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# STATUS OF OPEN-CYCLE GAS-CORE REACTOR PROJECT THROUGH 1970

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16. Abstract

Some recent gas-core rocket reactor research experiments are reviewed, and engine performance characteristics are estimated using these latest results. Flow experiments using air/air indicate that the uranium consumption might be less than 1 percent of the hydrogen propellant requirement. Specific impulses as high as 7000 seconds may be possible at rocket vehicle accelerations of $10^{-2}$. Additional work is required to more realistically simulate engine conditions in laboratory experiments.

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## SUMMARY

The idea of using gaseous uranium in a rocket engine to produce a specific impulse greater than 1000 seconds has been around for about 10 to 15 years. All the work to date has been aimed at establishing the basic feasibility of the concept. Much of the work has centered around isothermal flow experiments aimed at understanding, and then reducing to an acceptable minimum, the uranium loss rate. Attention has also focused on establishing the criticality requirements, reducing engine weights, and determining the engine cavity wall cooling requirements of gas-core engines. A number of recent experiments and calculations have produced rather favorable results.

The current status of gas-core reactors can be summarized as follows:

1. Gas-core reactors have the potential of producing specific impulses as high as approximately 7000 seconds.

2. At a specific impulse of 5000 seconds, engine weight varies from 51 000 to 132 000 kilograms for thrust varying from $2.22\times10^4$ to $2.22\times10^5$ newtons, respectively. This range corresponds to a specific mass that varies from 0.1 kilogram per kilowatt (at a thrust of $2.22\times10^4$ N) down to 0.02 kilogram per kilowatt.

3. Reactor experiments indicate that criticality can be achieved with a critical mass of 27 kilograms of uranium surrounded by about 27 000 kilograms of moderator-reflector materials.

4. Flow experiments using air/air indicate that the uranium plasma might occupy about 20 to 30 percent of the engine cavity volume for a hydrogen- to uranium-mass-flow ratio in the range from 100/1 to 400/1.

5. A radiant-heat-transfer analysis based on measured values of uranium and seeded-hydrogen absorption coefficients indicates that the cavity wall can be thermally protected. Wall heat fluxes are expected to be approximately $6.45\times10^2$ kilowatts per square meter and wall temperature in the range 1000 to 2780 K, for a specific impulse in the range 5000 to 7000 seconds.

6. Important future work areas that are pointed out by the results to date are

a. Large-scale hot-flow experiments
b. Nozzle cooling
c. Cold-flow (zero power) reactor experiment
d. Conceptual design study
e. Mission analysis and other applications
f. Engine startup and control

# INTRODUCTION

Reference 1 pointed out that virtually all existing or proposed rocket propulsion systems can be put into one of two general classes. Type I systems produce high thrust, but are limited to specific impulses less than 1000 seconds. Type II systems produce specific impulses of thousands, or even tens of thousands, of seconds; but they are limited to thrusts less than 45 kilograms. For fast interplanetary travel a third class is needed, or at least would be highly desirable. This "Type $1\frac{1}{2}$" engine should provide both high specific impulse and high thrust. The gas-core nuclear rocket engine seems to be emerging as such an engine. This report presents the current status of Lewis gas-core research.

The gas-core work is aimed at a basic feasibility evaluation of the engine concept. It is not a development program. The idea of a gas-core nuclear rocket engine is not new; related research studies have been underway for over a decade. Most of the work has been in the disciplines of fluid flow, radiant heat transfer, and reactor physics, although some attention has been directed to estimates of engine characteristics such as thrust, weight, operating pressure, and fuel loss rate (refs. 2 to 4). A recent symposium covered most of the gas-core technology, as well as other topics related to gaseous uranium plasmas (ref. 5).

There are currently two concepts of how to make a gas-core reactor. One idea is to allow direct contact between the uranium plasma and the surrounding stream of rocket propellant, hydrogen. This "open-cycle" engine concept is under investigation at the Lewis Research Center and is the subject of this report. A second gas-core idea is to encapsulate the uranium plasma within a solid but transparent material. This "closed-cycle" engine is being studied at United Aircraft Research Laboratories. A recent summary of this work is available in reference 6.

The topics to be covered in this report are as follows: First, the principle of operation of a gas-core nuclear rocket engine is discussed. Next, the specific impulse potential of this kind of engine is given. Then follows a brief review of the major gas-core research studies. Current results from these studies are used to project what kind of engine characteristics and performance might be expected. Finally, some as-yet-unexplored but important work areas are pointed out. The overall objective of this report is to show what a gas-core engine is, what is being done to determine its feasibility, what it would be like if it were feasible, and what remains to be done to demonstrate feasibility.

# PRINCIPLE OF OPERATION

Like the solid-core nuclear rocket engine, the job of a gas-core engine is to heat hydrogen and then expand it through a nozzle to convert the thermal energy into thrust. In order to obtain a higher specific impulse than the 825 seconds of the solid core, a gas core has to produce hotter hydrogen. For a specific impulse of 825 seconds, the hydrogen temperature at the nozzle inlet is approximately 2500 K. A temperature of 22 000 K is required for a specific impulse of 5000 seconds. The temperature levels required for specific impulses in the range 3000 to 5000 seconds cannot be obtained by simply running solid-core-type fuel elements at a higher temperature.

The gas-core concept is to use an incandescent, radiating ball of fissioning uranium plasma as the "fuel element." The nuclear heat released within the uranium plasma leaves its surface in the form of thermal radiation, or photons. This thermal energy is picked up by a surrounding stream of hydrogen propellant, which is then expanded through a nozzle to produce thrust.

Figure 1 illustrates schematically how this basic notion might be translated into a rocket engine. It is not unreasonable to picture this kind of engine as a nuclear "sun" with the central fireball and surrounding gas flow contained within a chamber surrounded by structural materials. The analogy is not exact, of course, because the heat generation is due to fission rather than fusion. However, in both cases, the amount of energy that can be generated in, and released from, the fireball is essentially unlimited. There is, however, a limitation on how much energy can be absorbed by the hydrogen and turned into thrust without overheating the cavity wall or the exhaust nozzle. It is the amount of energy that reaches various, solid, temperature-limited regions of the engine that ultimately limits the power generation and therefore the specific impulse.

The proposed reactor shown in figure 1 is basically spherical. It is composed of an outer pressure vessel, a region of heavy-water reflector, a beryllium oxide moderator, and finally a porous or slotted cavity liner. Approximately 7 to 10 percent of the reactor power is deposited in these solid regions of the reactor due to attenuation of high-energy gamma and neutron radiation. This heat is removed either by a helium coolant in an external space radiator loop, or regeneratively by the hydrogen propellant before it enters the central reactor cavity. The beryllium oxide region is operated at a temperature of about 1400 K, which is below the upper limit of approximately 1700 K and yet above the radiator temperature of 1100 K.

