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EXPLORING IN AEROSPACE ROCKETRY
19. NUCLEAR ROCKETS

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Presented to Lewis Aerospace Explorers
Cleveland, Ohio
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19. NUCLEAR ROCKETS

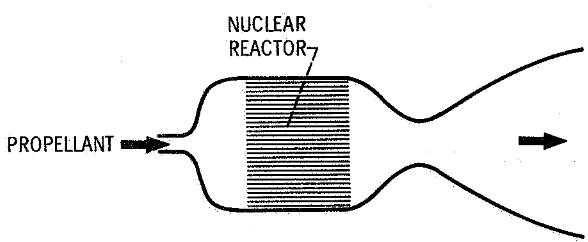
A. F. Lietzke*

Future interplanetary missions will require extremely heavy vehicles if chemical rockets are to be used for propulsion. Nuclear rockets have the performance potential to reduce the required weight for these advanced missions.

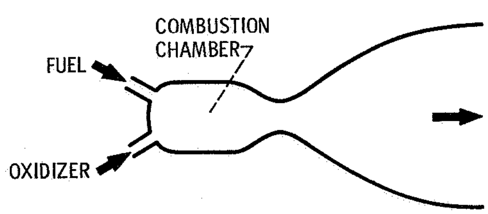
This chapter describes a nuclear rocket, how it functions, its limitations, and expected performance. The difference between chemical and nuclear rockets is illustrated. It is assumed that the reader is familiar with the general fundamentals of rockets. Therefore, only those aspects peculiar to nuclear rockets are emphasized herein.

A nuclear rocket, shown schematically in figure 19-1(a) uses a nuclear reactor to heat a propellant and a nozzle to accelerate the propellant.

The difference between a nuclear rocket and a chemical rocket can be seen by comparing figures 19-1(a) and (b). While the heat energy in a chemical rocket comes from burning the fuel with an oxidizer in a combustion chamber, the heat energy in a nuclear rocket comes from a nuclear reaction; the nuclear reactor (discussed later) replaces the combustion chamber. Moreover, the nuclear rocket uses a single propellant which does



(a) Nuclear rocket engine.



(b) Chemical rocket engine.

Figure 19-1. - Schematic diagrams of nuclear and chemical rocket engines.

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not react chemically, whereas the chemical rocket requires two propellants - a fuel and an oxidizer.

Therefore, the propellant for a nuclear rocket is not restricted to one which reacts chemically and may be selected on the basis of other properties. This fact leads to the advantage of a nuclear rocket.

The nuclear rocket and the chemical rocket both use a convergent-divergent nozzle to accelerate the propellant and so convert thermal energy to kinetic energy. From our knowledge of the flow process in the nozzle (chapter 2), the ideal exhaust velocity can be expressed by the following equation:

$$V_e = \sqrt{\frac{99\ 400\gamma T_i}{(\gamma - 1)m}\left[1 - \left(\frac{P_e}{P_i}\right)^{(\gamma-1)/\gamma}\right]}$$

where

V_e ideal exhaust velocity

γ ratio of specific heats of the propellant

T_i propellant temperature at the nozzle inlet

m propellant molecular weight

P_e propellant pressure at the nozzle exit

P_i propellant pressure at the nozzle inlet

If all of the factors in this equation are constant except T_i and m, then the ideal exhaust velocity is proportional to the square root of propellant temperature T_i and inversely proportional to the square root of the molecular weight m:

$$V_e \propto \sqrt{\frac{T_i}{m}}$$

The specific impulse I_{sp} is related to the exhaust velocity V according to the following equation (see chapter 2):

$$I_{sp} = \frac{V}{g}$$

where g is the acceleration due to gravity. Therefore,

$$I_{sp} \propto \sqrt{\frac{T_i}{m}}$$

Thus, I_{sp} increases as T_i increases and also I_{sp} increases as m decreases. The temperature T_i attainable in solid-core nuclear rockets is actually lower than the temperature in chemical engines. The advantage of the nuclear rocket over the chemical rocket results from the propellant selected. Because the nuclear rocket engine does not require a relatively high molecular weight oxidizer, the best propellant available can be selected, the one with the lowest molecular weight, pure hydrogen. Hydrogen H_2 has a molecular weight of 2 as compared with a value of 18 for one of the best chemical propellants, hydrogen-oxygen.

