supply hydrogen for a test of more than a few minutes. Furthermore, the capacity for storing the gaseous hydrogen needed to drive the turbopumps was quite inadequate. The latter problem was solved by the design of a novel heat exchanger in which hot water provided the thermal energy needed to convert liquid hydrogen to lukewarm gaseous hydrogen. Two new dewars, each of 150,000-kilogram capacity, were erected at Test Cell C. (The new dewars are shown in Fig. 5, overshadowing the original, smaller dewars.) All test cell modifications have been completed, the reactor has been assembled, and full power testing is scheduled for May 1968. In some ways the test will be anticlimactic because budget troubles have forced NASA to reconsider the development of an engine of 200,000-pound thrust and to aim instead for the development of one of 75,000-pound thrust. The immediate savings are appreciable, mainly because there already exists at the Nevada site an engine test stand which can be used in testing the smaller engine; the larger engine would require a larger and more expensive test stand. Nevertheless, the experience gained with Phoebus 2 should be very valuable for future work on nuclear rockets.

Present Status

The present situation can be summed up about as follows: Reactor technology is well in hand; what remains to be done in that area is the very important job of optimizing reactor performance. Here materials development is the key. It is not inconceivable that exit-gas temperatures of 3000°K can be achieved for operating times of 30 minutes. Temperatures much above that will be hard to achieve—indeed, 3000°K may elude us. An increase in power density would be useful since it would lead to reduction in reactor weight, but this increase may prove difficult to achieve because Rover reactors are already running at power densities far above those of conventional power reactors. There is also a need to improve the ability to make repeated thermal cycles, because some space missions require reuse of the nuclear engine. The Space Nuclear Propulsion Office, now under the management of Milton Klein, is vigorously pursuing both immediate and future goals. The Los Alamos Scientific Laboratory has the assignment of increasing reactor performance, while the NERVA contractors have that of developing a flyable engine which will incorporate the most advanced concepts of reactor technology. One useful innovation introduced by LASL is the development of a small test-bed reactor called Pewee, with which laboratory improvements can be tested in an actual reactor environment. Pewee is only one-fourth the size of Phoebus 1 or NRX-A and should afford a more economical and faster method of testing than we have had heretofore.

While reactor technology has progressed well, the work leading to the development of a flyable engine has suffered somewhat in financing priorities and is less far advanced. The first realistic engine configuration will be tested sometime this year. The development of a flyable nuclear rocket stage is even farther in the future. So, while much of the basic work has been done, completion of the nuclear rocket program still lies in the years to come. The time scale depends on the degree of financial support given the future NASA–AEC program.

Granted that the straightforward heat exchanger can be developed into a useful engine, the question remains: Is this the only way to use nuclear energy for space propulsion? The answer is, almost certainly, No. The advanced concepts divide into two general classes.

The first we might call high-thrust concepts. In these, high exhaust velocity is achieved in combination with high thrust. The gaseous core reactor is a good example; in principle it is not limited by melting points of materials, but no practical concept has clearly emerged in a decade of study. A quite different scheme is that of using a succession of nuclear explosions to propel a space vehicle (Project Orion); this may seem at first glance even farther removed from practicality, but in many ways it appears easier to describe an experimental program for Project Orion than for the gaseous core nuclear rocket. Orion does, of course, present unique political problems, since the explosive charges are small nuclear bombs.

More immediately practical are concepts of the second class, in which high thrust is sacrificed to gain high exhaust velocity. These low-thrust devices are also often called nuclear-electric drives because, for most of them, the approach is that of converting fission energy to electricity and using the electricity to accelerate charged particles to produce thrust. Invariably the power plants are heavy, the thrust is low, and the resulting vehicle accelerations are very low—less than 0.001*g*. Since the vehicle acceleration is low, the engine operating time has to be long (measurable in months for most missions) if a reasonable velocity and trip time are to be achieved. In order for such a propulsion engine to be attractive, the power in the exhaust jet per kilogram of engine weight should be as high as possible. A specific jet power of 0.05 kilowatt per kilogram will probably be useful, but 0.15 kilowatt per kilogram would be very much better. A lot of effort has been devoted, with a good deal of success, to developing thrust mechanisms such as ion accelerators and plasma accelerators, but the real crux of the problem is the power plant. There are numerous ways to convert heat energy into electrical energy, of which perhaps the most familiar are those based on use of thermodynamic cycles and rotating machinery. Another attractive approach is the direct conversion of fission heat into electricity by means of thermionic cells. The first demonstration in a nuclear reactor of such a device was made at Los Alamos as long ago as 1959. The development of a complete nuclear-electric propulsion system will be difficult and expensive, but if man wants to continue to explore space to the best of his ability, such a development seems inevitable.

References and Notes

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3. P. G. Johnson, *Astronaut. Aeron.* **2**, 22 (Dec. 1964); A. R. Chovit, C. D. Kylstra, R. K. Plebuch, *ibid.* **3**, 36 (June 1965). The June 1965 issue contains several articles on nuclear rockets.
4. I am indebted to the Westinghouse Astronuclear Laboratory for Fig. 4.

Friction of Rubber on Wet Surfaces

Knowledge of the mechanism of friction is important for progress in traffic safety.

E. M. Bevilacqua and E. P. Percarpio

In this article we describe recent progress in understanding friction of rubber on wet surfaces (lubricated friction of rubber) (*1*). When reading titles of articles in journals like *Physical Review Letters,* one sometimes wonders how many physicists riding to work with their heads in the cosmos among quasars and quarks realize that an important unsolved problem of physics travels with them. The control of friction is important in many aspects of life, including, most importantly, riding to work, for the interface between tires and roads is the only connection between vehicle and environment. A quick review of indexes of *Science* for the last two decades reveals only two entries under the heading "Friction." The first (*2*) deals with a simple laboratory device for an elementary mechanics experiment, a kind of experiment from which most scientists of the present generation probably learned most of what they know about friction. The second (*3*) is a book review in which the introductory paragraphs point out the wide range and importance of problems involving friction. Within these two decades there has been a substantial increase in research interest in such problems and, in the area covered by this review, substantial progress.

Lubricated Friction Mechanism

The importance of lubricated friction of rubber has become increasingly obvious in the past decade as driving speeds have increased. As a result, those who begin research on the subject soon drive more slowly when roads are wet, for high friction at the interface between tire and wet road is desired—a respect in which this problem differs from most others involving friction. This is an apparently uncomplicated problem; friction of rubber on wet surfaces, under the most important practical conditions, is determined entirely by energy losses in the rubber that are produced by its deformation by the hard surface over which it slides. The principal research problem is, then, to define how this hysteretic loss is evoked by the hard surface during sliding. It now turns out that knowledge of this mechanism is essential for the practical problems of designing tires and roads.

Because of the way in which friction arises when rubber slides over a hard surface, the structure of that surface determines the absolute friction level. This can be illustrated conveniently by the data of Table 1, assembled from several different experiments.

The data of row 1 in Table 1 show the friction of a standard specimen of rubber on a typical slippery road surface in the absence of ice. When water is substituted for the dilute glycol solution, so that a thin layer of ice is allowed to form, the surface is altered and the friction drops abruptly. Substitution of a piece of smooth wavy glass about as rough as the road causes a slight further drop in friction, showing that the ice did not entirely mask the

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