The hydrogen is pumped to a pressure of $5.07\times10^7$ to $10.14\times10^7$ newtons per square meter by means of a turbopump operated by hydrogen bled from an intermediate station in the propellant circuit. The hydrogen then is ducted into the spherical plenum behind a porous or slotted wall. Appropriate seed particles which are about the size of smoke particles are introduced into the hydrogen as it enters this plenum region. The seeded hydrogen then flows through the porous or slotted wall. By properly designing the shape of the porous wall and by proper injection and distribution of the hydrogen flow through this wall, a relatively stagnant nonrecirculating central region forms within the cavity. The cavity is about 2.44 meters in diameter. The central fuel region occupies about 40 percent of the cavity volume. However, this region may also contain some (up to 50 at %) hydrogen that would diffuse in from the outer edge of the fuel. Thus the "effective" volume of pure uranium would probably range from 20 to 30 percent of the cavity volume.

Uranium metal is injected into this region. It vaporizes and rises to temperatures sufficient to thermally radiate the energy that is generated by the fissioning uranium. A possible fuel injection technique consists of pushing a rod of solid uranium metal through a shielded pipe (perhaps made of cadmium oxide) that penetrates the moderator. As it enters the cavity, the uranium instantly vaporizes and rises in temperature to about 55 000 K. Reactor startup could be achieved by first establishing the hydrogen flow. Next uranium particles would be blown into the dead cavity region to achieve nuclear criticality. The power would then be increased to a level sufficient to vaporize the incoming uranium rod.

The seeded hydrogen is heated solely by absorbing the thermal radiation from the fissioning uranium fireball. The cavity walls receive only about 0.5 percent of the thermal radiation from the fireball. This wall protection is accomplished by introducing about 1 percent by weight of a seeding material, such as graphite or tungsten particles, into the hydrogen. This same technique is used in the nozzle region to reduce the hydrogen radiation heat load and the hydrogen temperature near the nozzle wall to tolerable levels. Seed concentrations of about 1 to 10 percent are required here. Figure 1 shows that some cold hydrogen can be introduced through the nozzle walls directly from the plenum at the downstream end of the engine if it is required. This would tend to reduce the specific impulse.

## GAS-CORE ENGINE DESCRIPTION

A gas-core rocket reactor would be composed of the features depicted in figure 1. The central cavity wall is formed from a relatively thin (approx. 0.6 to 1.7 cm), porous, high-temperature material such as graphite. The cavity is surrounded by nuclear moderator-reflector materials such as heavy water, beryllium, beryllium oxide, and graphite. The choice of a moderator material, or combination of materials, would be influenced by such factors as nuclear moderating efficiency (how low the critical mass requirement is) and operating temperature (how high a temperature they can be operated at).

Currently, beryllium oxide seems to be a good choice. The reactor is encased in an outer pressure vessel. The pressure vessel material would have a high strength-to-weight ratio. High-strength steels and fiber-reinforced filament materials are possibilities.

Typically, these engines tend to be big and heavy. The cavity diameter is approximately 2.44 meters. The operating pressure is between $10.14 \times 10^6$ and $10.14 \times 10^7$ newtons per square meter, depending on the reactor power level. The moderator weighs about 27 000 kilograms. For thrust levels from $2.22 \times 10^4$ to $2.22 \times 10^5$ newtons, the engine weight would vary from 51 000 to 132 000 kilograms, respectively. The reactor power would vary from 750 to 7500 megawatts, for this same range. Specific impulse can range from some minimum-interest value of about 2000 seconds to perhaps 7000 seconds.

Approximately 23 to 27 kilograms of uranium-235 is required inside the reactor cavity to maintain a chain reaction. The uranium plasma is at a temperature of approximately 56 000 K. Based on some recent flow experiments, the uranium loss rate is expected to be from 1/400th to 1/200th of the hydrogen propellant flow rate.

## SPECIFIC IMPULSE POTENTIAL

Specific impulse is a measure of the efficiency of a rocket engine, since it is pounds of thrust produced for each pound per second of propellant exhausted. An increase in specific impulse is achieved by adding more energy to the propellant in the rocket engine chamber. Thus higher specific impulse becomes simply a matter of attaining a higher propellant enthalpy.

The following numbers indicate how hot hydrogen must be to attain various values of specific impulse. A solid-core nuclear rocket engine heats hydrogen to approximately 2500 K, which results in a specific impulse of 825 seconds. A specific impulse of 1500 seconds requires a hydrogen temperature of 5600 K, and 5000 seconds requires 22 000 K. These are not precise numbers because the conversion of temperature to specific impulse is affected by nozzle heat losses, nozzle expansion ratio, and the overall efficiency of the expansion process; but they do give a fairly good idea of what temperature levels are involved.

The specific impulse of a gas-core rocket engine is limited by the fraction of the reactor power that reaches the solid, temperature-limited portions of the engine, and by how that heat is removed. It is an unavoidable characteristic of the nuclear fission process that about 7 to 10 percent of the energy release is high-energy gamma and neutron radiation that will go through the hydrogen gas but be stopped in the solid reactor structure.

The precise moderator heating percentage would be determined by such factors as the uranium dwell time in the cavity, the hydrogen density in the cavity, and the particular materials used as the engine moderator-reflector. The calculations of this study were based on 7 percent. If the actual value turned out to be as high as 10 percent, the radiator weight would have to be increased in proportion to the extra power that must be radiated.

The energy that is deposited in the moderator can be regeneratively removed by the incoming hydrogen propellant. There is, however, a limit to how much heat the hydrogen can accommodate. For a 3-000-second-specific-impulse engine, 7 percent of the reactor power will heat all the hydrogen propellant to 2780 K before it enters the reactor cavity. To achieve a higher specific impulse would require the solid parts of the engine to operate at an unrealistically high temperature. If the temperature of the porous cavity wall is limited to a little over 1000 K and the wall is cooled only by regenerative hydrogen circulation, the specific impulse would be limited to 2000 seconds.

Higher specific impulses are possible by using an external radiator to dump part of the moderator heat to space. As shown in figure 2, to bring the hydrogen into the reactor cavity at 1000 K for a specific impulse of 5000 seconds would require that the hydrogen remove no more than 1 percent of the reactor power from the moderator. The remaining 6 percent or so would have to be removed by the radiator loop.