The materials of which a nuclear rocket can be constructed will limit the hydrogen temperature T_i to less than 6000° R or a specific impulse of approximately 1000 pounds of thrust per pound of hydrogen flow per second. This specific impulse is over twice that of the best chemical propellants (see chapter 7).

As mentioned previously, the nuclear reactor replaces the combustion chamber or the "chemical reactor" in the chemical rocket. The operating principles of the nuclear reactor are based on the interactions between neutrons and atomic nuclei. Atomic nuclei consist of two kinds of primary particles, protons and neutrons. An atom consists of a nucleus surrounded by much smaller particles called electrons.

The chemical nature of an element depends on the number of electrons in orbit about the nucleus. This number of electrons is equal to the number of protons in the nucleus. Therefore, the chemical behavior depends on the atomic number of the element (atomic number = number of protons). Atomic numbers range from 1 for hydrogen to 92 for uranium.

The nuclear nature of an element depends on the conditions of the nucleus. The nucleus is made up of protons and neutrons. Atoms of a given element can exist with different numbers of neutrons in the nucleus. These different species of the same element are called isotopes of the element. Although the chemical properties of these isotopes are identical, their nuclear properties may be entirely different. Therefore, it is important to distinguish between isotopes of a given element. This can be done through the use of the atomic mass number, or simply mass number (mass number = number of protons plus number of neutrons). Thus, each isotope, instead of having a new name, is identified by writing the mass number after the chemical element or symbol. For example, the uranium isotope with a mass number of 235 is written as uranium-235 or U^{235}.

As neutrons pass through matter, they collide with atomic nuclei. The collisions cause various interactions between the colliding neutrons and nuclei. These interactions can be divided into three types: scattering, parasitic capture, and fission interactions.

Scattering interactions result from those collisions which disrupt the neutron from its path. During such collisions the neutron transfers some or all of its energy to the nucleus but a neutron remains free after the interaction.

Parasitic capture reactions result from those collisions in which the neutron enters the nucleus and remains absorbed in the nucleus. When this happens, other subatomic particles and/or radiation are released from the compound nucleus.

Nuclear fission reactions result from those collisions in which neutron capture causes the nucleus to break up, with a release of a large amount of energy. The fission process is illustrated in figure 19-2. The nucleus is broken into two primary fission fragments (elements of lower atomic number than the original nucleus), neutrons, and gamma radiation (high energy X-rays). Most of the energy from the fission process appears as kinetic energy of the fission fragments moving at high speed. The new neutrons are also ejected at high speed. The latter are available to cause more fissions and offer the possibility of maintaining a chain reaction.

The various interactions can be summarized as follows. Each collision between a neutron and a nucleus will result in scattering and slowing down of the neutron, neutron capture, or nuclear fission. Most reactions produce damaging radiation requiring a protection or shield. Which of these interactions occur and the probability of each depend on the type of nucleus involved and the neutron energy.

Although essentially all of the elements can take part in scattering and parasitic capture of neutrons, the probability of such interactions occurring varies greatly from one element to another. On the other hand, only the heaviest elements will fission as a result of neutron collision. Of these heavy elements, uranium and plutonium are of pri-

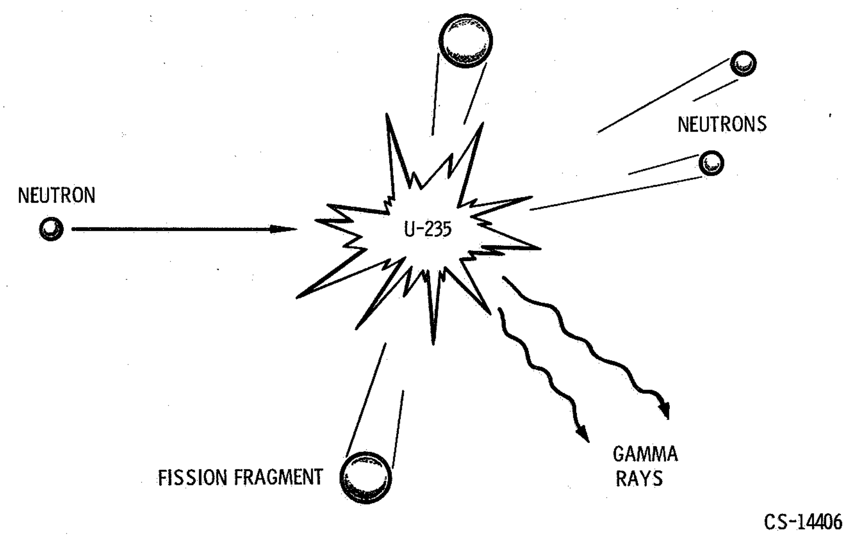


Figure 19-2. - Nuclear fission process.

