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NUCLEAR-ROCKET PROPULSION

by Frank E. Rom

Lewis Research Center

Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • NOVEMBER 1968

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ABSTRACT

The three basic types of nuclear-rocket powerplants (solid, liquid, and gas core) are compared. Solid-core systems are expected to have specific impulses of 850 seconds with negligible fuel loss. The liquid-core nuclear rocket will have a uranium loss rate of 0.01 to 0.1 mass unit per mass unit of hydrogen if specific impulses in the range of 1200 to 1500 seconds are desired. The gas-core system will have similar loss rates of uranium but will produce specific impulses in the range of 1500 to 2500 seconds.

NUCLEAR-ROCKET PROPULSION*

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Lewis Research Center

SUMMARY

The three basic types of nuclear powerplants (solid, liquid, and gas core) are compared on the bases of performance potential and the status of current technology. The solid-core systems are expected to have impulses in the range of 850 seconds, any thrust level (as long as it is greater than 10 000 lb (44 480 N)), and thrust-to-engine-weight ratios of 2 to 20 pounds per pound (19.7 to 197 N/kg). There is negligible or no fuel loss from the solid-core system. The solid-core system, of course, has had the most work done on it. Large-scale tests have been performed on a breadboard engine that has produced specific impulses greater than 700 seconds at thrust levels of about 50 000 pounds (222 000 N).

The liquid-core reactor would be interesting in the specific impulse range of 1200 to 1500 seconds. Again, any thrust level can be obtained depending on how big or small the reactor is made. The thrust-to-engine weight ratio for these systems would be in the range of 1 to 10. The discouraging feature of the liquid-core system is the high fuel-loss ratio anticipated. Values of 0.01 to 0.1 pound (0.00454 to 0.0454 kg) or uranium loss per pound (0.454 kg) of hydrogen are expected, if impulses in the range of 1200 to 1500 seconds are desired.

The gas-core reactor shows specific impulses in the range of 1500 to 2500 seconds. The thrust levels should be at least as high as the weight so that the thrust-to-weight ratio does not go below 1. Because the engine weight is not expected to be under 100 000 pounds (444 800 N), thrust levels higher than 100 000 pounds (448 000 N) are of interst. The thrust-to-engine weights, in that case, would run from 1 to 20 pounds per pound (9.8 to 19.7 kg). Gas-core reactors tend to be very large, and can have high thrust-to-weight ratios. As in the case of the liquid-core system, the fuel loss that will be attendant with gas cores as envisioned today will be rather high. The loss rates will be 0.01 to 0.1 pound of uranium (0.00454 to 0.0454 kg) for each pound (0.454 kg) of hydrogen.

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*Presented at the Conference on NonChemical Space Propulsion, January 12, 1967, at the Catholic University of America, Washington, D. C.

INTRODUCTION

The nuclear-rocket engine appears to be a major contender for the propulsion system of manned interplanetary space vehicles. There are three basic types of nuclear rockets (solid, liquid, and gas cores) that can be considered for such applications. Examination of their characteristics, including problems and performance potential when compared with conventional chemical-rocket engines, leads to some interesting conclusions concerning the prospects for their future development.

The objective of all rocket engines, chemical or nuclear, is to produce the highest possible specific impulse (thrust per propellant flow rate) so that the amount of propellant required to accomplish a mission is minimized. The well-known principle for obtaining high specific impulse is to heat the propellant with the lowest molecular weight to the highest possible temperature. The best chemical rockets burn a low-molecular-weight propellant like hydrogen with oxygen or fluorine to produce the lowest-molecular-weight gas at a high temperature (see fig. 1). The combustion products are discharged from the combustion chamber through a nozzle to produce thrust. In the case of the hydrogen-oxygen chemical rocket, the exhaust temperature is about 6000° R (3330 K), and the molecular weight of the propellant is about 8. The resultant specific impulse (pounds of thrust per pound per second) of the best chemical systems is limited to about 450 seconds. The specific impulse is limited by the energy available from the chemical combustion of propellants.

The use of nuclear energy offers a way of heating hydrogen without increasing its molecular weight. In a solid-core nuclear rocket, for example, fissionable material is contained within solid materials arranged in such a way as to provide heat-transfer surfaces for heating hydrogen. The hydrogen, which flows over these surfaces, can be heated to any temperature desired, limited only by the melting point or the strength of high-

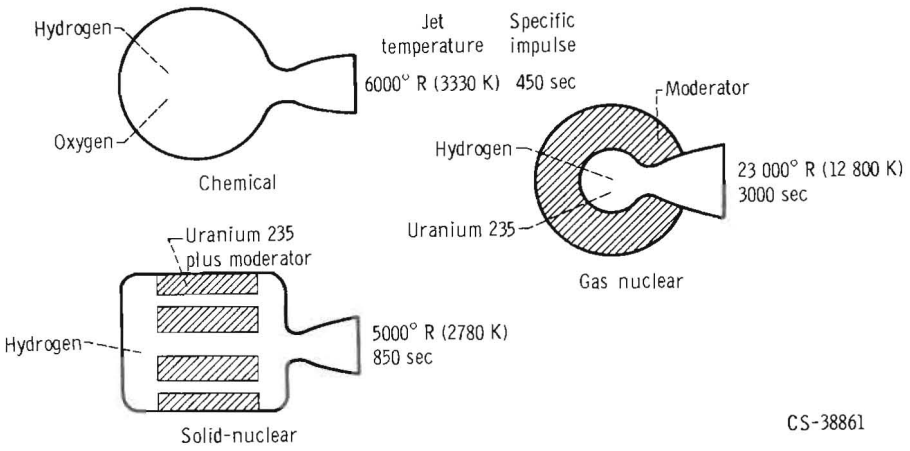


Figure 1. - Chemical and nuclear rocket engines.

temperature materials. It should be possible to heat hydrogen to about 5000° R (2780 K) in solid-core reactors that limit the specific impulse to about 850 seconds.

Liquid-core nuclear rockets are also considered. The hydrogen, in this case, would be heated by a fissioning liquid material. The hydrogen temperature would only be limited by the boiling point or by excessive vaporization rate of the liquid fuel material.

Because fission produces of the order of a million times the energy as chemical combustion, there is no basic reason why much higher temperatures could not be attained. Temperatures of the order of millions of degrees Rankine (Kelvin) are produced, for example, in atomic explosions. The materials, of course, are all gaseous at these temperatures. In a gas-core nuclear rocket fissionable material, as uranium 235, is caused to fission and gasify within a cavity that is very similar to a chemical-rocket combustion chamber. The propellant, hydrogen, is heated by thermal radiation from or mixing with the hot fissioning gas. The specific impulse of gas-core engines can be as high as 3000 seconds. Typically, the fissioning fuel would operate at a temperature of about 100 000° R (55 600 K) to produce a jet of about 23 000° R (12 800 K).

Each nuclear-rocket powerplant is discussed in more detail in the sections that follow. The characteristics, performance potential, and problems of solid-, liquid-, and gas-core nuclear rockets are considered in turn.

SOLID-CORE NUCLEAR ROCKETS

The first system to be discussed, the solid-core heat-transfer type of nuclear rocket, is shown in figure 2. The hydrogen is heated as it flows through a reactor core, which

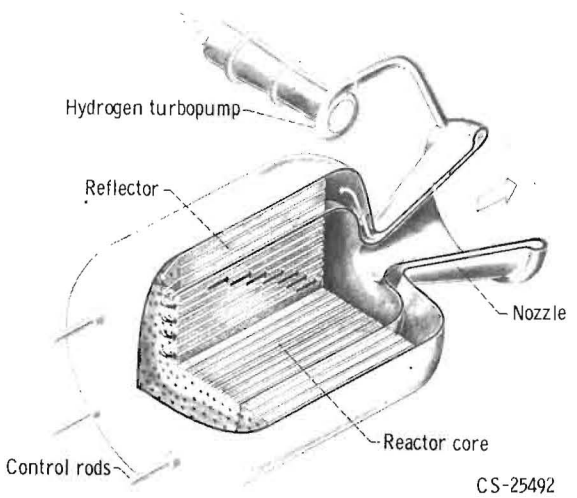


Figure 2. - Solid-core heat-transfer nuclear rocket.

contains the fissioning material. The hot hydrogen is ejected through a nozzle to produce thrust. Hydrogen is supplied by means of a liquid-hydrogen turbopump. The hydrogen is used to cool the nozzle and the reflector or any other parts of the reactor or structure that require cooling. Reactor control is provided by reactor control rods or drums.

Types of Solid-Core Nuclear Rockets

Figure 3 shows two solid-core reactor configurations that might be considered for a solid-core nuclear rocket: the homogeneous reactor and the heterogeneous reactor.

In the homogeneous reactor the fuel and moderator are intimately mixed so that the fission heat is generated in the mixture of the two materials. Heat-transfer surface is provided by passages through the solid core for the hydrogen propellant. In the case of the heterogeneous reactor the fuel bearing material (fuel element) is separated from the moderator material. The fuel elements are shown schematically in isolated zones surrounded by moderating material.

In the case of the homogeneous reactor, the moderator must be a high-temperature material as well as a material that has good moderator properties. This dual requirement limits the choice of materials available for such a reactor. The virtue of a heterogeneous reactor is that the fuel may be contained in the best high-temperature materials, while the moderator can be made of the best moderator materials. The moderator can be a high- or low-temperature material because it can be separately cooled to any desired temperature. Another type of solid-core reactor that can be considered is the fast reactor. It is a homogeneous reactor with no moderator material. The only materials in the core in this case are fuel-bearing high-temperature core materials. The elimination of the moderating material eliminates the limitations imposed by the dual require-

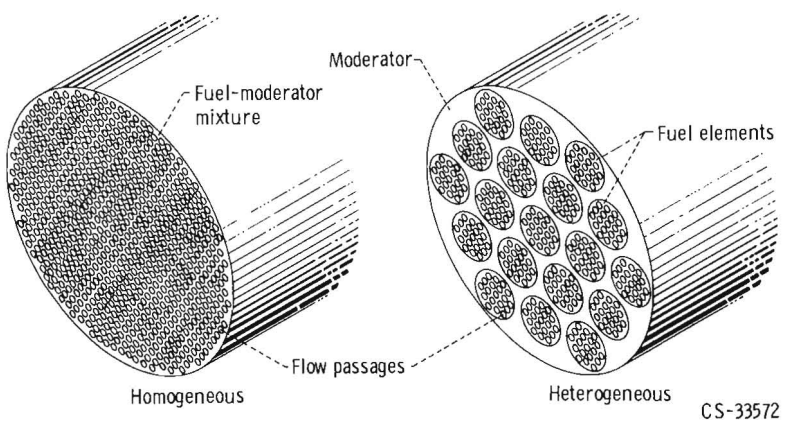


Figure 3. - Solid-core reactor configurations.

ment of moderators that have good neutron moderation and high-temperature capability. A major disadvantage is that more fissionable material is required for this reactor which adversely affects the high-temperature properties of the core material.

In summary, solid-core reactors can be constructed in various ways but they are limited in operating temperature by the materials of which they are constructed.

Fuel Elements for Solid Core Reactors

Figure 4 shows the various forms that the fuel-element portion of a reactor may take. The fuel (fissionable material) is contained in high-temperature materials that can be formed, for example, into flat plates, concentric rings, tubes, matrices with coolant passages, and honeycombs.

There are as many varieties of fuel-element designs as there are designers. Each of these fuel-element designs has certain advantages and disadvantages which are determined in the course of the development of the reactor. Some of the designs are advantageous from the heat transfer standpoint but represent difficult fabrication problems. Some are simple to fabricate but may be less than optimum as far as heat transfer or core structure is concerned.