The idea of using a radiator to achieve high-specific-impulse, gas-core engines is not new. It was discussed by the author of reference 7 about 10 years ago. Although the principle was never in question, the practicality of employing it was. The general idea that a space radiator for a gas-core engine would be either prohibitively big or heavy prevented serious consideration of the concept until recently. The use of light-weight, compact radiator systems developed for space power systems (ref. 8) now makes this old idea quite attractive.

It appears that the ultimate limitation on the specific impulse of a gas-core engine will depend on the ability to protect the cavity and nozzle walls from an excessive thermal radiation heat flux. Based on current estimates of the optical absorption and emission properties of the gases involved, it looks as though the maximum specific impulse is in the range 5000 to 7000 seconds. The energy transfer processes are quite involved, however, and more theoretical and experimental work is required to determine with much reliability the specific impulse capability of a gas-core engine.

## MAJOR RESEARCH STUDIES

The research studies are aimed at establishing the basic feasibility of the gas-core concept illustrated in figure 1. This comes down to answering the following questions:

(1) What critical mass and what weight of moderator-reflector materials are required for a gas-core engine configuration?

(2) Can a large fuel volume (greater than 20 percent of the engine cavity volume) be obtained with a low uranium loss rate?

(3) Can the engine cavity walls be protected by absorbing practically all the thermal radiation emitted by the fuel in the seeded hydrogen propellant?

There are of course many other questions we might ask, but these seem to be the crucial ones. The research studies which are aimed at answering these questions and which are described in the following paragraphs are

(1) Full-scale reactor experiments

(2) Cold-flow experiments and hot-flow experiments

(3) A radiant-heat-transfer analysis based on measurements of uranium and seeded-hydrogen absorption coefficients

## Full-Scale Reactor Experiments

Through an AEC/NASA-Lewis interagency agreement, extensive critical experiments have been carried out by Idaho Nuclear Corporation on cylindrical (ref. 9) and spherical the full-scale gas-core cavity reactor mockups shown in figures 3(a) and (b). (The work on spherical reactor mockups is being done under NASA grant C-67747A.) The cylindrical reactor cavity is 1.83 meters in diameter and 1.22 meters long. It is surrounded by a 0.9-meter-thick reflector-moderator region of heavy water on all sides. The outer diameter of the reactor is 3.6 meters and it is 3.0 meters long. Generally, uranium foils 1-mil (0.025-mm) thick are distributed in the cavity region to simulate the gaseous uranium. (Experiments were also run in which uranium hexafluoride gas was used to give a more accurate representation of gaseous uranium.) The fuel was distributed within the cavity in many ways to simulate the shape, size, and concentration distribution of fuel as it might occur in real reactor operation. The effects of hydrogen propellant between the fuel zone and the cavity wall, and also mixed with fuel, have been investigated. The effect of lumpy fuel distributions, such as might occur when the coflowing hydrogen and uranium gases pass through the cavity, has been investigated. Currently, experiments are underway on a spherical reactor configuration, shown in figure 3(b).

The experiments have yielded a good understanding of gaseous cavity reactors, which was impossible to obtain by analysis. The body of data now available constitutes a challenge to the analyst to provide theoretical solutions that can be used within the limitations of today's computers. In $2\frac{1}{2}$ years of operation, over 600 configurations have been investigated. All our critical mass estimates are based on these experiments. The present indications are that about 23 to 27 kilograms of uranium will be required to achieve criticality with 23 000 to 32 000 kilograms of moderator-reflector surrounding the cavity.

## Cold-Flow Experiments

United Aircraft Research Laboratories under NASA-Lewis contract support and direction has been carrying out cold-flow experiments (ref. 10) on a pure coaxial-flow system shown schematically in figure 4(a). Figure 4(b) depicts the experimental apparatus. The objective of the experiments is to determine if a relatively large, stable fuel-rich volume can be maintained within the test cavity at simulated propellant- to fuel-mass-flow ratios of 100 and greater.

Initial experiments were only moderately encouraging. Figures 5(a) and (b) show the flow at mass-flow ratios of 30 and 55, respectively. The acceptable fuel volume of about 25 percent of the cavity volume at a flow ratio of 30 did not persist at a flow ratio of 55. The turbulence already quite apparent in figure 5(a) at the fuel-propellant interface, developed into a major recirculation flow pattern that greatly diluted the fuel when the mass-flow ratio was increased from 30 to 55. This was clearly an unacceptable flow pattern.

Additional experiments have shown that this recirculation pattern can be eliminated, or at least the onset of it can be delayed, so that much higher mass-flow ratios can be achieved. It was discovered that most of the turbulence seen in figure 5(a) was being introduced into the cavity with the incoming flow. When a thick, high-porosity material was placed across the inlet face, a quite stable, laminar-like interface between the simulated fuel and propellant persisted at flow ratios of 100 (fig. 6(a)) and even as high as 370 (fig. 6(b)).

These results have been quite encouraging. The apparent fuel volume in figure 6(b) is about 30 percent of the cavity volume. There may well be some dilution with the "propellant" so that the effective fuel volume is more like 20 or 25 percent of the cavity volume. Experiments are now underway to measure the actual fuel concentrations at these high-mass-flow-ratio conditions. The cold-flow results to date indicate that the fuel volumes of 20 to 30 percent can be achieved at mass-flow-rate ratios in the range 100 to 400.

## Hot-Flow Experiments

Under NASA-Lewis contract support and direction, TAFA Division of Humphreys Corporation has conducted hot-flow experiments. The basic hot-flow test configuration is shown schematically in figure 7(a) and is depicted in figure 7(b). Induction heating is used to electrically simulate the heat generation that would occur by nuclear fission in an engine. The objective of these tests is to determine if hot, heat-generating plasma flows exhibit the same general flow characteristics as cold flows, and, more generally, to develop a technique to provide nonnuclear simulation of gas-core flow conditions.

This line of research has been quite productive and has provided a number of positive, encouraging results. With the exception of absolute size, power level, and pressure, most of the important reactor features have been incorporated into various phases of the induction experiments. Solid particle and rod feed systems have been used; curved porous wall geometries have been operated; choked-flow, transpiration-seeded-gas, nozzle tests have been made; and induction torches have been operated at pressures above $5\times10^{6}$ newtons per square meter. In addition, tests have been conducted at increasing sizes and correspondingly lower electrical frequencies, in order to develop the capability of large-scale, high-power testing. Figure 7(b) shows a 0.15-meter-diameter torch operating at an electrical power level of 1 megawatt, with 600 kilowatts generated in the plasma. Figure 8 shows a 0.3-meter-diameter test section that was recently operated successfully using a 960-hertz, 1.25-megawatt, motor-generator power supply.