mary interest. The possibility of fission, however, depends on the particular isotope and the neutron energy. Considering uranium, for example, slow and fast neutrons will fission uranium-233 and uranium-235, whereas only fast neutrons will fission uranium-238. The probability of fission is greatest with uranium-233 and uranium-235; therefore, these isotopes are most desirable for nuclear reactors. Unfortunately, uranium appears in nature in the following isotopic proportions:

Isotope	Percent in nature
Uranium-234	0.006
Uranium-235	.712
Uranium-238	99.282

Plutonium and uranium-233 are essentially nonexistent in nature. Consequently, most current nuclear reactors utilize uranium-235 which has been separated from the other isotopes of uranium in the gaseous diffusion plants at Oak Ridge, Tennessee; Paducah, Kentucky; or Portsmouth, Ohio.

The interactions of neutrons with nuclei are studied by means of the concept of nuclear cross sections. The cross section for a reaction may be defined as a measure of the probability of that reaction taking place under prescribed conditions. It is a property of a material and is a function of the energy of the incident neutron. A typical curve illustrating this variation with neutron energy is shown in figure 19-3.

At low energy (slow neutrons) the probability of reaction (cross section) is inversely proportional to the neutron velocity. This can be thought of as the cross section being proportional to the time the neutron is in the vicinity of the nucleus.

In the intermediate energy range, the cross section curve typically has peaks at certain energies, and this portion of the curve is called the resonance region.

At high energies, the cross section decreases steadily as the energy increases, and finally it approaches the geometrical cross section of the nucleus.

As a result of the interactions of neutrons with nuclei, a nuclear reactor can be designed which for steady state requires the following neutron balance:

$$\text{Production} = \text{Absorption} + \text{Leakage}$$

The fission of a uranium-235 nucleus by reaction with a low energy neutron <u>produces</u> an average of 2.5 neutrons. (The number of neutrons produced is not an integer because some fissions produce 2 neutrons and some fissions produce 3 neutrons.) If an average

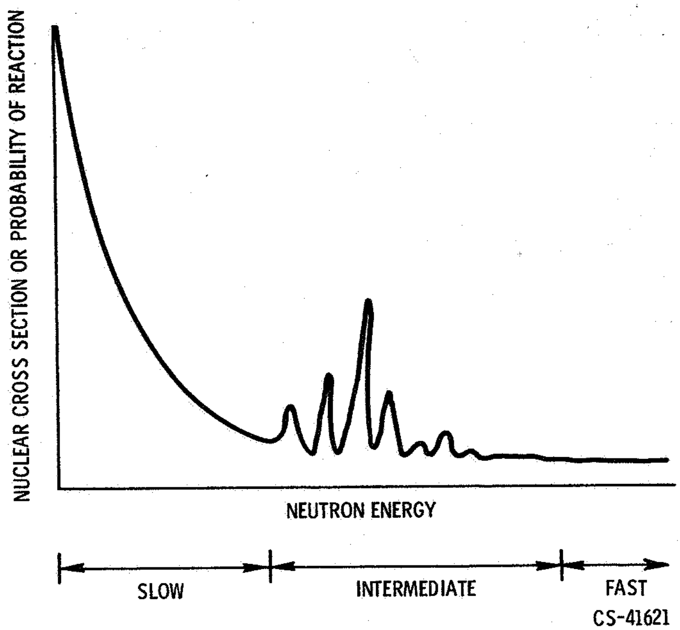


Figure 19-3. - Typical variation of nuclear cross section with neutron energy.

of one of these neutrons interacts to produce another fission before it is absorbed in parasitic capture or leaks (escapes) from the reactor, then a self-sustaining chain reaction results and nuclear energy will continue to be generated. This critical condition can be achieved most easily by restricting the materials of the reactor to fissionable materials and materials that have low parasitic capture cross sections and also by limiting the leakage from the reactor. The manner in which this critical condition is achieved determines the reactor type.