Some of the more desirable fuel-element characteristics are listed as follows:

(1) High operating temperature (~5500^{o} R) (~3060 K)

(a) Low evaporation rate

(b) Adequate strength

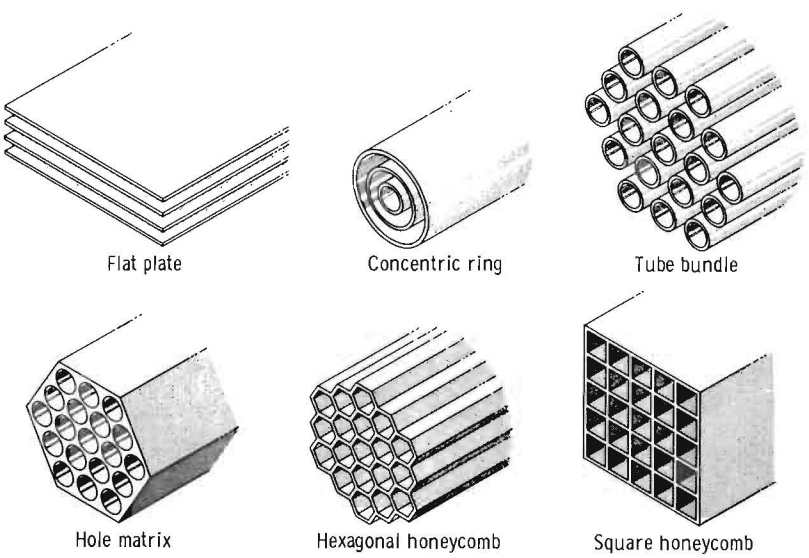


Figure 4. - Solid-core nuclear-rocket fuel element designs.

(2) Compatibility with fissionable material
(3) Compatibility with hydrogen
(4) Recyclability
(5) Low neutron absorption cross section
(6) Fabricability

First of all, in a solid-core reactor hydrogen should be heated to as high a temperature as possible. Therefore, fuel elements that are capable of operating at the highest possible temperature (of the order of 5500° R (3060 K)) are desired. At these high temperatures the evaporation rate should be low enough so that the reactor can last for the required operating time. Adequate strength materials that will withstand the high temperature are required. The fuel-element structural material must be chemically compatible with the fissionable material to prevent chemical reactions or solutions that destroy the high-temperature properties of the fuel element or permit the loss of fuel. Because the fuel element heats the hydrogen, the fuel-element material must be chemically compatible with hydrogen. In addition, the presence of hydrogen, which can diffuse through the fuel-element materials, must not affect the compatibility of the fissionable material with the material that contains it. To start and stop the reactor, the fuel element must be recyclable. It must be capable of operating at high temperatures at high-power densities and of being quickly cooled or heated without destruction due to thermal stresses or shocks. In the case of thermal neutron spectrum reactors, in particular, the fuel element must have desirable nuclear properties; for example, a low neutron cross section. It should not parasitically absorb neutrons that would normally be available for fissioning uranium. And, of course, the fuel element must be made of materials that can be fabricated. It is beyond the scope of this paper to discuss all these characteristics in detail (See ref. 1 for further discussion).

The high-temperature operating capability is discussed further because it is the most important single requirement. Table I shows the melting points of typical fuels, and metals or ceramics that might be used as fuel-bearing materials. It would be most desirable to use uranium metal as the fissionable material because it has the highest density and it would, therefore, occupy the least volume within the fuel-bearing material. However, the melting point of uranium metal is only 2530° R (1405 K) compared with the 5500° R (3060 K) temperature that is desired. Of the fuel materials, uranium nitride (UN) has the highest melting point (5690° R (3160 K)). Unfortunately, uranium nitride decomposes unless a nitrogen atmosphere is supplied; therefore, its use must be restricted to special cases where this nitrogen atmosphere can be provided. Uranium dioxide (UO_2) has the next highest melting point (5535° R (3070 K)). Uranium carbide (UC) has a higher uranium density because there is only one atom diluting the uranium compared with uranium dioxide where there are two atoms diluting the uranium. Unfortunately, the melting point of uranium carbide is considerably lower than uranium dioxide,

TABLE I. - MELTING POINTS OF SOLID-CORE

REACTOR FUEL-ELEMENT MATERIALS

Type of material	Fuel-element materials	Temperature	
		^{o}R	K
Fuels	Uranium nitride[a]	5690	3160
	Uranium dioxide	5535	3073
	Uranium carbide	4810	2670
	Uranium	2530	1408
Metallic refractories	Tungsten	6580	3655
	Rhenium	6200	3445
	Tantalum	5890	3273
	Molybdenum	5170	2872
Nonmetallic refractories	Hafnium carbide	7490	4161
	Tantalum carbide	7480	4157
	Carbon[b]	7190	3995
	Niobium carbide	6790	3495
	Zirconium carbide	6210	3450

[a]Decomposes.
[b]Sublimes.

and, unless provisions can be made to accommodate molten fuel, it would be disadvantageous to use uranium carbide. Uranium carbide and uranium nitride both have the advantage of having a relatively high thermal conductivity compared with uranium dioxide, which is important for fuel-element designs that utilize relatively large thicknesses of fuel. There are many considerations in the selection of a fuel material, which depend very much on the application or the particular design.

The choice of the proper fuel-bearing material is just as complex. Tungsten is the most refractory of any of the metals with a melting point of 6580^{o} F (3660 K). Rhenium and tantalum have lower melting points and high neutron-absorption properties which make make them less desirable than tungsten. Molybdenum has a considerably lower melting point than tungsten, and its use would be limited. The nonmetallic refractory materials have the highest known melting points of any other materials. Hafnium carbide and tantalum carbide have the highest known melting points of the ceramics. Unfortunately, these carbides are unstable; that is, they tend to lose carbon at high temperature, and, in addition, in the presence of hydrogen they are reduced. Carbon sublimes at 7160^{o} R (3980 K) and is being seriously considered as a nuclear-rocket material because it is both a moderator and a high-temperature material; however, carbon reacts very strongly with hydrogen. A coating must, therefore, be used to prevent the carbon from reacting with hydrogen if it is to be used in a nuclear rocket. Also shown are niobium carbide and zir-

conium carbide with melting points of 6790° and 6210° R (3770 and 3450 K), respectively. As contrasted to hafnium and tantalum carbide, they are low-neutron-absorbing materials, but, their melting points are considerably lower than hafnium and tantalum carbide.

Another important consideration of high-temperature materials is the rate at which they evaporate at high temperatures. Figure 5 shows the vaporization rate of high-temperature materials as a function of temperature. The top curve is uranium oxide which has the highest vaporization rate of all the materials shown. The other fuel-bearing material shown is uranium carbide, which has about a two order of magnitude less vaporization rate than uranium dioxide. The melting point that is represented by the tick at the end of the vaporization curves is almost 1000° R (556 K) less. Carbon has a high vaporization rate compared with niobium carbide and tungsten. At 5500° R (3060 K) carbon has about three orders of magnitude and niobium carbide has about a one order magnitude greater rate of vaporization than tungsten. Tungsten has the lowest vaporization rate of all materials.

Figure 5 shows that it would not be practical to make a reactor out of plain uranium dioxide because of its excessive vaporization rate. There are, of course, many other reasons why uranium dioxide could not be used as a fuel material, but this feature alone is sufficient to prohibit it use. In order to reduce the vaporization rate, the uranium dioxide should be completely contained within a fuel-element material that has a much lower vaporization rate and that is compatible with hydrogen. An obvious selection for

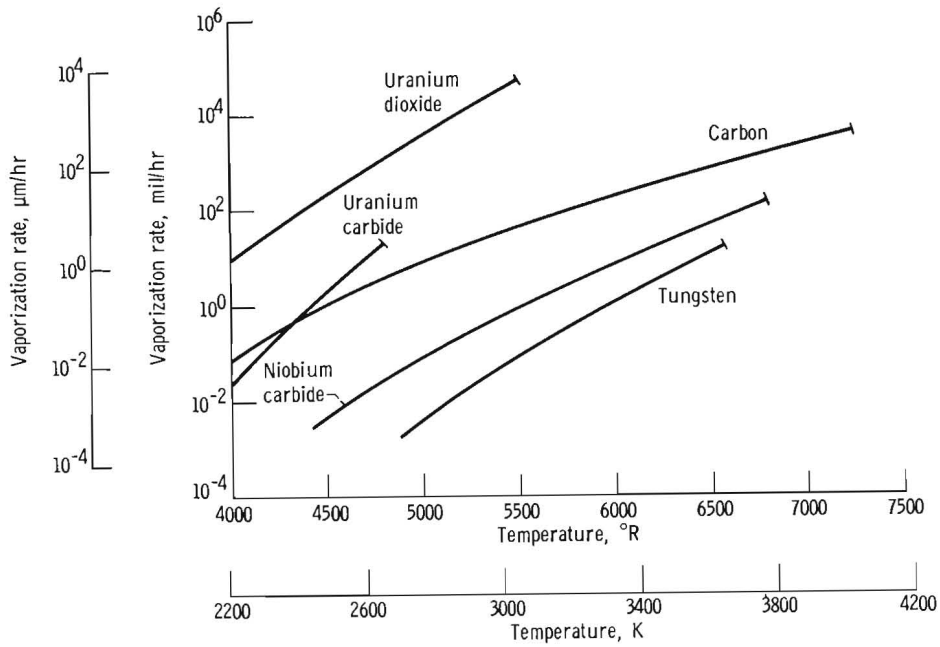
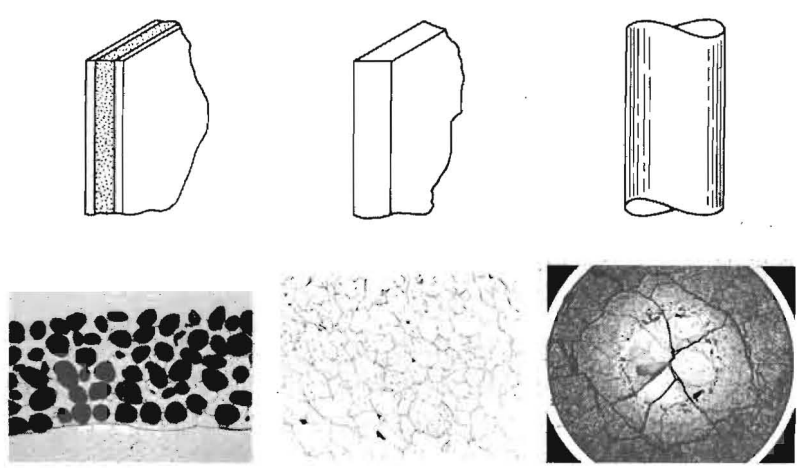


Figure 5. - Vaporization rate of some solid-core nuclear-rocket materials.

the fuel element would seem to be uranium dioxide encapsulated within tungsten, inasmuch as tungsten has the lowest vaporization rate of all materials and also has a high melting point. If we wish to use carbon as a fuel-element material, uranium dioxide fuel could not be used because it would be converted to uranium carbide in the presence of carbon. Carbon or graphite elements would therefore use uranium carbide as a fuel material. Because carbon is attacked by hydrogen chemically, the carbon must be protected. A good protecting material is niobium carbide because it would be fairly compatible with carbon. With these data, we are logically drawn to two types of fuel elements: one is a tungsten fuel element containing particles of uranium dioxide, and the other is a graphite element containing uranium carbide and clad with niobium carbide on the surfaces exposed to hydrogen.

Figure 6 shows some of the basic types of fuel-element materials. In cermets, the uranium bearing compound (like uranium dioxide) is dispersed in a matrix of a material such as tungsten. This matrix, containing the uranium dioxide, is clad with pure tungsten so that uranium dioxide is not in direct contact with the hydrogen through the reactor. This will minimize any reaction that would occur between uranium dioxide and hydrogen and also prevent the loss of uranium dioxide by vaporization. Another type of fuel element is the solid-solution element. For example, uranium carbide could be dissolved in niobium carbide to make a fuel element. A third type of fuel element is the bulk fuel pin. In this case a tube of refractory materials such as tungsten is filled with the uranium compound such as uranium dioxide.

The fuel elements described previously (fig. 4) could be fabricated from basic materials of this type. For example, plate or concentric-ring elements could be fabricated from cermet plates. Pin fuel elements, where clusters of fuel pins are held together while the coolant flows over the outside of the pins, could be formed by the bulk fuel pin



Cermet Solid solution Bulk fuel

Figure 6. - Basic fuel-element types. CS-40150

shown on the right of figure 4. Only the imagination of the designer limits the configurations that are possible with these basic fuel-element types.