Figure 9 shows some measurements that have been made in the induction torches. Concentration profiles measured with and without heating (figs. 9(a) and (b)) indicate that heat generation eliminates the recirculation flow and mixing that occurs with cold flow. Figure 9(c) shows the temperature field achieved with induction heating. Volumetric heat generation rates expected in a low-thrust, gas-core engine have been simulated. For example, the volumetric heat generation in the fuel region of a 5000-second-specific-impulse, $2.22\times10^{4}$-newton-thrust, gas-core engine would be about 400 megawatts per cubic meter. In a 0.15-meter-diameter, 1-megawatt induction torch, volumetric heating rates of 900 megawatts per cubic meter were achieved. Anticipated fuel temperatures of approximately 56 000 K have not been reached in these tests because of the smaller absolute size, power level, and pressure of the induction torches.

The results of the heated-flow experiments have been promising. Hot-flow is at least as good as cold flow, and perhaps better from the point of view of stable flow and low mixing rates between the two streams. Further, this technique provides a good way to study most of the important characteristics of a gas-core engine without actually building a more complicated and expensive nuclear device.

## Radiant Heat-Transfer Analysis

The ability to absorb the thermal radiation from the central fuel ball in the surrounding flow of seeded hydrogen propellant will be the key to achieving a specific impulse in the range 3000 to 7000 seconds. No more than approximately 1 percent of the radiated reactor power can be allowed to reach the inner surface of the reactor cavity. Even that amount of heat will result in a wall temperature in the range 1000 to 2780 K, depending on the specific impulse. An analysis has been carried out to determine if it is reasonable to expect that the cavity wall can be thermally protected.

The absorption properties of the gases involved are necessary to carry out such an analysis. Under NASA grant support and Lewis direction, spectral absorption coefficients of uranium gas have been measured over a limited wavelength range at the University of Maryland, and those of hydrogen seeded with carbon and with tungsten at the Georgia Institute of Technology (ref. 5). Based on these measurements and related opacity theories, a radiant-heat-transfer analysis has been carried out (ref. 11) to determine the temperature profile and heat-flux distribution in a gas-core engine.

It appears that the wall can be protected for a specific impulse of at least 5000 seconds, although this maximum specific impulse may be a function of the thrust level. Figure 10 shows the temperature profile expected in the reactor cavity of a 5000-second-specific-impulse, 130 000-newton-thrust, gas-core engine. This reactor develops 4500 megawatts of power in a fuel volume that is 25 percent of the cavity volume. The radiant heat flux leaving the edge of the fuel region is $1.9\times10^5$ kilowatts per square meter.

More than 99 percent of the radiated power is absorbed in the seeded propellant stream. The radiant heat flux reaching the cavity wall is $6.45\times10^2$ kilowatts per square meter. In this example, the cavity wall is constructed of porous graphite that is 0.6-centimeter thick. An additional 0.2 percent of the reactor power is deposited in this wall due to gamma-ray heating. The total hydrogen flow rate of 2.7 kilograms per second is passed uniformly through the cavity wall to pick up both the thermal radiation and the gamma heating. This total amount of heat produces a temperature rise of 830 K in the hydrogen. For a hydrogen temperature just outside the porous wall of 170 K, the hydrogen would enter the reactor cavity at 1000 K, which would also be the inner wall surface temperature.

There is obviously more to this problem than just this one calculation. More information is needed about the absorption properties of seeded hydrogen in the temperature range 2780 to 5600 K. Although uranium at 11 000 K behaves optically pretty much as theory would predict, it would be desirable to have experimental measurements in the over-56 000-K range as well. Steps are underway to obtain these and other missing pieces of information. The present indications are that from a cavity wall cooling viewpoint, a specific impulse of at least 5000 seconds, and perhaps 7000 seconds, is possible.

## PROJECTED ENGINE CHARACTERISTICS

It is interesting and helpful to use the best current information available from the research studies to project what gas-core engine characteristics might be. This information can then be used to provide valuable feedback into the research program by establishing, through mission analysis, desirable specific impulse, thrust, and engine weight goals.

Engine weight would increase approximately as the square root of the engine thrust level. This is shown in figure 11 for a 5000-second-specific-impulse engine that has a 2.4-meter-diameter reactor cavity surrounded by 28 000 to 132 000 kilograms of moderator-reflector for thrust levels from $2.2\times10^4$ to $2.2\times10^5$ newtons. This corresponds to a specific mass that varies from 0.1 kilogram per kilowatt (at $2.2\times10^4$-N thrust) down to 0.02 kilogram per kilowatt.

For thrusts less than $4.4\times10^4$ newtons, the engine weight is composed primarily of moderator and pressure shell weights. Above a thrust of $4.4\times10^4$ newtons, the radiator weight becomes increasingly significant. Reactor power also varies for the conditions shown in figure 11, in proportion to engine thrust. A reactor power of 750 megawatts is required for a thrust of $2.2\times10^4$ newtons, and 7500 megawatts for a thrust of $2.2\times10^5$ newtons.

The thrust, weight, and specific impulse characteristics of a gas-core engine can be used to determine its mission capability on a space mission. One example of its performance capability is shown in table I for an advanced Mars mission.[1] For comparison, the performance capability of a solid-core engine is also shown. The mission is a round trip to Mars that departs Earth orbit with a payload of 230 000 kilograms and returns a payload of 90 000 kilograms to Earth. The return payload is composed of life-support and Earth-reentry equipment.

The advantage of the 5000-second specific impulse of a gas-core engine shows up in terms of reduced trip time. The solid-core trip time of 500 days is reduced to 200 days with the gas-core engine. For this mission the optimum thrust level of the gas-core engine is $2.2\times10^4$ newtons. Three $3.3\times10^5$-newton-thrust, solid-core engines would be required to provide the optimum thrust of $8.8\times10^5$ newtons at the lower specific impulse of 825 seconds.

The gas-core propelled vehicle requires a little less hydrogen propellant for the mission than does the solid-core; namely, 350 000 kilograms compared to 400 000 kilograms. For a uranium flow rate that is 1/400th of the hydrogen flow rate, the total uranium investment for the mission would be 950 kilograms, including an allowance of four critical masses expended during reactor startup and shutdown operations. The three solid-core engines would contain 680 kilograms of uranium. The exact values of the numbers are not important, because they could easily change by a factor of at least 2. The point is that once the gas-core hydrogen- to uranium-mass-flow ratio gets into the range of 100 to 400, the uranium consumption on a space mission would be the same order of magnitude as that of a solid-core engine.