Merely increasing the number of nuclear fuel atoms (uranium-235) increases the probability of the neutrons hitting a fuel atom. The assembly of an amount of fuel necessary to achieve the critical condition results in a fast reactor, so-called because there is no neutron scattering or moderating material incorporated to slow down the neutrons and all the fissions must result from capture of fast neutrons. Because the cross section for fission is relatively low at these high energies, this type of reactor requires a large amount of nuclear fuel.

Leakage of neutrons from the reactor can be decreased by the addition of a material that scatters the neutrons but does not capture them to any appreciable extent. This material, in effect, increases the probability of fission capture by increasing the number of passes a neutron makes through the reactor. It is usual practice to select a low-atomic-weight element for this material in order to make it more effective in slowing down neutrons and thus increasing the fission cross section of the fuel. Such a reactor is called a moderated reactor. If enough of this moderating material is utilized to slow down the neutrons to be in thermal equilibrium with the material, most of the fissions will occur as a result of capture of thermal neutrons. This is a special case of a moderated reactor called a thermal reactor.

Scattering material may also be used to surround the fuel and decrease the leakage by reflecting the neutrons back into the fuel of the reactor. This technique may be used for both the fast and moderated reactors.

When the concept of nuclear cross section (discussed earlier) is used, the interaction rate of neutrons with nuclei is given by

$$\text{Rate of interaction per cubic centimeter} = N\sigma nv$$

where

N number of target nuclei per cubic centimeter

σ nuclear cross section, cm^2/nucleus

n neutron density, neutrons/cm^3

v neutron velocity, cm/sec

The rate of energy release, or the power of the reactor, is then given by

$$\text{Power per cubic centimeter} = E_f N\sigma_f nv$$

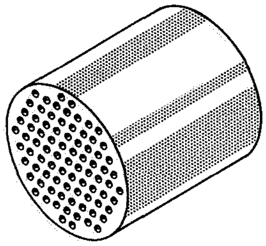
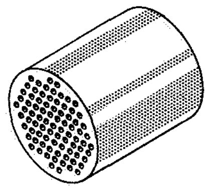
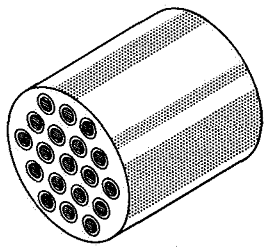
where E_f is the energy per fission and σ_f is the fission cross section of the fuel nuclei. Inasmuch as nuclear reactions are independent of the direction of neutron motion, it is usual to refer to neutron flux rather than neutron current. The product nv is called neutron flux, and this concept of flux can be applied to neutrons moving in random fashion.

A reactor can generate any power. The desired power is obtained merely by controlling the neutron population n. The neutron population, in turn, can be controlled by regulating (a) production (inserting or withdrawing fuel), (b) absorption (inserting or withdrawing material of high parasitic capture cross section), or (c) leakage (moving a reflector toward or away from the reactor).

The energy from the fission process is mainly in the form of kinetic energy of the fission products which is converted to heat energy as these products are stopped by the material of the reactor. The power of a reactor is limited only by the capability for removing this heat. In a nuclear reactor of a rocket the heat is transferred to the propellant, and provision must be made to allow passage of the propellant through the reactor.

Some of the reactor types and the materials which have been considered for nuclear rockets are listed in table 19-I. Two thermal reactors and one fast reactor are listed.