Current Graphite Reactor Program

There is currently an active NASA-AEC solid-core nuclear rocket program called Rover. The program began in 1955 at the Los Alamos Scientific Laboratory of the AEC. In 1958, a joint NASA-AEC effort was initiated to conduct the Nation's nuclear-rocket proactivity. The work at Los Alamos led to the first reactor test in 1959 of the Kiwi-A reactor which was designed for 100 megawatts of thermal energy. The Kiwi reactors are research and development reactors named after the flightless kiwi bird.

The tests on the Kiwi-A series of reactors was followed by a Kiwi-B series, which was designed to operate at 1100 megawatts. The tests of the Kiwi-B4A reactor of November, 1962, produced excessive fuel-element damage that occurred because of a pressure and flow induced vibration problem. During 1963 component and flow tests were conducted to simulate the operating conditions that occur in the Kiwi-B type reactors. These laboratory tests determined the cause of the difficulty, and the power testing was then resumed in May, 1964. Since May, 1964, seven Kiwi and NERVA reactors and one breadboard engine system have been tested. NERVA stands for nuclear engine for rocket vehicle application. All these reactors have the same basic design. They are made up of clusters of graphite fuel elements through which the hydrogen propellant or coolant is passed. The fissionable material in the graphite fuel elements is in the form of particles of uranium carbide coated with pyrolytic carbon. The flow passages in the fuel elements are coated with niobium carbide to protect the graphite from the corrosive effect of the hydrogen propellant. As shown in figure 7 the reactors are tested in a vertical upfiring position. The propellants and instrumentation are supplied from a shielded blockhouse on the left side of the picture (fig. 7). The hydrogen is exhausted vertically upward to minimize the problem of handling high-temperature gaseous hydrogen. An important point is that several reactors have been restarted and run several times. For example, the Kiwi-B4E reactor was tested twice, the NRX-A2 was tested twice, the NRX-A3 reactor was tested three times at full power, and the breadboard engine NRX-EST (standing for Engine System Test) was restarted many times during its test series. All these reactor tests demonstrated that the vibration problem encountered in Kiwi-B4A have been solved. The Kiwi-TNT test gave data on the release of radioactivity during the most serious accident that could be produced. The total operating time at full power for all the reactors is approximately 2 hours at this time. The Phoebus tests showed the feasibility of operating at higher power density.

Figure 7. - Graphic reactor and engine system.

The most significant test series was the tests on the NRX-EST breadboard reactor. This reactor was started and shutdown 10 times. Of the 10 tests, four were run for a total of 28 minutes at full power.[1] The maximum exhaust temperature achieved during these tests was 4170° R (2320 K). The tests proved that the system could start on its own power (bootstrapping). In all the starts the engine used reactor heat and the energy available in the pressurized propellant tank to provide the starting energy. No external sources of pumping energy was provided. The reactor startups were completely automatic and indicated that the time to increase power from about 1 megawatt to full power kept to less than a minute.

Figure 8 shows performance anticipated for the NERVA II engine.[2] The thrust level is in the range of 200 000 to 250 000 pounds (880 000 to 1 110 000 N). The power level is about 5000 megawatts. The chamber temperature is 4500° R (2500 K), which would give a specific impulse of 825 seconds.

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[1]Since the original presentation of this material in 1967, the NRX-A6 reactor has been tested for 60 min at full power, and the Phoebus 2A reactor has been operated for 12 min at a power level above 4000 mW.

[2]The NERVA II engine development program has been dropped in favor of a 1500-mW NERVA engine with a thrust level of about 75 000 lb (333 600 N).

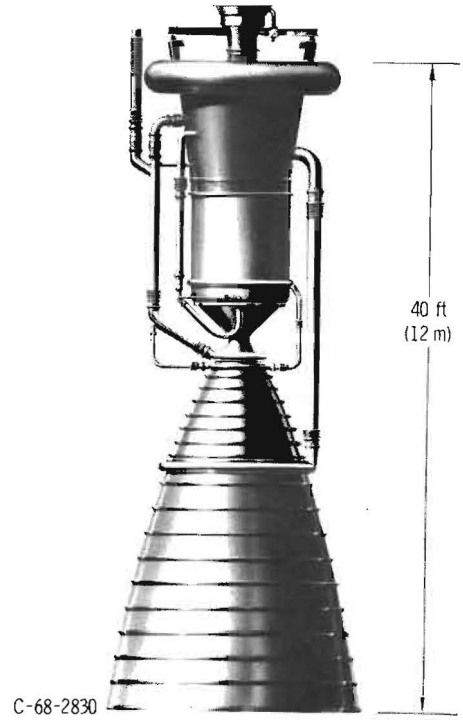


Figure 8. - NERVA engine. Thrust, 200 000 to 250 000 pounds (8 900 000 to 11 100 000 N); power, 4000 to 5000 megawatts; chamber temperature, 4500° R (2500 K); specific impulse, 825 seconds.

Tungsten Reactors

Although the main effort in our National nuclear-rocket program has been on graphite reactors, other reactor types have received some attention. In particular, the Argonne National Laboratory has studied a tungsten - uranium dioxide fast neutron reactor concept, and the Lewis Research Center has investigated a tungsten - uranium dioxide water moderated concept.

Following the earlier discussions on the materials available for nuclear rockets, it is apparent that tungsten - uranium dioxide represents a material combination that would have substantial promise for nuclear rockets. At the time of the initiation of the National nuclear rocket program, very little was known about the properties of tungsten as a fuel-element material. There was a lack of data on its high-temperature properties and little experience on fabrication of tungsten and tungsten - uranium dioxide fuel-element configurations. The decision was, therefore, made to go ahead with graphite as the basic nuclear-rocket material because of the large amount of experience with it. There did exist, however, concurrent small-scale efforts on the tungsten reactors mentioned previously. These studies concluded that tungsten - uranium dioxide may offer the potential of longer life and better recyclability and restart capability than graphite reac-

tors. However, it was anticipated that the achievable hydrogen temperatures or specific impulses would not be greatly different from the graphite system when it is assumed that the problems of coating graphite could be solved. The studies at Lewis Research Center indicated that the tungsten - uranium dioxide fueled reactor using water as a moderator appeared to offer very good potential for a developable long-lived, and recyclable high-temperature nuclear rocket.

Figure 9 shows a photograph of a model of a tungsten-water-moderated nuclear-rocket. The reactor shown was designed for a reactor power of 300 megawatts or 15 000 pounds (67 000 N) of thrust. The use of water, which is one of the best neutron moderators, makes it possible to design small lightweight reactors, such as shown in the figure. In this concept, water-cooled aluminum tubes house the tungsten fuel elements. The aluminum tubes pass through a tank of water. The water circulates along the outside of the aluminum tubes. The fuel elements are located within and are insulated from the aluminum tubes by means of a small stagnant hydrogen-gas filled gap. The water moderator is pumped through the core region and is then cooled by means of water to cold hydrogen heat exchangers to remove the gamma and neutron heat energy that is deposited in the water.

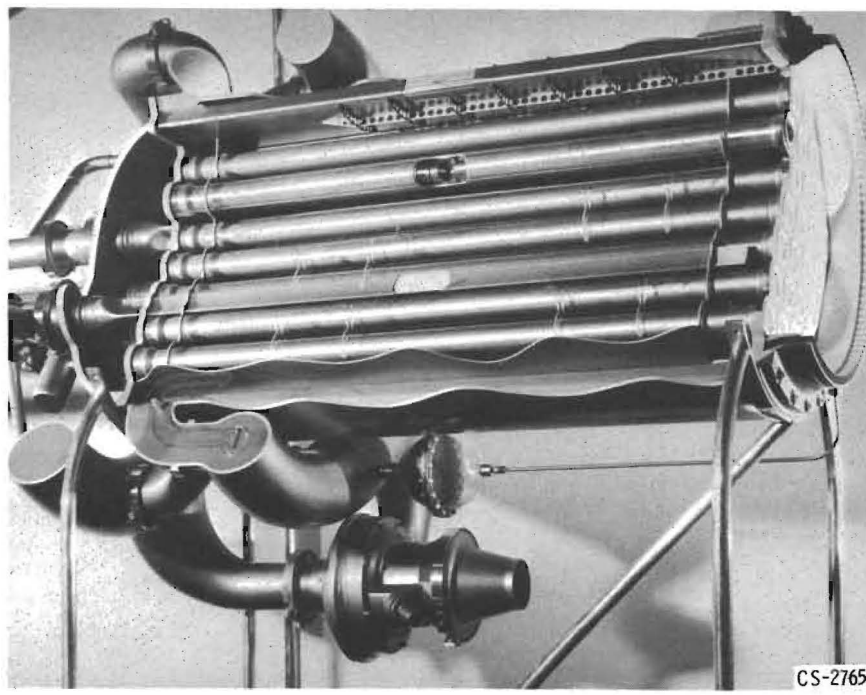


Figure 9. - Water-moderated tungsten-uranium dioxide nuclear-rocket reactor.

Solid-Core Nuclear-Rocket Performance

Estimates of the weight of nuclear rocket powerplants have been made. The approximate thrust-to-engine-weight ratios for solid-core nuclear rockets are shown in figure 10. This ratio is plotted as a function of thrust level for tungsten-water-moderated reactors, a tungsten fast-neutron reactor, and a graphite reactor. Because of the superior moderating properties of water, the engine weight for tungsten-water-moderated reactors is lower particularly at the smaller reactor sizes, which leads to the relatively high thrust-to-engine-weight ratio shown. At a thrust level of 50 000 pounds (222 000 N) the graphite reactor would weigh about twice as much as a tungsten reactor; therefore, producing a thrust-to-weight ratio of approximately one-half that for the tungsten-water-moderated uranium dioxide reactor. However, as the thrust levels increase, the weight of the reactor is determined more by the fuel elements than by the moderator. For all three reactor systems, at thrusts of 200 000 pounds (880 000 N) and higher, the thrust-to-weight ratios are in the range of 14 to 20 pounds thrust per pound. Because they are calculations, these thrust-per-engine weights are anticipated to be the best that could be obtained. The first powerplants built will no doubt fall in the lower range, perhaps lower than any value shown on this curve. With further development it would be anticipated that thrust-to-weight ratio would approach 20. In summary then, solid-core nuclear rockets would be expected to produce specific impulses in the range of 800 to 900 seconds and thrust-to-

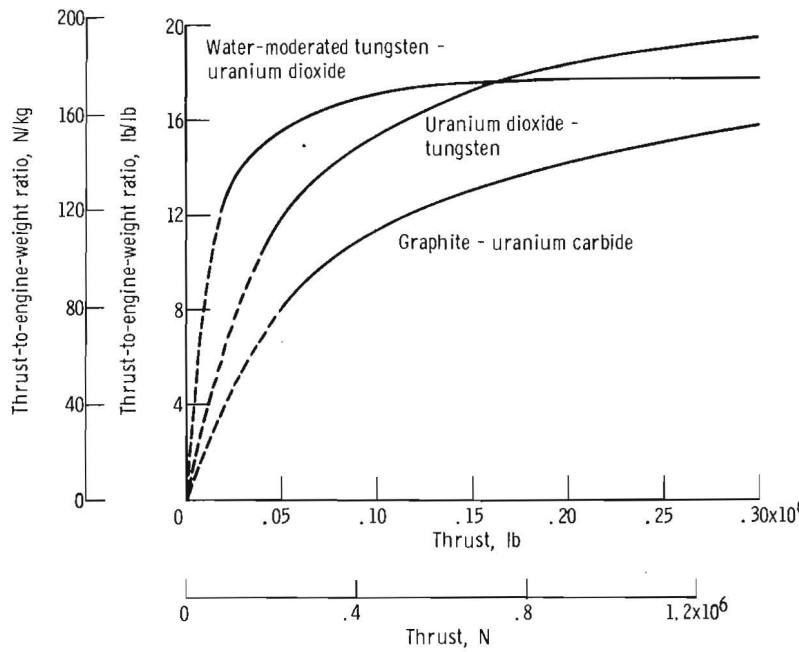


Figure 10. - Approximate thrust-to-engine-weight ratios for solid-core nuclear rockets.

engine weight ratios of from 10 to 20 pounds force per pound mass (9.8 to 19.6 N/kg).