[1]Based on unpublished work at NASA-Lewis.

## KEY WORK AREAS

The present work is continuing in the major areas discussed in this report. Isothermal flow tests are underway on more complicated, and more realistic, geometries incorporating curved, porous walls and more accurate simulation of the fuel injection phenomena. Induction-heated flow experiments are being conducted on configurations that more closely represent engine features. Reactor experiments using gaseous fuel in a spherical geometry are being conducted. In addition, more basic theoretical and experimental studies on gas optical properties continue.

The results obtained to date are quite promising, but the returns are not all in. The following aspects of gas-core engines are felt to be the major unexplored areas remaining to be investigated:

(1) Large-scale hot flow
(2) Nozzle cooling
(3) Cold-flow (zero power) reactor experiment
(4) Conceptual design study
(5) Mission analysis and other applications
(6) Engine startup and control

Some work either has already been done, or is being started, in each of these areas. The work will be difficult, and there is certainly no guarantee of success, but the results to date and the potential engine performance justify, and in fact impel, the effort.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, January 8, 1971,
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TABLE I. - COMPARISON OF GAS-CORE AND SOLID-CORE NUCLEAR ROCKETS

Basis: Mars round trip with 230 000-kg/90 000-kg payload.[a]

| | Gas-core rocket ($I_{sp}$ = 5000 sec) | Solid-core rocket ($I_{sp}$ = 825 sec) |
|---|---|---|
| Trip time, days | 200 | 500 |
| Ratio of engine thrust to weight, N/kg | $2.2\times10^{4}/51\ 000$ | $8.8\times10^{5}/30\ 000$ |
| Hydrogen mass, kg | 350 000 | 400 000 |
| Ratio of hydrogen to uranium mass flow rates | 400 | -------------- |
| Uranium investment, kg | 950 | 680 |
| Initial vehicle gross weight, kg | 770 000 | 770 000 |

[a]Payload of 230 000 kg departing Earth orbit, 140 000 kg deposited at Mars, 90 000 kg returned to Earth.

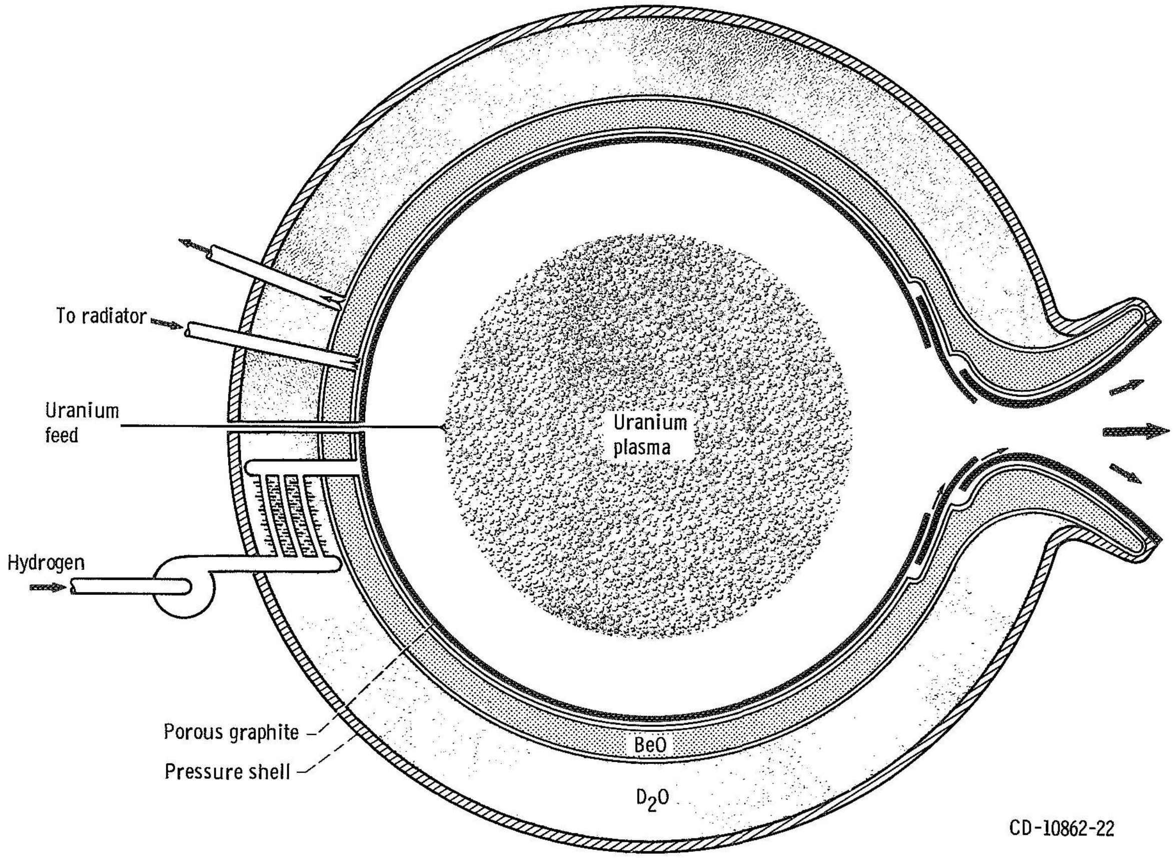



Figure 1. - Porous-wall, gas-core engine.