TABLE 19-I. - NUCLEAR ROCKET REACTORS AND MATERIALS

Reactor type	Configuration	Moderating material	Fuel-bearing material
Thermal (homogeneous)		Graphite Beryllium oxide	Coated graphite
Fast		None	Tungsten Molybdenum Zirconium carbide
Thermal (heterogeneous)		Water Heavy water Beryllium Beryllium oxide Metallic hydrides	Tungsten Molybdenum Coated graphite

The thermal homogeneous reactor has nuclear fuel dispersed throughout the moderating material and can be visualized as a large block with a number of cooling passages for propellant flow. The fission energy heats the block and this heat is transferred to the propellant as it flows through the holes in the block. Since heat transfer can only occur from a hotter to a cooler substance, the block must be at a higher temperature than the propellant. As shown previously, propellant temperature should be as high as possible. The fuel-bearing material for this reactor, therefore, must not only be a lightweight element but must also have high temperature capability. This dual requirement limits the choice to the two materials shown in the figure, graphite (carbon) and beryllium oxide. Of these two materials, graphite has the higher temperature capability and is preferred. Graphite reacts chemically with hydrogen, however, and must be coated with some other refractory material for protection. Because graphite is not one of the best moderating materials, substantial quantities are required to slow the neutrons and the reactor is necessarily large, even for low power levels. Beryllium allows a smaller reactor, but one that must operate at lower temperatures.

The fast reactor contains no moderating material. The low fission cross sections at the high neutron velocity prevailing must be compensated for by greatly increasing the quantity of fuel. While the fission cross section is low at the high energy of the neutrons, the parasitic capture cross section for other materials is also low for the same reason. Any refractory material may therefore be considered for the fuel bearing material of a fast reactor with but little regard for nuclear properties. Refractory materials such as tungsten, molybdenum, and metallic carbides may be used. The high uranium concentrations required for the fast reactor compromise the high temperature capabilities of these materials because uranium compounds have melting points considerably lower than those of the fuel bearing materials.

The heterogeneous thermal reactor separates the moderator material from the fuel-bearing material. This separation permits independent cooling of the moderator, allowing it to run at much lower temperatures than the hot fuel element heat transfer surfaces. Water, heavy water, beryllium, and beryllium oxide may be considered for the moderator. The fuel-bearing material can be any of the best refractory materials such as tungsten or graphite but must be a low neutron absorbing material as well. If tungsten were to be used, it should be enriched with tungsten-184 because the other isotopes of tungsten are high neutron absorbers.

Reactors are employed in nuclear rockets in the manner illustrated in figure 19-4. This figure shows the propellant flow path. Liquid hydrogen is pumped from a storage tank through the nozzle walls and the reflector to cool these components. The hydrogen then flows through the reactor, where it is heated to a high temperature, and finally out the nozzle to produce thrust.

Power to drive the pump is supplied by a turbine which can be at one of several locations. Figure 19-5 shows an engine system using what is called a bleed turbine driven by hot hydrogen bled off the main hydrogen stream at the nozzle inlet. This bleed flow exhausts through auxiliary nozzles. Only a small percentage of the total flow is required to drive the turbine. Except for this bleed flow, the hydrogen flow path is the same as in figure 19-4.

Calculated weights of rocket engines employing the three reactor types of table 19-I are shown in figure 19-6. To these weights must be added the weight of shielding required to protect the cargo or crew from nuclear radiation. The minimum weights are of the order of a few thousand pounds; they cannot be made lighter, even if the thrust is zero. Consequently, a small scale working model is out of the question. An actual nuclear rocket engine is currently being developed under joint sponsorship of the AEC and NASA. A photograph of this engine under test is shown in figure 19-7.

The weight associated with the nuclear reactor and its radiation shield results in nuclear rocket engines being heavier than chemical rocket engines. Therefore, nuclear rockets offer better performance only when the engine weight is small relative to the propellant weight. In such cases, the higher specific impulse reduces the weight of propellant more than enough to compensate for the heavier engine. Therefore, high-energy missions (for example, interplanetary flight) can be accomplished with nuclear rocket vehicles that weigh considerably less than chemically powered vehicles.