All work has been stopped on tungsten nuclear-rocket reactors. This has been done in the interest of having at least one reactor developed within the funding limitations imposed.

LIQUID-CORE NUCLEAR ROCKETS

Liquid-core nuclear rockets represent the next step in temperature beyond solid-core systems. There are three basic types of liquid-core nuclear rockets that have been proposed: (1) the bubble-through reactor, (2) the radiation reactor, and (3) particle or droplet reactor.

Bubble-Through Liquid Core

Figure 11 shows the first of these - the bubble-through liquid-core system. The basic feature of this system is that the reactor core is rotated at high speed so as to maintain a layer of liquid fuel around the cylindrical surface of the core. As the hydrogen is bubbled through this liquid fuel, it is heated to the temperature of the liquid fuel. The hot hydrogen then passes through the nozzle to produce a thrust. The basic limitation of this system is that the hydrogen would be saturated with the liquid fuel that it passes through. These vapors would be carried through the nozzle and lost. The higher the temperature, the greater would be the loss of fuel.

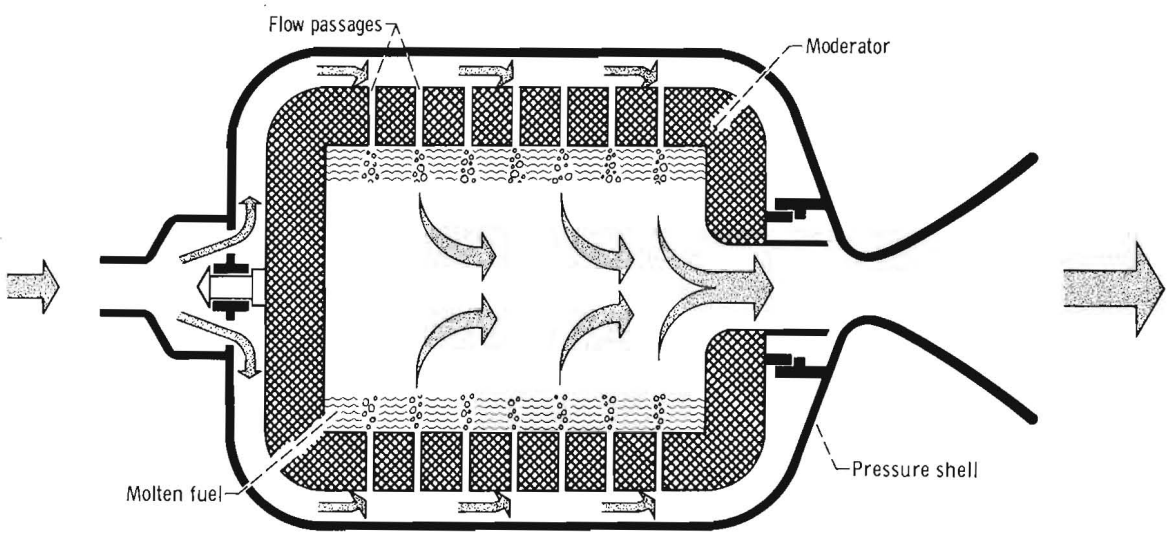


Figure 11. - Bubble-through liquid-core reactor.

Another serious problem with this system is that the high-density liquid in the high-gravity field produced by the rotation would tend to flow back down through the flow passages through which the hydrogen flows. There is serious question whether it is possible to design gas passages that would prevent the flow of the liquid back down through the passages. The mechanics of multiple cylinders, bearings, dynamic balance, fuel makeup systems, starting and stopping, and other similar design problems are expected to be formidable.

Radiation Liquid Core

Another type of liquid core is the radiation liquid core shown in figure 12. It attempts to minimize the problem of the vapor loss as described for the bubble-through reactor. In this reactor the hydrogen is flowed axially down the center of rotating tubes. Fissioning liquid fuel is held on the walls by centrifugal forces. The hydrogen is heated by radiation from the liquid. The hydrogen in this case would not be saturated with the fuel material. The actual concentration of the fuel material would depend on the length-to-diameter ratio of the tube and the mass-transfer characteristics of the rotating tube with flowing hydrogen. In order that the hydrogen absorb heat by radiation, the hydrogen must be seeded with radiation-absorbing particles. In the figure 12 several tubes would be arranged within a moderating material to make up a complete reactor. A potential problem area of this concept results from the fact that the liquid must operate at a higher temperature than in the previous system to produce the same exhaust temperature. This results from the fact that the heat is transferred by radiation from the surface to the gas.

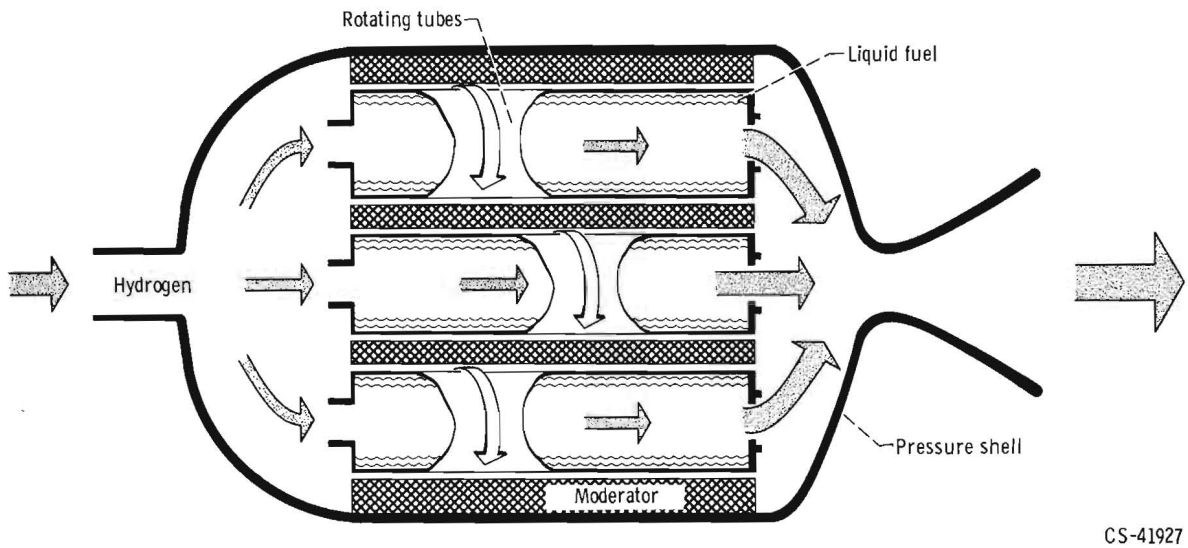


Figure 12. - Radiation liquid-core reactor.

In addition there is a potential problem of compatibility between the liquid and the containing wall material. Although this problem also exists in the bubble-through reactor, it may be more severe in the radiation reactor because the temperature of the liquid would be higher than for the bubble-through system. The mechanical problems of this reactor would be similar to the bubble-through type.

Particle or Droplet Reactor

A third type of liquid-core reactor, the particle or droplet reactor, is shown in figure 13. The essential feature of this reactor is that hydrogen, introduced at a fairly high velocity at the bottom, entrains fuel particles or liquid droplets, conveys them toward the top of the reactor, and then, because of the reduction in velocity of the propellant, the particles fall back down along the sides of the chamber toward the bottom where they are then reetrained. The fuel particles or liquid droplets are continuously recirculated in the activity zone of the reactor. The attempt here is to eliminate the problem of containing

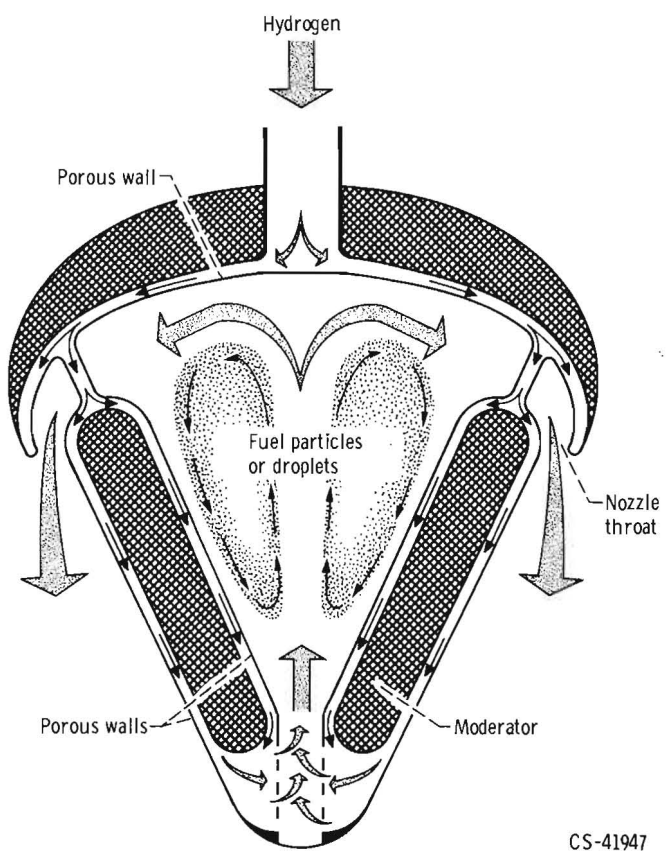


Figure 13. - Particle or droplet liquid-core reactor.

high-temperature liquid against a solid wall. In the particular arrangement shown in figure 13, the heated hydrogen, devoid of the fuel particles or droplets, passes through an annular plug nozzle. The nozzle is an external expansion nozzle formed by the outer walls of the reactor. All the walls of the reactor, external and internal, that are close to high-temperature gases are cooled either by means of porous walls or film cooling. The hydrogen enters this system from the top and flows through the passages behind the porous or film cooled walls. The hydrogen is also used to cool both the upper and lower portions of the moderator. The hydrogen that does not pass through the porous walls is collected in the plenum at the lower end of the reactor where it is introduced into the bottom of the core. It then entrains and recirculates the fuel particles or droplets. It would be anticipated that the temperatures attainable in this type of reactor would be similar to the bubble-through reactor and that the hydrogen would tend to be saturated with the fuel material. The chief advantage of this type of reactor is that it minimizes the containment problem.

Vaporization Problem

In all the liquid reactor systems, the problem of fuel loss due to the vaporization of the fuel material limits the specific impulse available. The limitation in specific impulse occurs because of the increase in the molecular weight caused by the presence of the heavy heavy metal vapors. In addition, excessive loss of fuel due to vaporization causes the propulsion system to become economically unfeasible.

Figure 14 shows the vapor pressure of carbides as a function of temperature. The vapor pressure is plotted as a function of temperature. The figure shows that uranium carbide, representing the fuel material that has the lowest vapor pressure, still has a much higher vapor pressure than other nonfuel materials such as niobium carbide. In this case, there is about a two order of magnitude difference in the vapor pressure. The obvious thing to do would be to dilute the uranium carbide with niobium carbide so that the effective vapor pressure of uranium carbide is reduced. If the fuel mixture contained only 1 percent uranium carbide, then the uranium carbide loss rate would be reduced approximately by a factor of 100. This would allow a several thousand degree Rankine (Kelvin) increase in operating temperature for the same rate of uranium loss.