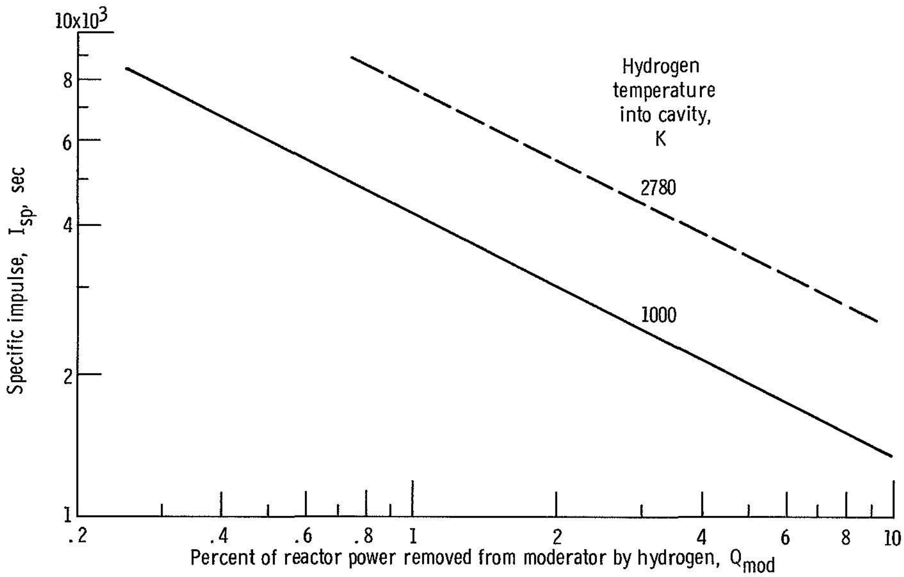
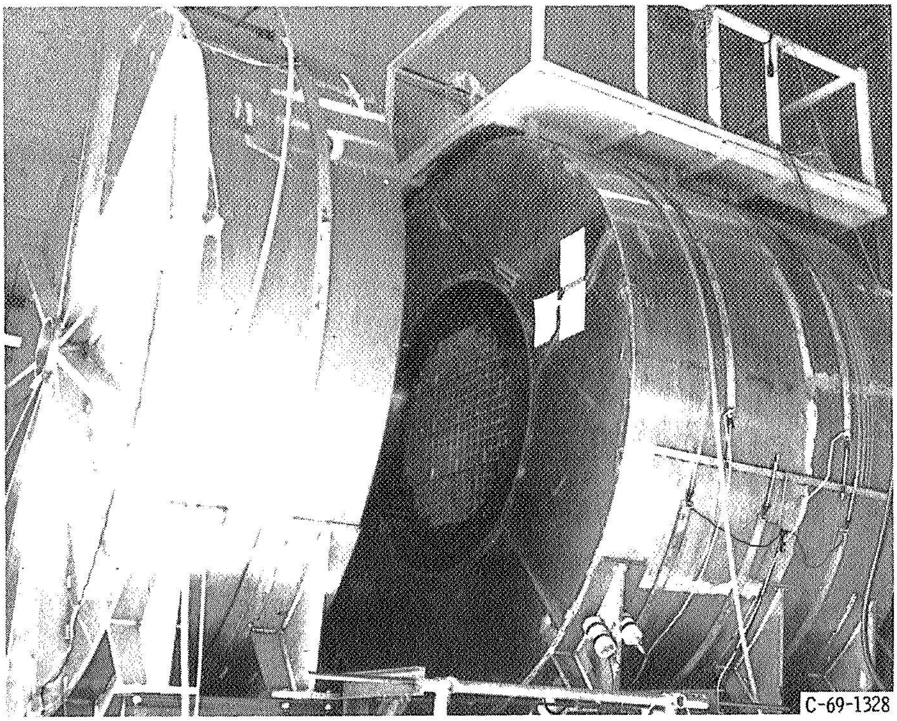
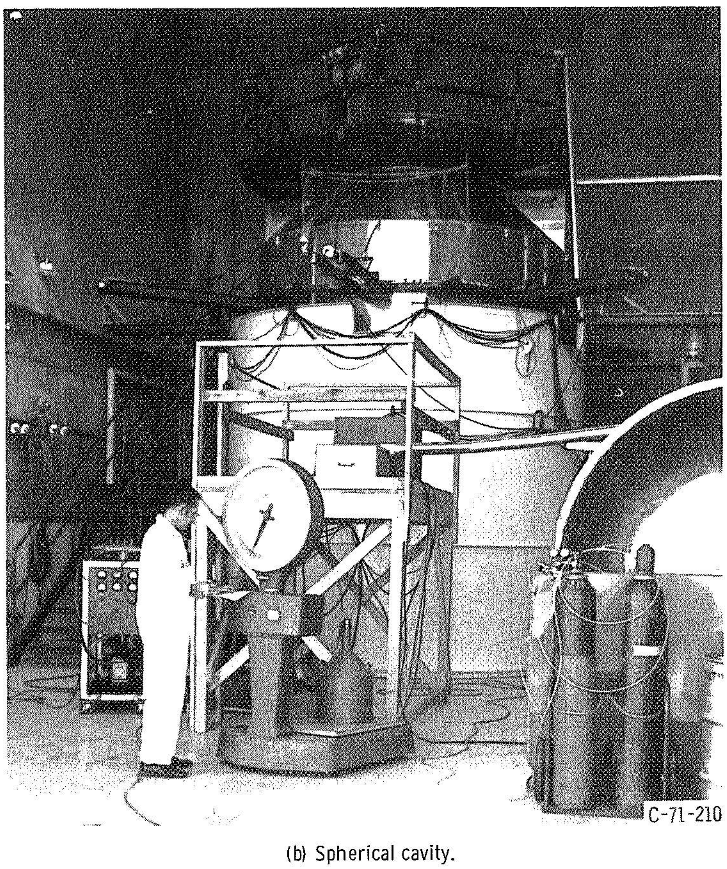



Figure 2. - Gas-core-rocket specific impulse.

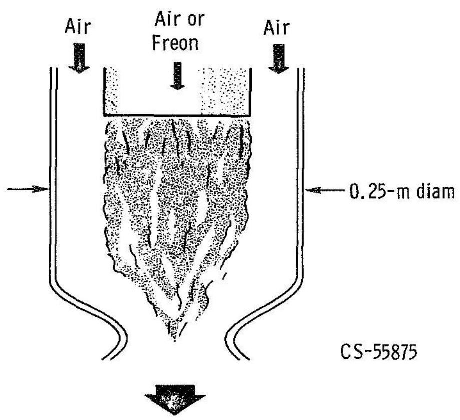



(a) Cylindrical cavity.

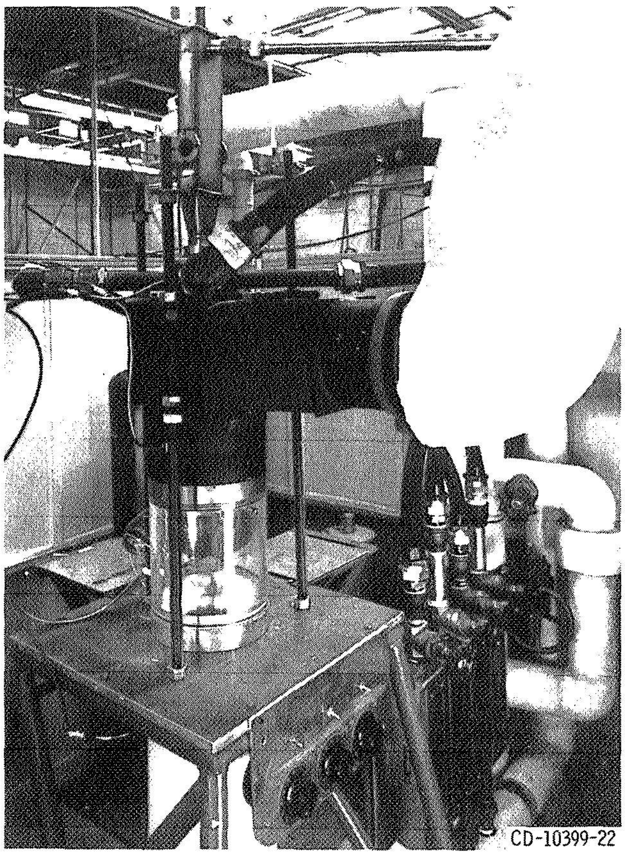



(b) Spherical cavity.