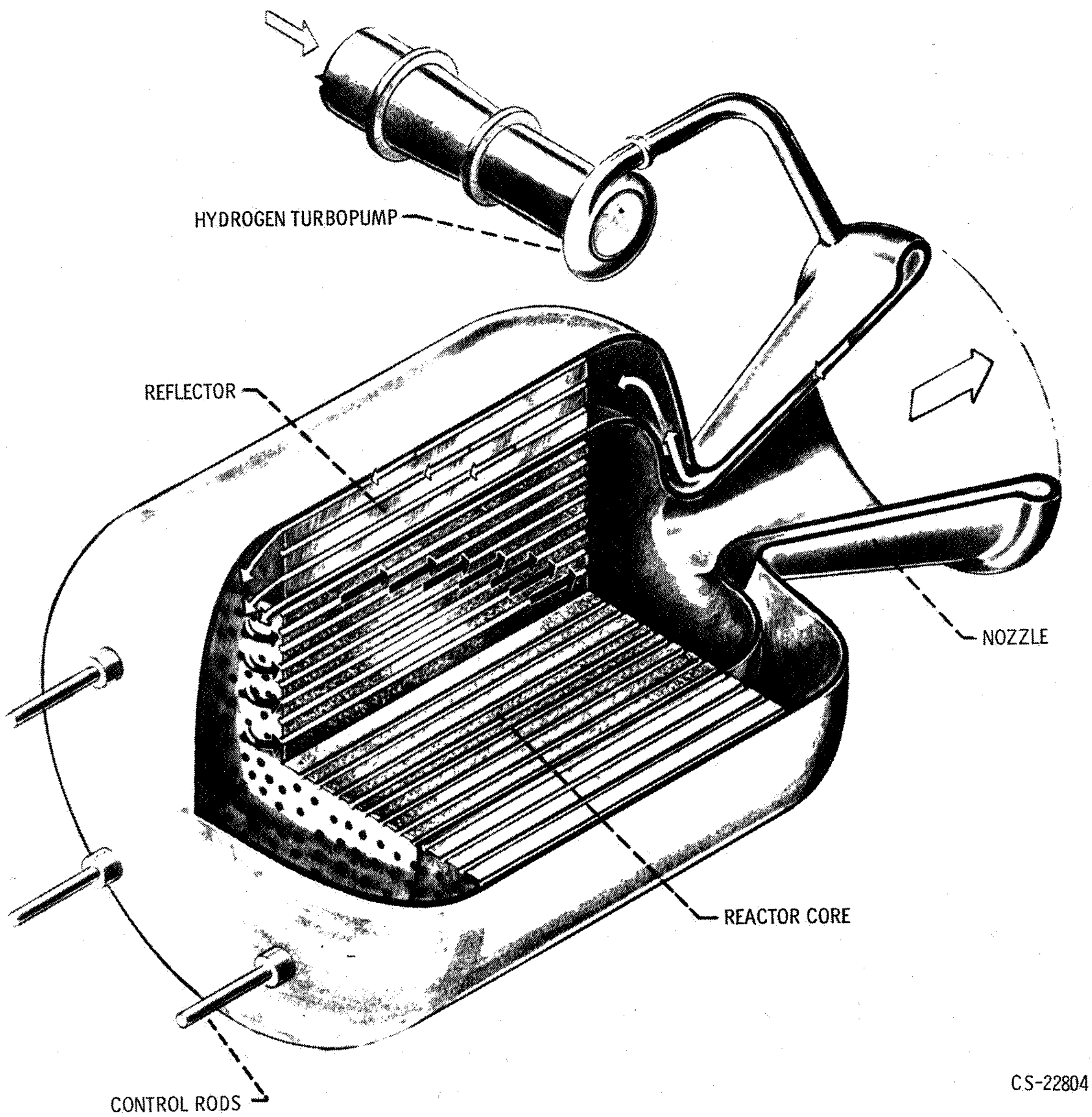


Figure 19-4. - Propellant flow path through nuclear rocket.