Calculations have been made of the uranium loss rate for the radiation system and the bubble-through system. These data are shown in figure 15. The uranium mass fraction in the exhaust is plotted as a function of liquid temperature for the bubble-through system and the radiation system. The calculations were carried out for a reactor pressure of 200 atmospheres (20 300 000 N/m^2) and a uranium carbide to niobium carbide mass ratio of 0.02, that is, a dilution of 1 in 50. The radiation system was calculated

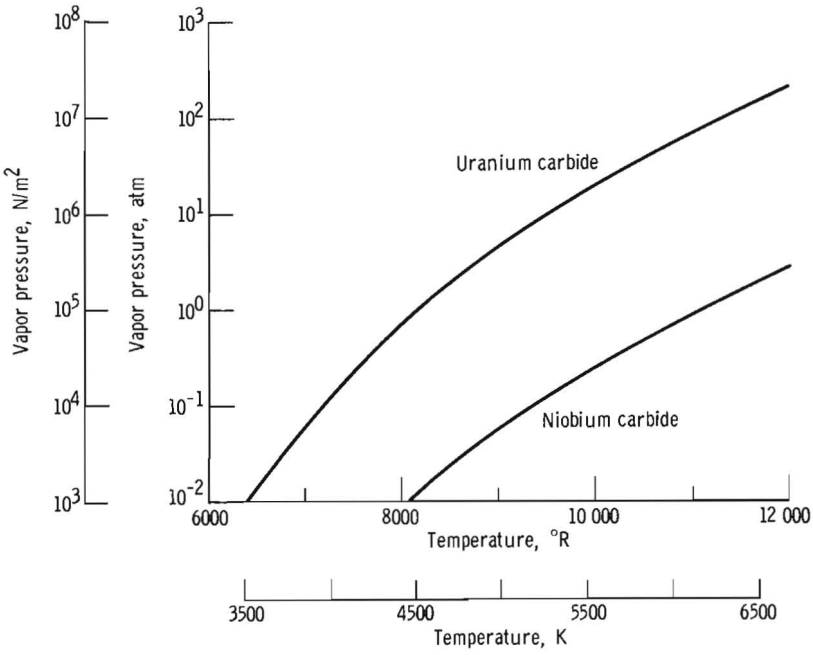


Figure 14. - Vapor pressure of carbides.

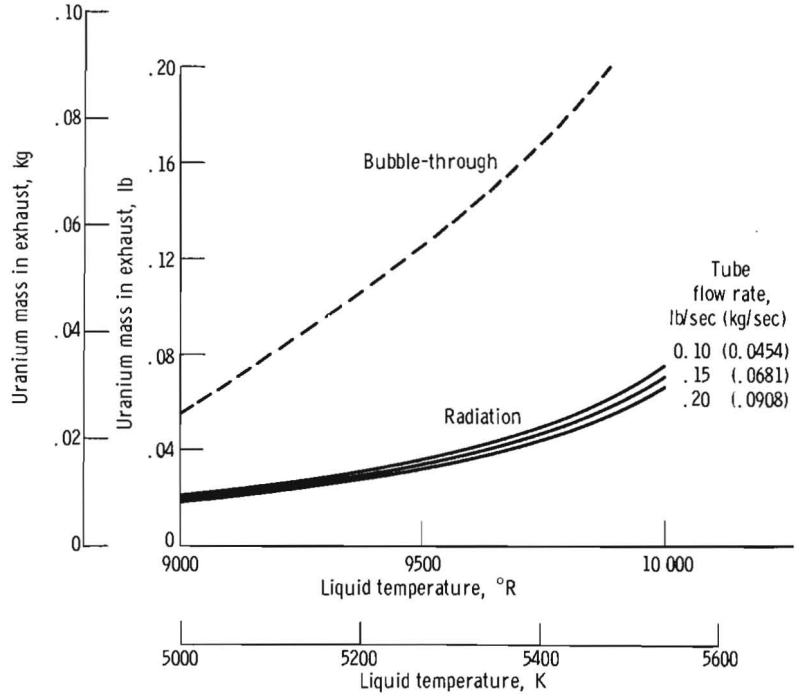


Figure 15. - Comparison of uranium mass fraction in exhaust of bubble-through and radiation liquid-core reactors. Pressure, 200 atmospheres (20 300 000 N/m^2); uranium carbide - niobium carbide mass ratio, 0.02.

for a tube flow rate of 0.1, 0.15, and 0.2 pounds per second (0.0454, 0.068, and 0.0908 kg/sec) for a 2-inch (5.08 cm) diameter tube. The uranium fractions in the exhaust vary from about 0.02 (i.e., 1 part in 50 at 9000° R (5000 K)) up to about 0.07 (i.e., 1 part in 14 for 10 000° R (5560 K)). For any given liquid temperature the bubble-through system has a much higher uranium mass fraction in the exhaust because the bubble-through system is saturated in the carbides.

The effect on specific impulse of these two systems of the heavy materials in the exhaust is shown in figure 16. The specific impulse is plotted as a function of liquid temperature for both the bubble-through system and the radiation system. For reference purposes the specific impulse of pure hydrogen is shown as a solid line. The calculations assume a pressure of 200 atmospheres (20 300 000 N/m^2) and a uranium carbide to niobium carbide mass ratio of 0.02. In the case for the radiation liquid-core reactor the tube length is 60 inches (152.5 cm), and the tube diameter is 2 inches (5.08 cm). The hydrogen flow rates shown on the figure are 0.1, 0.15, and 0.2 pounds per second (0.0454, 0.0681, and 0.0908 kg/sec). In all cases the specific impulse is less than that for pure hydrogen because the hydrogen has heavy material mixed with it. The low specific impulse of the bubble-through system is due solely to the high heavy mass content of the ex-

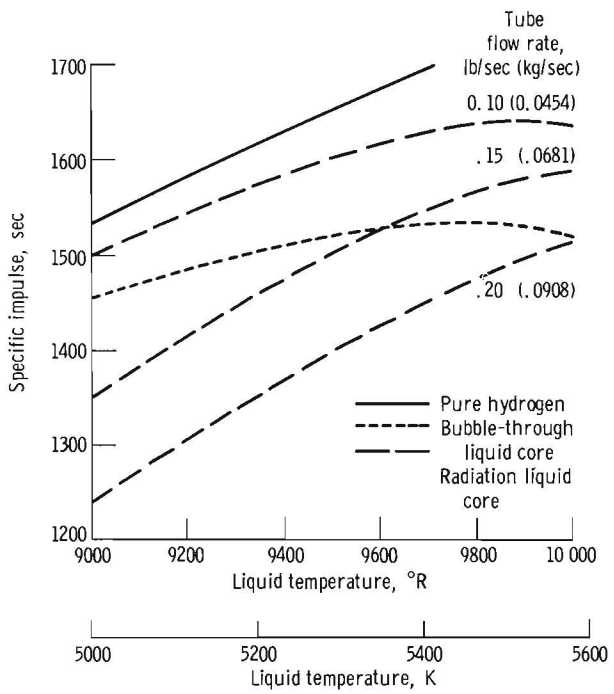


Figure 16. - Specific impulse for pure hydrogen and for bubble-through and radiation liquid-core nuclear rockets. Pressure, 200 atmospheres (20 300 000 N/m^2); uranium carbide - niobium carbide mass ratio, 0.02. Radiation liquid core tube dimensions: length, 60 inches (152.5 cm); diameter, 2 inches (5.08 cm).

haust gas. In the case of the radiation liquid core, there are two reasons why the specific impulse is lower than that for hydrogen: (1) there is heavy vapor present, and (2) the tem-temperature of the exhaust from a radiation system is lower than the liquid temperature. In the radiation liquid core the heat flux into the hydrogen is fixed by the liquid temperature so that higher flows result in lower gas temperature rises. Therefore, the higher the flow rate, the lower the temperature of the exhaust gas and, hence, the lower the specific impulse. The specific impulse level for the liquid-core bubble-through system is 1450 to 1500 seconds at temperatures in the range of 9000° to $19\ 000^{\circ}$ R (5000 to 10 560 K). For the lower tube flow rates, the specific impulse of the radiation system varies between 1500 and 1625 seconds. Figure 15 showed that the uranium loss for the bubble-through system would be excessive compared with the radiation system of 9000° R (5000 K). Therefore, the bubble-through system would probably be operated at temperatures closer to 8500° (4720 K) than 9000° R (5000 K). In this case the specific impulse would be reduced down to about 1400 seconds and would correspond to the radiation reactor with flow rates of about 0.15 pound per second (0.0681 kg/sec) operating at a temperature of 9000° R (5000 K). It is apparent then that the radiation could produce specific impulses 100 or 200 seconds higher than the bubble-through system for the same uranium loss rate.

Thrust-to-Core-Weight Ratios

Some approximate calculations shown in figure 17 were also made of the thrust-to-core-weight ratio of the bubble-through and radiation systems (see refs. 2 and 3). The thrust-to-core weight ratio is plotted as a function of liquid temperature for the radiation and the bubble-through system (solid and dashed curves, respectively). The calculations were carried out for a pressure of 200 atmospheres (20 300 000 N/m^2) and uranium carbide to niobium carbide mass ratio of 0.02. The tube diameter is 2 inches (5.08 cm) and tube length for the radiation system is 60 inches (152.5 cm). The tube flow rates used for the radiation system are 0.2, 0.15, and 0.1 pound per second (0.0908, 0.0681, and 0.0454 kg/sec). It is interesting to note that both the bubble-through and radiation systems have thrust-to-core-weight ratios greater than 1. The range shown varies from 2 to 8.

Liquid-Core Performance

In summarizing the liquid-core reactor systems, specific impulses in the range of 1300 to 1500 seconds would appear to be attainable with thrust-to-weight ratios that are in the range of 2 to 10. The corresponding loss rates of uranium, however, are quite

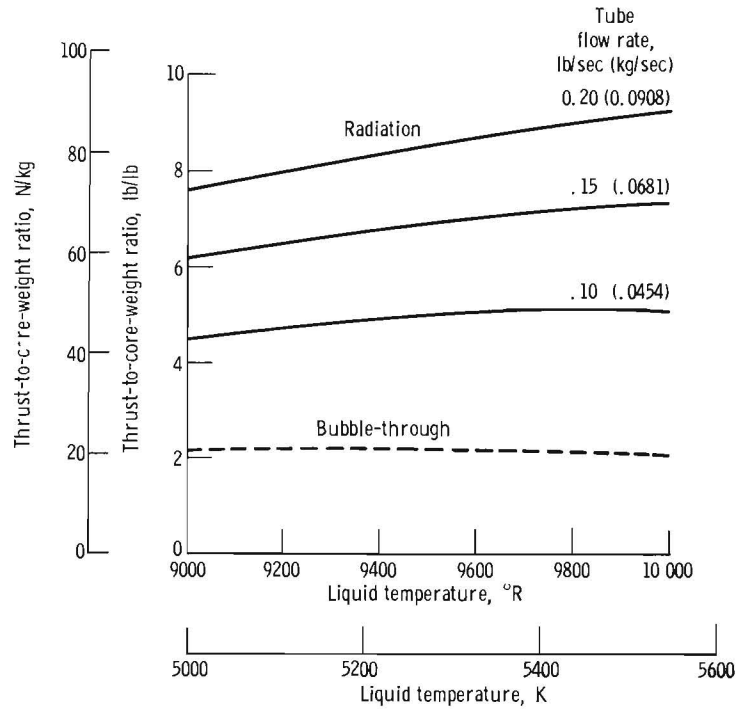


Figure 17. - Thrust-to-core-weight ratios for bubble-through and radiation liquid-core reactors.. Pressure, 200 atmospheres (20 300 000 N/m^2); uranium carbide - niobium carbide mass ratio, 0.02.

high. Typical mass fractions of uranium in the exhaust would tend to be about 0.02. In other words, 1 pound (0.454 kg) of uranium leaves the reactor for every 50 pounds (22.7 kg) of hydrogen that flows through. The only way that this number can be reduced is to reduce the specific impulse down to the range of 1000 to 1100 seconds. Therefore, even though high specific impulse and high thrust-to-core-weight ratios are feasible with liquid-core systems, the loss rate of uranium appears to be excessive.