Figure 3. - Full-scale gas-core critical experiment.

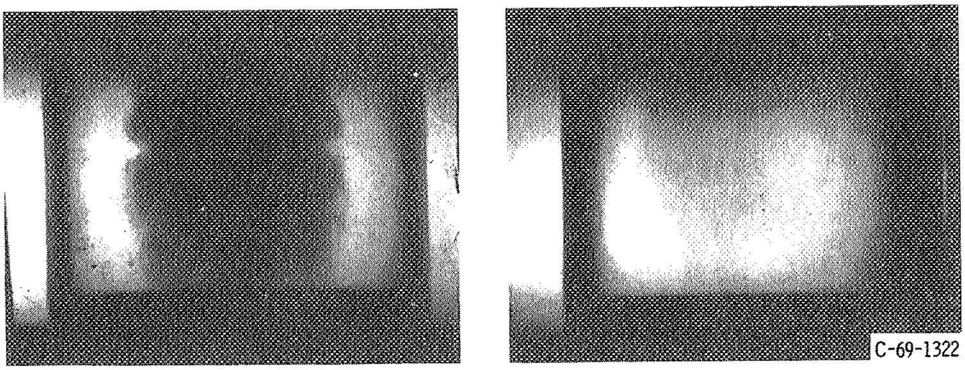



(a) Schematic of pure coaxial-flow system. Mass-flow ratio, 10 to 500; density ratio, 1 to 4.




(b) Cold-flow test apparatus.

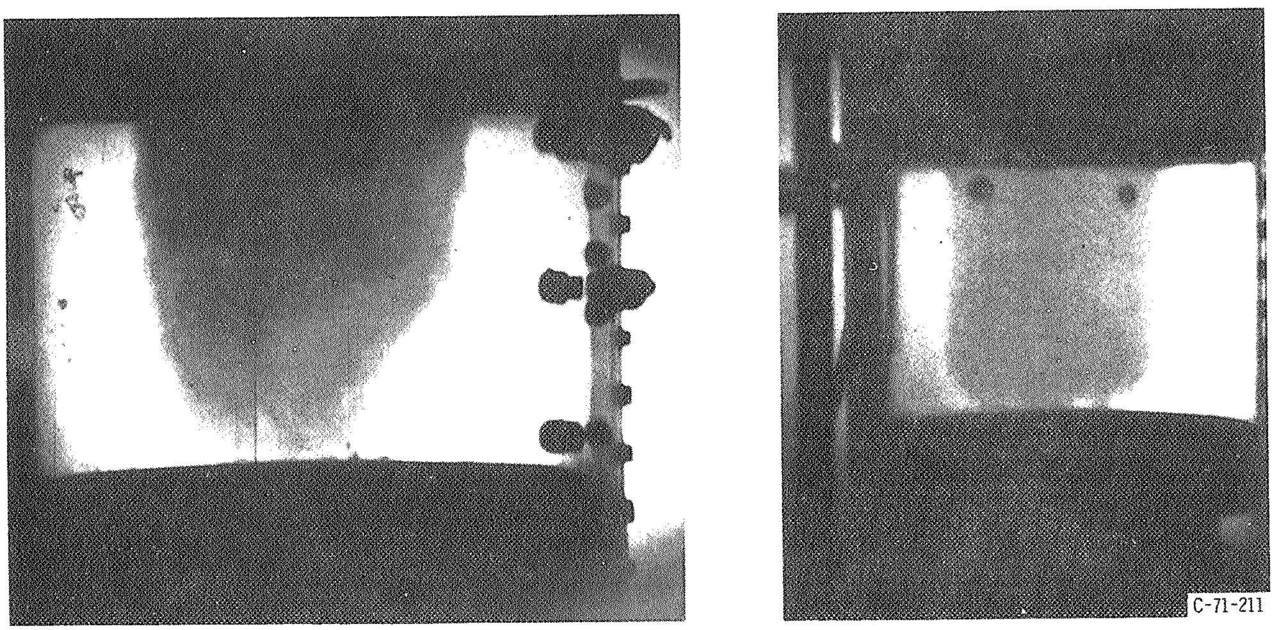
Figure 4. - Cold-flow experiment.




(a) Outer- to inner-mass-flow ratio of 30, showing good fuel-region containment.

(b) Outer- to inner-mass-flow ratio of 55, showing very poor fuel-region containment.

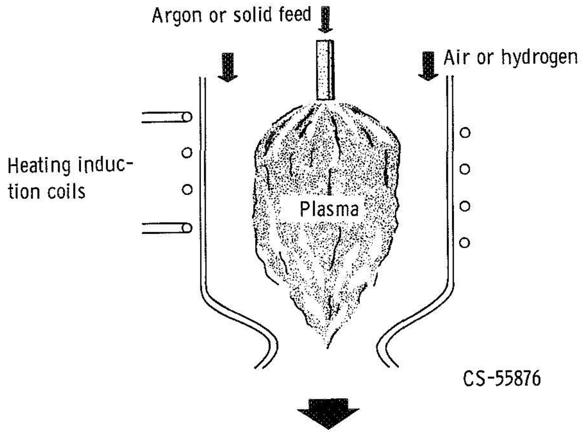
Figure 5. - Cold-flow test results with no porous material at inlet.