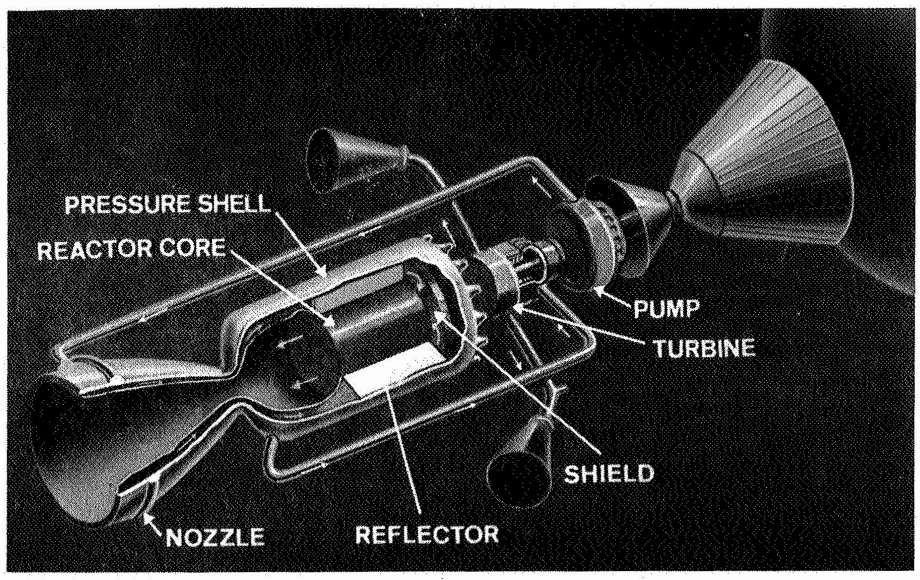


Figure 19-5. - Nuclear rocket engine.

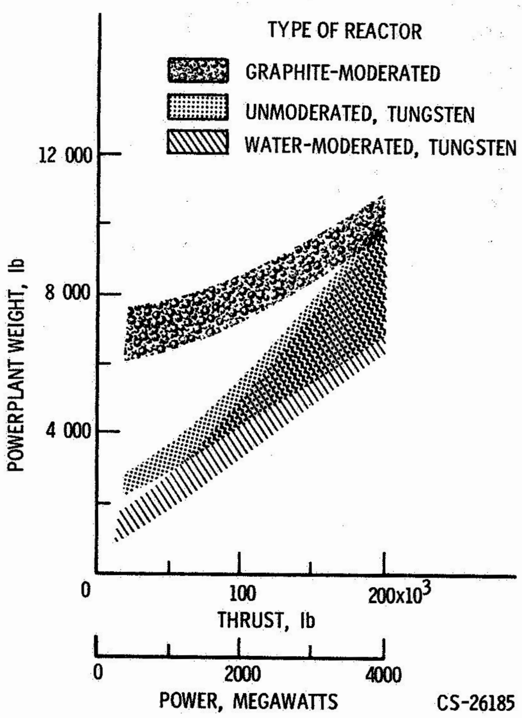


Figure 19-6. - Nuclear rocket powerplant weight.

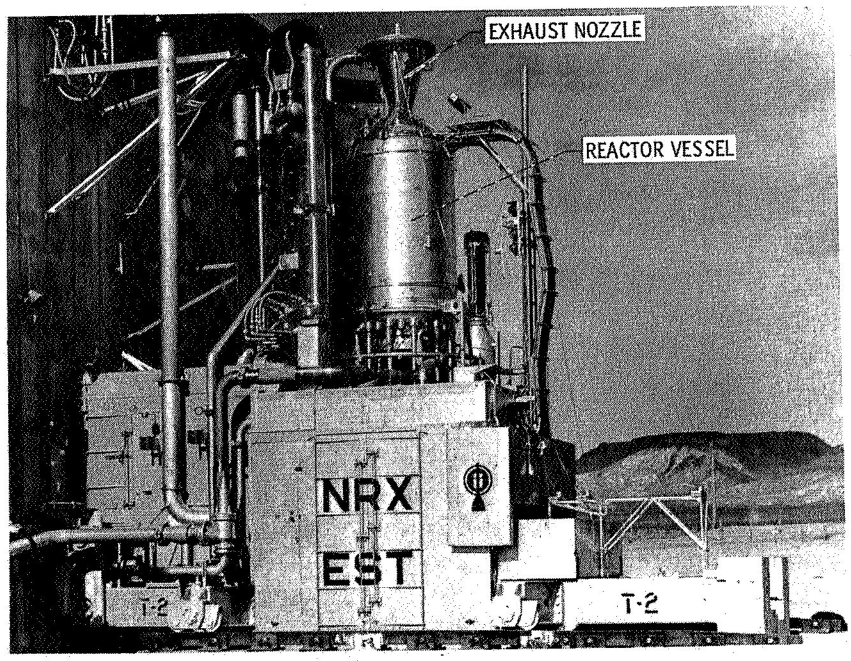


Figure 19-7. - Nuclear rocket engine under test.

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