GAS-CORE NUCLEAR ROCKETS

The final type of nuclear-rocket engine to be discussed is the gas-core nuclear rocket. Figure 18 shows a conceptual design of a coaxial flow gas-core nuclear rocket. Uranium flows into the gaseous cavity where it is vaporized and forms a fissioning gas vapor. The energy generated by the fissioning process is thermally radiated to hydrogen which flows around the uranium mass. The hydrogen is introduced through porous walls or slotted walls with seed material entrained so as to render the hydrogen opaque to the thermal radiation eminating from the fissioning gas. The hydrogen then heated by radiation passes through the nozzle to produce thrust. Nuclear criticality is maintained by

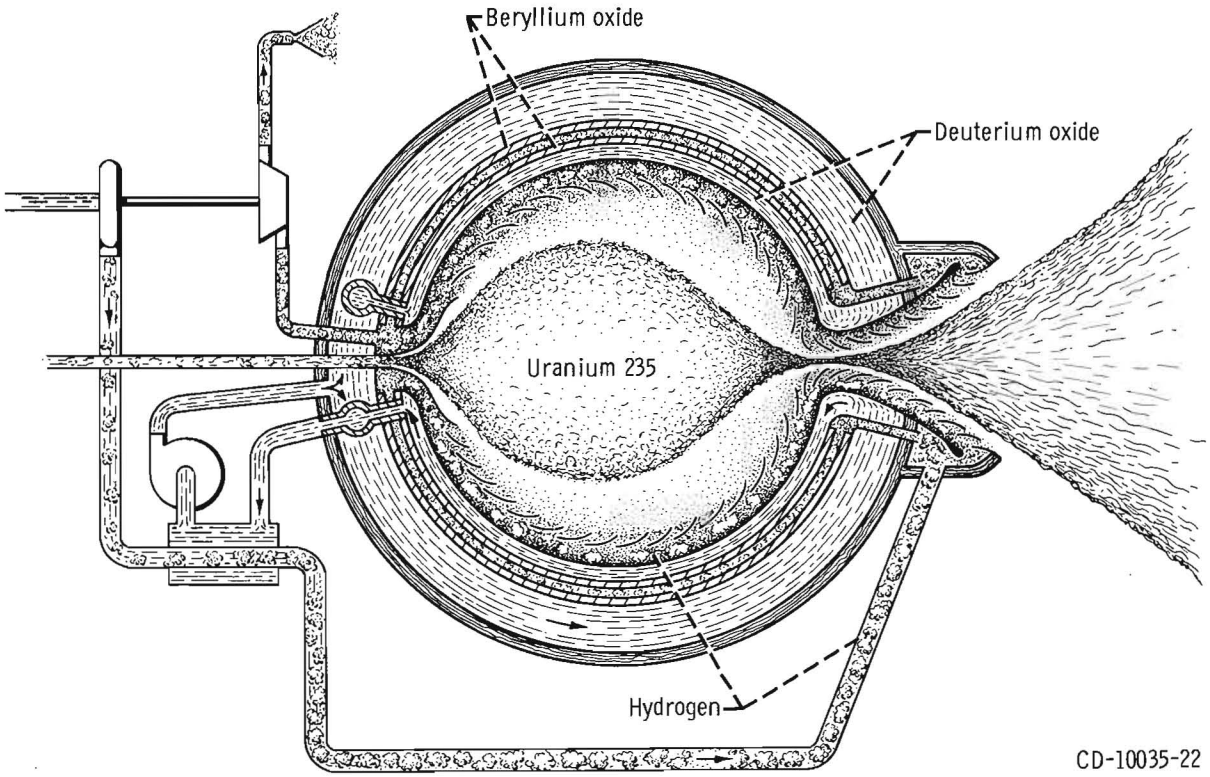


Figure 18. - Coaxial-flow gas-core nuclear rocket.

providing a sufficient amount of uranium gas within the cavity which is reflector moderated by means of a combined deuterium oxide and beryllium oxide moderator system. The beryllium oxide is cooled by direct contact with flowing hydrogen passing through this beryllium oxide region. The deuterium oxide in the spherical shells is circulated through a heat exchanger which is cooled by the incoming hydrogen. The hydrogen, after it picks up the heat from the deuterium oxide, is ducted to a plenum toward the rear of the engine which feeds the hydrogen forward into the beryllium oxide regions for cooling purposes. The hydrogen then reverses direction and flows toward the rear of the reactor between the porous or slotted walls and the inner deuterium oxide liner. Hydrogen is also bled from this cooling circuit to run the turbine which drives the pump for circulating the hydrogen.

Gas-Core Problem Areas

The following table lists some of the gas-core problem areas:

Area	Importance
Neutronics	Criticality and pressure
Fluid mechanics	Fuel loss rate
Heat transfer	Temperature, heat loads, and pressure

Criticality determines the amount of fuel that is required in the reactor to maintain the chain reaction. Inasmuch as the fuel is in the gaseous state, the criticality requirement, which prescribes the number density of fuel atoms, is a determining factor of the pressure in the reactor.

The fluid mechanics problem area is concerned with minimizing the fuel loss rate. In the gas core, if the uranium and hydrogen are completely and thoroughly mixed, the uranium loss rate would be prohibitive. Fluid mechanics studies are required to determine ways and means for increasing the residence time of the uranium while the hydrogen flows through the reactor as quickly as possible (while entraining a minimum amount of uranium). Producing and understanding flow fields that do this is the major challenge to a successful gas core.

The third area listed is heat transfer. Heat transfer determines the temperature, the heat loads, and the pressure level within the reactor. Almost every gas-core concept conceived involves radiant heat transfer from the fuel to the hydrogen. The study of radiant heat transfer and the absorption characteristics of the gases involved in the gas cores is a major area of research. The operating temperatures of the fuel regions must be known so that the pressure can be determined for any gas-core system. The emissivity and absorptivity of fuel and propellant gases with and without seed materials must be known to design the reactor so that the thermal heat flux on the wall can be held to tolerable limits.

Gas-Core Reactor Criticality

Over the years many estimates have been made of the fissionable material mass required to make cavity reactors critical. Table II summarizes the results of various investigators using different kinds of calculations for a completely filled cavity 100 centimeters in radius using uranium 235 as a fuel, and with a deuterium oxide reflector 100 centimeters thick. The first three cases considered spherical cores. All three calculations were based on transport theory. The first, by Los Alamos, and the second, by United Aircraft Corporation (UAC), predicted critical masses of 2.3 and 2.6 kilograms. The third by Allison, calculated for plutonium, gave a critical mass of 2 kilograms and is expected to be lower than for uranium 235. The next group of calculations are for

TABLE II. - CAVITY REACTOR CALCULATIONS

[Reflector material, deuterium oxide; fuel, uranium 235; reflector thickness, 100 cm; cavity radius, 100 cm.]

Geometry	Wall material	Fuel radius ratio	Type of calculation	Source	Date	Critical mass, kg
Sphere	None	---	Transport	Los Alamos	1959	2.3
		---	Transport	UAC	1966	2.6
		---	Transport	Allison	1965	[a]2.0
Cylinder[b]	None	1.0	Transport	Los Alamos	1959	2.0
	None	1.0	Diffusion	NASA	1962	3.0
	Aluminum	1.0	Transport	Los Alamos	1959	3.5
	None	.5	Transport	Los Alamos	1959	4.0
	None	.5	Diffusion	NASA	1962	3.5

[a]Calculated for plutonium.

[b]Length-to-diameter ratio, 1.

a cylinder with a length to diameter ratio of 1. One used transport theory and the other one diffusion theory. The critical mass again is about 2 to 3 kilograms. These calculations were done on an ideal basis at room temperature without any structural material between the deuterium oxide and the cavity. Los Alamos considered a case with an aluminum wall. This increased the critical mass from 2 to 3.5 kilograms, indicating the sensitivity of even relatively low neutron-absorbing materials like aluminum. Calculations were then made where the fuel occupied only a central region with a radius of 0.5 of the cavity internal diameter. The cylindrical cavity length to diameter ratio was 1. Both Los Alamos and NASA calculations show increases in critical mass due to fuel compression. The entire range of critical masses for the large variety of cases done by several groups at different times is from 2 to 4 kilograms.

For various reasons the validity of these calculations was suspected. The cavities are geometries that are quite unusual compared with a normal reactor. The calculations are very sensitive to precise composition and temperature. The Lewis Research Center decided to carry out some criticality experiments to verify calculational procedures on a full-size cavity system. Figure 19 shows the criticality experiment test installation. This experiment is being done for Lewis at the National Reactor Testing Site of the Atomic Energy Commission in Idaho by the General Electric Company. The experiment consists of a deuterium oxide reflector moderated cavity. The cavity is 6 feet (1.83 m) in diameter and 4 feet (1.22 m) long, and it contains a rack with a minimum amount of aluminum necessary to hold the uranium foils in place. The deuterium oxide reflector is 3 feet (0.915 m) thick. The outside diameter of the reactor is then 12 feet (3.66 m), and

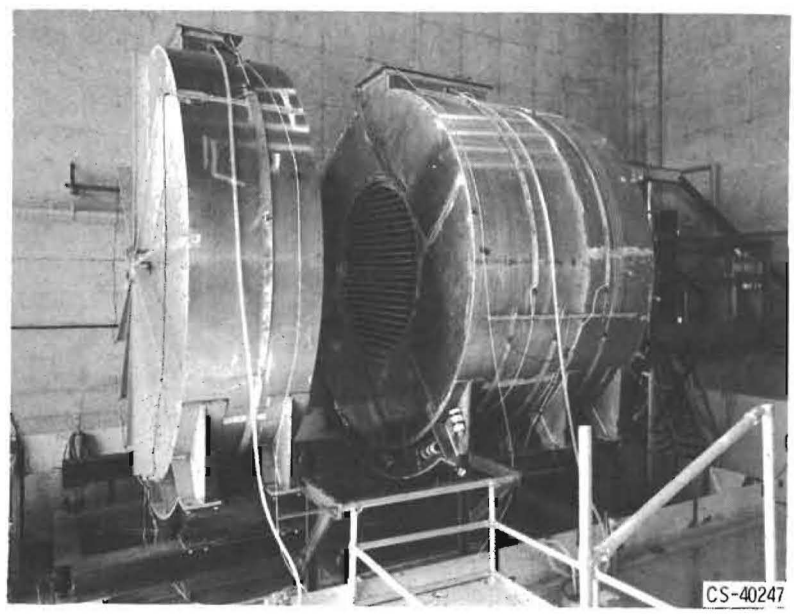


Figure 19. - Cavity critical experiment facility.

the length is 10 feet (3.05 m). Approximately 20 tons (18 100 kg) of deuterium oxide is required in this facility. Figure 19(b) is a photograph of the cavity region with a man inserting a tray of uranium foils.

Some results of this experiment are shown in figure 20. The critical mass in kilograms of uranium 235 is plotted as a function of fuel-to-cavity radius ratio. The experimental points are indicated by circles with the solid line drawn through them. The estimates made previously show critical masses in the range of 3.5 to 4 kilograms for a fuel-to-cavity radius ratio from 1 down to 0.5. There exists a large difference between the analysis and the experiment in spite of the fact that the experiment was designed to be a very clean calculable geometry. Even though some of the differences may probably be simply explained, the fact remains that the calculated data shown were used to predict reactor pressure levels. The critical masses are anywhere from three to four times what has been calculated in the past. This, of course, means that the pressure levels in the reactor will be from three to four times what have been previously predicted.

Table III shows some cavity reactor characteristics as affected in going from a room-temperature critical experiment to a hot operating reactor. The case we have considered is a deuterium oxide reflected cavity 8 feet (2.44 m) in diameter and 8-feet long (2.44-m). The fuel region is 6 feet (1.83 m) in diameter, while the reflector thickness is 3 feet (0.915 m), giving an overall outer diameter of 14 feet (4.27 m). The first case shown assumes that there is no hydrogen in the core and that the uranium is vapor at room temperature. The critical mass based on the extrapolation of the previous experiment is 9 kilograms. Uranium in a gaseous state at room temperature would yield a pressure of 0.19 atmosphere (19 250 N/m^2). If we introduce hydrogen at a temperature of 530° R (294 K), with an atom density of 10^{21} atoms per cubic centimeter in the region between the fuel and the cavity walls, while maintaining the uranium at room temperature, the critical mass would be increased by 11.2 kilograms because of the presence of the hydrogen. This increases the pressure of the uranium to 0.24 atmospheres (24 300 N/m^2).