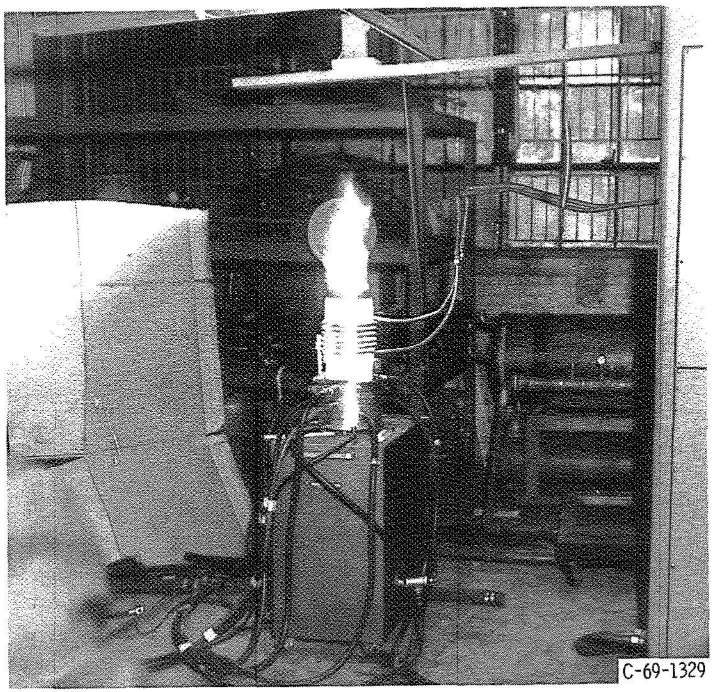

(a) Outer- to inner-mass-flow ratio of 100, showing good fuel-region containment.

(b) Outer- to inner-mass-flow ratio of 370, showing good fuel-region containment.

Figure 6. - Cold-flow test results with porous material at inlet.

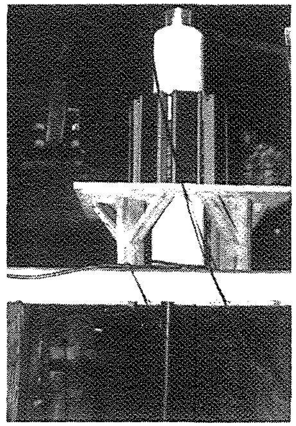



(a) Schematic of test apparatus.

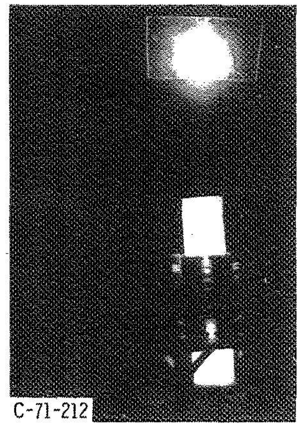



(b) Test apparatus operating at 1 megawatt of electrical power.

Figure 7. - Hot-flow experiment.

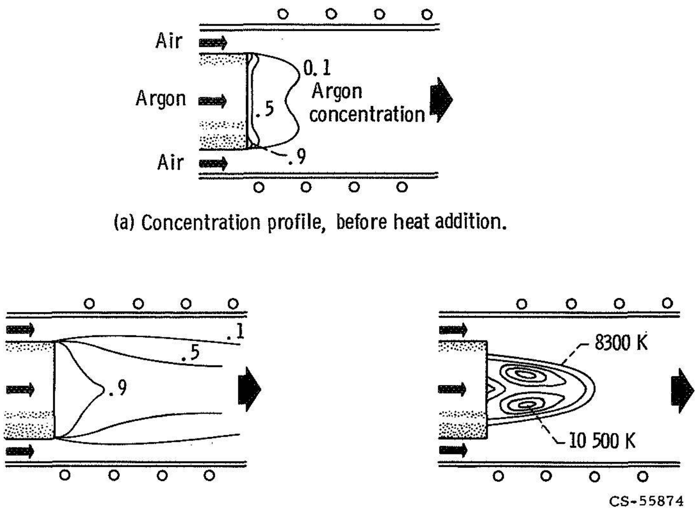


(a) Test apparatus, 0.3-meter diameter, showing laminated magnetic flux reflectors.




(b) Test in progress, showing mirror view from above.

Figure 8. - Hot-flow experiment using 960-hertz motor-generator power supply.




(a) Concentration profile, before heat addition.

(b) Concentration profile, with heat addition.

(c) Temperature distribution, with induction heating.

Figure 9. - Hot-flow measurements.

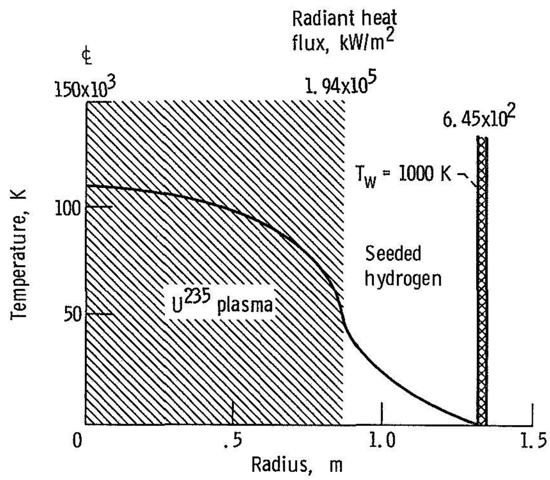



Figure 10. - Cavity temperature distribution for specific impulse of 5000 seconds.

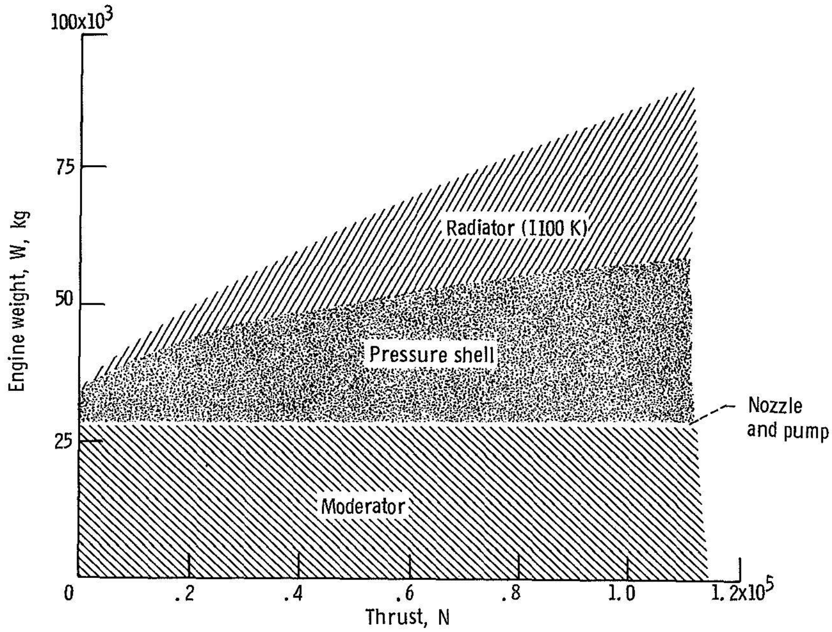



Figure 11. - Engine weight breakdown for specific impulse of 5000 seconds.

*"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."*

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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