The next case considers the effect of operating temperature levels. The average hy-

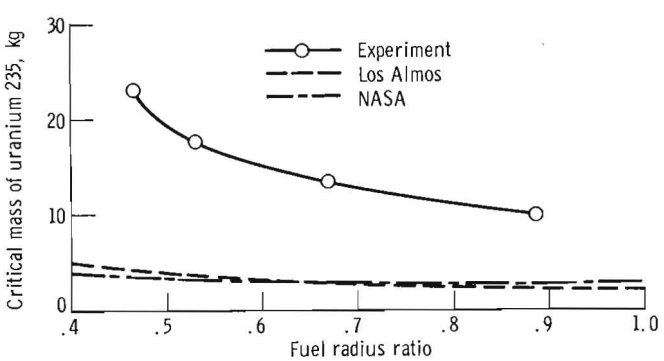
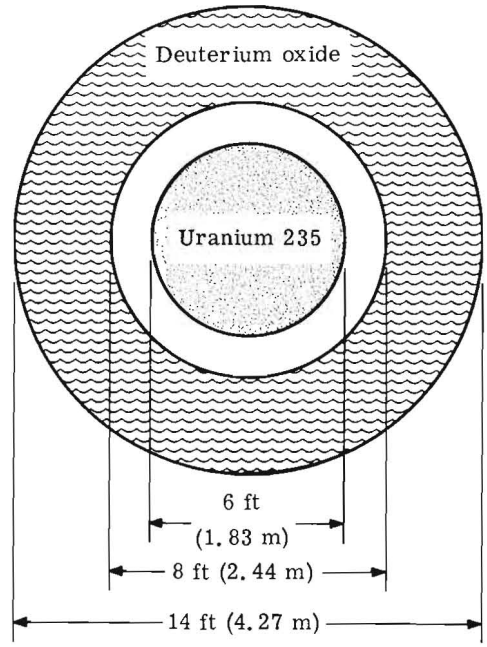


Figure 20. - Cavity critical experiment results.

TABLE III. - GAS-CORE OPERATING PRESSURE ESTIMATES



	Temperature				Critical mass, kg	Minimum pressure	
	Hydrogen		Uranium			atm	N/m^2
	^oR	K	^oR	K			
Fuel	None	----	530	295	9.0	0.19	19 300
	[a]530	295	530	295	11.2	.24	24 300
	6000	3330	80 000	44 400	16.8	54.4	5 520 000
	6000	3330	80 000	44 400	16.8	209	21 400 000
Structure	----	----	-----	-----	32.3	404	40 900 000
Fuel distribution	----	----	-----	-----	47.8	595	60 300 000
50 Percent containment	----	----	-----	-----	47.8	1190	120 600 000

[a]Hydrogen number density, 10^{21} atoms/cm^3.

[b]Assumes no ionization of uranium 235.

drogen temperature within a gas core with an specific impulse of 1500 seconds would be about 6000° R (3330 K). The average uranium temperature would be about 90 000° R (50 000 K). The primary effect here is to increase the critical mass to 16.8 kilograms because of the upscattering of neutrons (to higher temperature) by the hot hydrogen. The uranium pressure is now 54.4 atmospheres (5 520 000 N/m^2) assuming that the uranium was not ionized. The next line indicates the increase in pressure due to the ionization of the uranium. At this temperature the uranium would be more than triply ionized. The pressure is then 209 atmospheres (21 200 000 N/m^2). All these calculations were carried out assuming that there was not structural material between the deuterium oxide and the uranium. Actually some structure would have to be provided to contain the deuterium oxide. And, if it is assumed that this structure is equivalent to 1.5 centimeters of aluminum, the critical mass increases to 32.3 kilograms, which results in a pressure of 404 atmospheres (41 000 000 N/m^2).

The fact that the fuel is not uniformly distributed within the fuel region must also be considered. Critical experiments at the National Reactor Testing station in Idaho were run in which uranium was distributed as it might be in a typical gas-core reactor. The critical mass increased by 50 percent because of this effect. This would increase the pressure to 595 atmospheres (60 300 000 N/m^2).

Finally, in any gas-core system the uranium would not be completely separated from the hydrogen zone as shown in the schematic drawing. There would be a certain amount of hydrogen that would mix with the uranium. The uranium concentration could easily be reduced by 50 percent as a result of the mixing indicated by our experimental work in fluid mechanics. If there is no change in critical mass, the pressure would be doubled, giving 1190 atmospheres (120 600 000 N/m^2). The pressure for an operating uranium 235 cavity with a diameter and length of 8 feet (2.44 m) is not apt to be much less than 1000 atmospheres (101 300 000 N/m^2). Some new idea that would reduce the mixing between the hydrogen and uranium is necessary or some new concept is required to minimize fuel requirement without increase the loss rate of fuel. The use of uranium 233 would give some relief. The magnitude of this relief cannot be determined until we know how to calculate this reactor satisfactorily; however, a factor of 2 improvement is anticipated.

The results of this neutronic work came as a surprise. With hindsight the discrepancy between calculation and experiment can be greatly reduced. The calculations and experiment were performed using deuterium oxide as the moderator. Other materials would be expected to give even higher critical masses than deuterium oxide.

Gas-Core Fluid Mechanics

The fluid mechanic problems of the gas-core reactor will now be discussed with

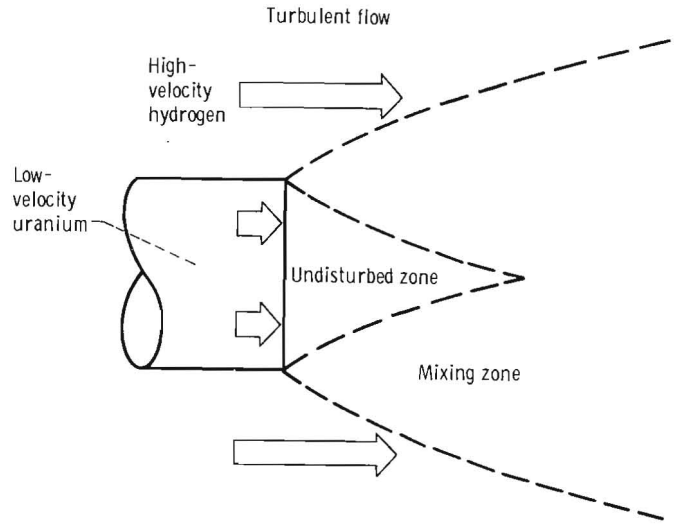


Figure 21. - Basic coaxial-flow model.

emphasis on the fluid mechanics problems of the coaxial flow system. The basic coaxial flow model is shown in figure 21. Low-velocity uranium enters through the center duct, while high-velocity hydrogen flows around this duct. Because of the velocity difference, there will be a mixing between the hydrogen and uranium. This results in what is called a mixing zone. There will be an undisturbed zone as shown. This zone is formed by the inner boundaries of the mixing zone. The undisturbed zone is where most of the fuel would be contained. Several coaxial-flow mixing experiments have been carried out both at Lewis and at the Illinois Institute of Technology (IIT) under contract to Lewis. In addition, theoretical calculations have been made to determine the flow fields, velocity fields, and concentration fields that exist in a coaxial-flow situation. Idealized coaxial-flow experiments have been run at Lewis and at IIT. At Lewis experiments were run with bromine and air. Bromine was injected in a low-velocity central region to represent the uranium while air was flowed around this region at high velocity to represent the hydrogen. The velocity ratios and flow rates were varied over a wide range to obtain data for an analytical correlation required for prediction of coaxial flows at other conditions.

Similar data have been taken recently at IIT using freon as a heavy gas simulator and air as the hydrogen simulator. One of the results from this experiment is shown in figure 22. Here, the average freon concentration is plotted as a function of axial downstream position in units of jet radii. The experimental points are indicated by the square data points, for an initial velocity ratio of 31 to 1; that is, the air is flowing at 31 times the velocity of freon. The theoretical prediction, based on some work at Lewis is shown superimposed on these data. The agreement is good. Many other checks have been made on the theoretical predictions so that at present we are fairly confident that the theoretical estimates give a fairly good representation of both the concentration and velocity

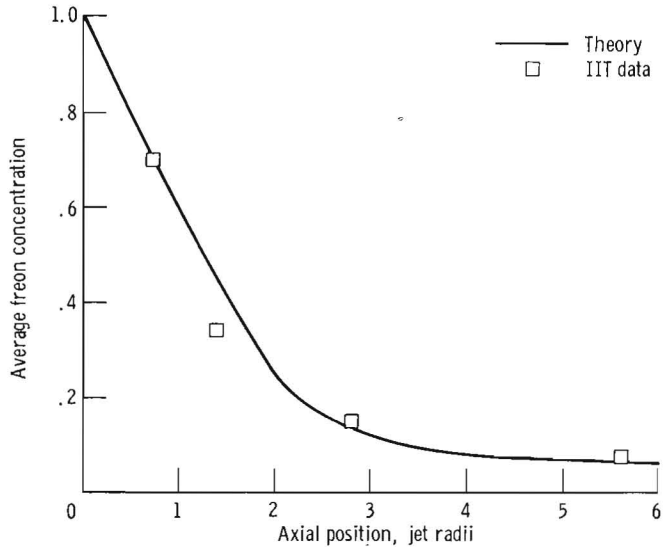


Figure 22. - Comparison of IIT data and NASA Lewis theory. Initial velocity ratio, 31.

fields that exist in a coaxial-flow reactor, when it is assumed that temperature gradients and radiant heat transfer do not affect the mixing process except as they affect density and gas properties.

Figure 23 shows a typical result of such a calculation. The case shown is for a velocity ratio of 30 to 1 and a mass flow ratio of 35 to 1, which is representative of a gas-core reactor. Shown are relative concentration profiles for 95, 70, 40, and 10 percent fuel. Most of the fuel is concentrated in the undisturbed region near the entrance. This is typical of the concentration distribution that was used in a critical experiment to determine the effect on nonuniform distribution of fuel. The purpose of this figure is to indi-

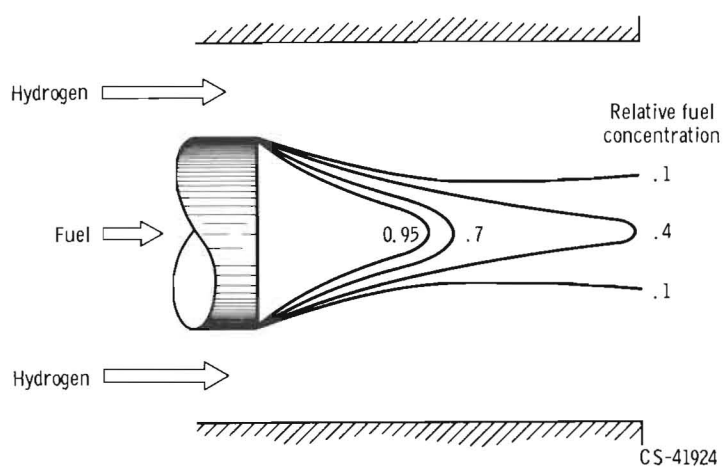


Figure 23. - Concentration field in coaxial-flow engine.

cate that the concentration distributions can be calculated for isothermal conditions within the core with a theory that has been substantiated by laboratory experiments. It is also possible to calculate the corresponding velocity profiles throughout the core region.

Gas-Core Heat Transfer

There are two general problems of interest for gas-core heat transfer. One is the calculation of radiant heat transfer between two gases, and the second is the determination of the absorption coefficient of the gases so that the first calculations can be made.

Figure 24 shows examples of the absorption coefficients as a function of temperature for the various regions in the reactor. The first region is the nuclear fuel region. Here, the absorption coefficients are very high compared with the hydrogen propellant. In the case of the hydrogen propellant the absorption coefficient becomes very small at temperatures below 10 000° R (5550 K). At 40 000° R (22 200 K) it reaches a peak value and again starts to fall off in the 100 000° R (55 500 K) range. In the gas core the hydrogen enters at a relatively low temperature. In this case the hydrogen itself cannot absorb radiation; therefore, particulate matter (seed) must be introduced into the hydrogen to render it opaque to thermal radiation. A typical absorption coefficient for hydrogen seeded with particles is shown by the line on the left. When the propellant seed increases in temperature toward 10 000° R (5500 K) it will evaporate and may leave a window if the vapor of the seed material does not absorb radiation. Experimental as well as theoretical predic-

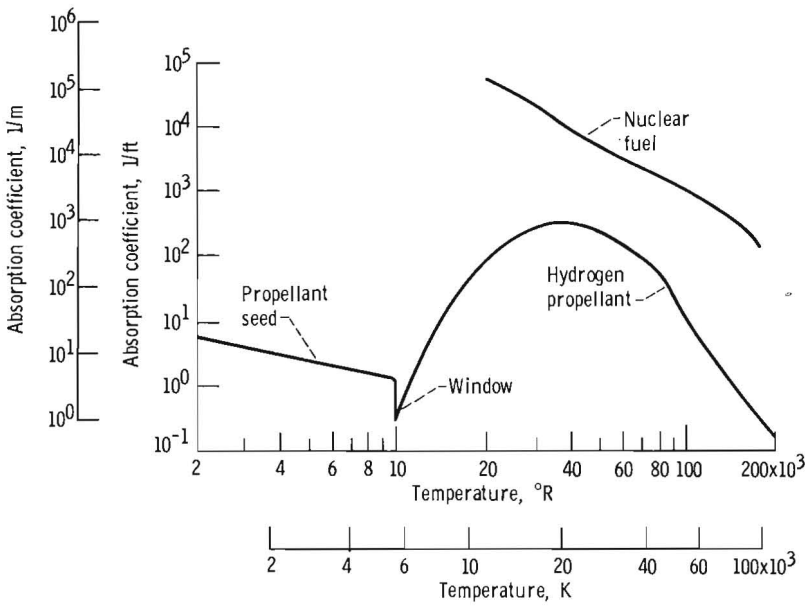


Figure 24. - Pure absorption coefficients for 500 atmospheres (50 700 000 N/m^2).

tions for determination of all these absorption coefficients have been made and are continuing to be improved so that heat-transfer calculations can be made. From a physicist's point of view the knowledge of absorption coefficients for both hydrogen and nuclear fuel and the propellant seed is in a very poor state. However, from the point of view of engineering feasibility studies, calculated absorption coefficients appear to be adequate.

Figure 25 shows the calculated results of the temperature field in a coaxial-flow engine. Considered is both the nonuniform fuel distribution and nonuniform heat generation that would exist in a real case. Shown here are the isotherms for 4000°, 7000°, 9000°, $11\ 000^{\circ}$, $80\ 000^{\circ}$, $100\ 000^{\circ}$, and $120\ 000^{\circ}$ R (2200, 3890, 5000, 6110, 44 400, 55 000, and 66 600 K). The incoming hydrogen temperature for this case was 3500° R (1945 K). Seeding was introduced into the hydrogen to render it opaque in a low-temperature region. The isotherms bend toward the wall as the temperatures get into the 7000°, 9000°, and $11\ 000^{\circ}$ R (3890, 5000, and 6110 K) range because of the evaporization of the seed. At $11\ 000^{\circ}$ R (6110 K) the hydrogen becomes opaque, and the contours once again come toward the center. The maximum fuel temperature are in the range of $120\ 000^{\circ}$ R (66 600 K) and the average fuel temperatures are about $90\ 000^{\circ}$ R (50 000 K). The average hydrogen temperature will be about $10\ 000^{\circ}$ to $20\ 000^{\circ}$ R (5550 to 11 100 K) to produce specific impulses in the range of 1500 to 2000 seconds. The amount of seed material required to produce this temperature profile was less than 1 percent of the hydrogen mass flow introducing a negligible effect on the specific impulse. This seed also was sufficient to reduce the heat flux to the wall to less than 1 kilowatt per square inch (0.155 kW/cm^2) which can be readily handled by a cooling system. This calculation indicates that as far as heat-transfer problems are concerned, the coaxial-flow reactor is feasible. Very

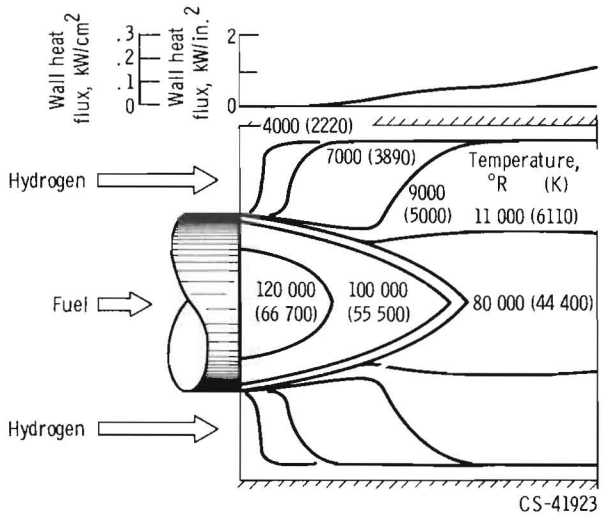


Figure 25. - Temperature field in coaxial-flow engine.

little seeding material is required to reduce wall heat fluxes well below that which has been achieved in cooling chemical rocket nozzle walls.

Gas-Core Performance

Rough estimates of the performance that might be obtained from coaxial gas-core reactors are shown in the following table:

Thrust, lb_{force}; N	>250 000; >1 112 000
Weight, lb_{mass}; kg	>100 000; >45 360
Thrust per engine weight	2 to 20
Specific impulse, sec	1500 to 2500
Pressure level, atm; N/m^2	1000; 101 330 000
Uranium-to-hydrogen flow ratio	0.01 to 0.10
Average uranium temperature, ^oR; K	~80 000; ~44 400

The estimates are based on calculations using theoretical techniques that have been checked by experimental studies such as discussed previously. For the kinds of missions that can be envisioned for gas cores, the required thrust levels will be on the order of 250 000 pounds (1 112 000 N) or higher. In this type of a system the thrust level can be essentially any level desired. We do not feel that the weight of the gas-core system can be much less then 100 000 pounds (444 800 kg). The thrust-to-engine weight ratio will vary from 2 to 20. There is very little increase in fuel temperature required to increase the thrust by a factor of 10. (The thrust increase is obtained by increasing the hydrogen flow.) Because the power is radiated to the propellant, the fuel temperature increases approximately as the fourth root of the required reactor power. Specific impulses will be in the range of 1500 to 2500 seconds. The hydrogen-outlet temperature will be in the range of 10 000^o to 20 000^o R (5550 to 11 100 K). Pressure levels will be in the range of 1000 atmospheres (101 300 000 N/m^2) unless new cavity configurations or the use of uranium 233 reduces the critical mass requirement. Lower pressures hinge on the criticality studies that are presently receiving a lot of attention and in the fluid mechanics area where techniques may be discovered to permit uranium to occupy a larger portion of the available cavity volume. The uranium-to-hydrogen flow ratio will be in the range of 0.01 to 0.1; that is, 1 pound (0.454 kg) of uranium is required for each 10 or 100 pounds (4.54 or 45.4 kg) of hydrogen. Numbers lower than this will probably not be obtained unless a breakthrough occurs which radically increases the holdup of the uranium. The use of magnetic and/or electrical fields in the nozzle may offer such a possibility. The average uranium temperatures run around 90 000^o R (50 000 K) with peak temperatures over 100 000^o R (55 500 K).

FUTURE PROSPECTS

Whether or not nuclear rockets will be used for interplanetary missions depends on three factors: the need, the cost, and the timing.

The first factor, the need, requires that manned interplanetary missions be designated as a national goal. Following the example of the Apollo manned moon exploration program, it could be anticipated that, if a manned interplanetary mission becomes a national goal, only one or two manned flights would be approved. Whether further manned missions would be approved may be open to question. Judging from the apparent hostile nature of the environment of the near planets, it is not likely that numerous manned flights after the first exploratory flights will be planned in the foreseeable future. Some new yet undiscovered reason for extensive exploration, exploitation, or colonization would have to be uncovered to justify large-scale manned interplanetary operations beyond the first one or two exploratory flights.

The second factor that would determine whether nuclear rockets will be used for interplanetary missions is the cost. The most optimistic cost estimates that have been made indicate it might be possible to pay for the development of the nuclear-rocket space vehicle system with savings that could result from the first flight mission if it were done with nuclear rather then chemical rockets. Other more pessimistic estimates require many flights to pay for the development.

The potential lower cost for nuclear rockets would have to be weighed against the higher cost, but demonstrated capability, performance, and reliability of chemical systems. Because the Nation's space program has concentrated on chemical rockets for all its missions, the confidence in producing any new successful chemically powered man-rated space vehicle is at a very high level.

Estimated vehicle and powerplant development and operational costs for chemical systems should also have a high degree of validity because of the number of successful manned and unmanned space vehicles that have been developed and flown.

No nuclear-rocket engines or vehicles have been developed for flight and, of course, there is no operational experience on which to base cost estimates.

It would seem to follow that when a decision is made to go ahead with the first manned interplanetary mission the chemical rocket will probably be chosen for the powerplant, unless this decision is delayed sufficiently long that new and competitive systems appear.

This leads to the third factor, timing. If the decision to carry out a manned interplanetary trip is delayed long enough, it is possible that today's advanced concepts, or concepts not yet invented, will be the best choice for the powerplant. In the case of extensive manned interplanetary voyages, the time for decision on these may be long enough, so that it is highly probable that a new concept could be invented, proven feasible, and developed in time for this application.

It would seem, therefore, that great emphasis should be placed on research and feasibility studies of advanced nuclear propulsion systems of all types. The hope is that a practical system with a clear advantage over chemical systems might be discovered. Such a discovery could probably make manned interplanetary trips more attractive and cause a decision in their favor at an earlier date than otherwise.

SUMMARY OF RESULTS

A review of the three basic types of nuclear powerplants, compared with respect to performance potential and the status of current technology, has shown their differences and their respective advantages and/or disadvantages. The major points of this comparison are presented as follows:

The solid-core systems are expected to have impulses in the range of 850 seconds, any thrust level (as long as it is greater than 10 000 lb (44 500 N)), and thrust-to-engine-weight ratios of 2 to 20. There is negligible or no fuel loss from the solid-core system, which has had the most work done on it. Large-scale tests have been performed on a breadboard engine which has produced specific impulses greater than 700 seconds at thrust levels of about 50 000 pounds (222 000 N).

The liquid-core reactor would be interesting in the specific impulse range of 1200 to 1500 seconds. Again any thrust level can be obtained depending on how big or small the reactor is made. The thrust-to-engine weigh ratio for these systems would be in the range of 1 to 10 pounds per pound (9.8 to 98 N/kg). The discouraging feature of the liquid-core system is the high fuel-loss ratio anticipated. Less values of 0.01 to 0.1 pound (0.00454 to 0.0454 kg) of uranium per pound (0.454 kg) of hydrogen are expected for impulses in the range of 1200 to 1500 seconds.

The gas-core reactor shows specific impulses in the range of 1500 to 2500 seconds. The thrust levels should be at least as high as the weight in order that the thrust-to-weight ratio does not go below 1 pound per pound (9.8 N/kg). Because the engine weight is not expected to be under 100 000 pounds (45 400 kg), thrust levels higher than 100 000 pounds (445 000 N) are of interst. The thrust-to-engine weights, in that case, would run from 1 to 20 pounds per pound (9.8 to 19.6 N/kg). Gas-core reactors tend to be very large, and can have high thrust-to-weight ratios. As in the case of the liquid-core system, the fuel loss that will be attendant with gas cores as envisioned today will

be rather high. The loss rates will be 0.01 to 0.1 pound (0.00454 kg) of uranium for each pound (0.454 kg) of hydrogen.

Lewis Research Center,
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