PRELIMINARY STUDY OF A NUCLEAR ROCKET SYSTEM FOR MANNED PLANETARY MISSIONS

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The primary purpose of the NERVA nuclear rocket currently under development is to demonstrate the feasibility of nuclear rocket propulsion. Once developed, it may have application in missions such as a manned lunar landing or space station supply. Unfortunately, it is too small for manned interplanetary missions. This being the case, it was decided to examine a second-generation nuclear rocket suitable for manned interplanetary flight in order to get an idea of component characteristics and problem areas. This examination is, in general, based on current technology and includes the graphite reactor concept, a nozzle fabricated from Inconel X tubing, and conventional turbopump blading and bearings. Some of the preliminary results of this examination are reported herein.

The manned planetary mission on which the study of a second-generation nuclear rocket system is based is illustrated in figure 1. Some of the ground rules for this mission were as follows:

(1) Seven-man mission with four men on Mars for a 40-day stay

(2) Separate nuclear engines for all three propulsion phases starting with departure from Earth's orbit

(3) Empty tanks and used engines jettisoned

(4) Noncoplanar, elliptic planetary orbits considered

(5) 1979 Departure date

The component weights assumed were as follows:

Earth return vehicle, lb	14,000
Space vehicle quarters and radiation shield (solar and nuclear), lb	57,000
Mars landing vehicle, lb	96,000
Consumables, lb/day	45

The mission study involved an optimization of energy requirement, weight, trip time, perihelion, and so forth. Much more detail will be given in papers by Mr. R. W. Luidens. A summary of the results obtained is presented in figure 2, which shows first-phase power requirement as a function of trip time. The region of interest includes power requirements ranging from about 4000 to 24,000 megawatts. The low end of this range will presumably be taken care of by the growth potential of the NERVA engine, but the high end will require a new engine development program. Inasmuch as 15,000 megawatts represents an order of magnitude increase in size over the NERVA, it was decided that this would be a good place to start the examination.

The effect of some cycle parameters on the performance of nuclear rockets is presented in figure 3 as a plot of engine specific impulse against rocket chamber pressure for both the "topping" and "hot-bleed" cycles. These cycles differ principally in the source of the turbine gas supply. For the hot-bleed cycle, a small amount of hot gas is bled off at the reactor exit, blended with some cold gas to a temperature of about 2000° R, and then supplied to the turbine. The turbine is preferably a multistage unit operating at a pressure ratio in the range of 10 to 20. For the topping cycle the propellant is partway heated in one or more of the engine components (such as the nozzle, core support, shield, etc.); most of it is then passed through the turbine, after which it is returned to the cycle to be heated to the rated propellant temperature. The turbine for this cycle is one stage and operates at a relatively low temperature and pressure ratio (1.8 to 2.0).

The performance obtained with the topping cycle is represented by the dashed line (fig. 3); the numbers on the line indicate the turbine-inlet temperature requirement. Although chamber pressure has no effect on specific impulse for the topping cycle, the turbine-inlet temperature requirement is a direct function. For pressures less than or equal to 500 pounds per square inch absolute the turbine energy requirement can possibly be met by the heat extracted from the nozzle, core support, and shield. For pressures greater than 500 pounds per square inch absolute an additional heat source is needed. Inasmuch as the only remaining source is the reactor, a two-pass reactor will thus be required. This gets considerably more complicated than the single-pass reactor.

The performance obtained with the hot-bleed cycle is represented by the two solid lines. The upper curve is for an overall turbopump efficiency of 50 percent, and the lower one is for an efficiency of 30 percent. (The lower curve is representative of current performances.) The numbers on the curves represent the percent turbine bleed required if the turbine is operated at a pressure ratio of 20. For the hot-bleed cycle, specific impulse is an inverse function of turbine bleed, which, in turn, is a function of chamber pressure and turbopump efficiency. For every 1 percent of turbine bleed, there is a loss of about $4\frac{1}{2}$ points of specific impulse.

The information in figure 3 may be summed up as follows:

(1) For the topping cycle, it appears desirable to keep chamber pressure low so as not to complicate the reactor.

(2) For the hot-bleed cycle, it appears desirable to keep chamber pressure low and turbopump efficiency high so as to minimize specific impulse losses.

The effect of cycle pressure on the estimated weight and size of the turbopump required for a 15,000-megawatt engine is presented in figure 4. Inasmuch as turbopump weight is primarily a function of pump discharge pressure, this is the variable against which weight is plotted. The curve shown is based on existing technology and is applicable to both axial and centrifugal units.

Examination of the curve reveals that turbopump weight and size are quite sensitive to pump discharge pressure. For example, for a pump pressure of 1000 pounds per square inch absolute the turbopump would weigh about 12,000 pounds and would be 7 to 10 feet long. For a pump pressure of 3500 pounds per square inch the weight would increase to about 42,000 pounds and the length from 10 to 15 feet. It is estimated that turbopump weight could be reduced by half with the development of advanced blading and bearings. If this is so, then it is apparent that advanced technology becomes more and more desirable as pump discharge pressure is increased. For example, at a discharge pressure of 3500 pounds per square inch absolute, advanced technology would save about 20,000 pounds, whereas at 1500 pounds per square inch absolute and less, the savings would be less than 10,000 pounds.

The effects of changes in chamber pressure on turbopump weight are considerably influenced by the cycle selected. This can be illustrated with the aid of figure 4, which presents plots of chamber pressure against pump discharge pressure for both the hot-bleed and topping cycles. (It will be recalled that the topping cycle requires higher pump pressures because the turbine pressure drop is in series with that of the other components.) For an increase in hot-bleed-cycle chamber pressure from 500 to 1500 pounds per square inch absolute, the turbopump weight would increase about 6000 pounds (from 12,000 to 18,000 lb), whereas a similar change in topping-cycle chamber pressure would increase the weight about 22,000 pounds (from 16,000 to 38,000 lb). Thus, from the standpoint of turbopump weight, chamber pressures of the order of 500 pounds per square inch absolute appear preferable.

The variation of nozzle-throat heat flux and tube-wall temperature with chamber pressure for the 15,000-megawatt engine with Inconel X tubes and operating at a chamber temperature of 4500° R is presented in figure 5. It should be remembered that these curves are for a series of optimum designs and are not the performance of one design. The significant item to note in this figure is that as chamber pressure is increased, wall temperature can be held to a desired value until the coolant passage chokes. After this, the heat-flux requirements cannot be met on the coolant side, and a considerable increase in maximum wall temperature is encountered. For example, a wall temperature of 3500° R is indicated for a chamber pressure of 1500 pounds per square inch absolute. This is far in excess of current material capabilities. If the maximum wall temperature is limited to the current practice of 2000° R, then the chamber pressure is limited to about 700 pounds per square inch absolute. If it is assumed that future material improvements will permit a maximum wall temperature of 2600° R, the limitation can be extended to about 1000 pounds per square inch absolute. Ceramic coatings, ablative coatings, film cooling, and so forth, may permit higher pressures if they are required, but considerable development will be required in order to apply these techniques.

The effect of the chamber pressure in the 15,000-megawatt engine on nozzle-throat tube-wall strain is presented in figure 6 for the same conditions as the lower tube-wall temperature curve in figure 5. Two curves are shown, one for the tangential and one for the longitudinal strain. The tangential strain is a result of the pressure difference and temperature gradient across the hot wall of the tube (see sketch in fig. 6). The longitudinal strain is a result of thermal stresses in the hot wall caused by the difference in temperature between the inner and outer nozzle walls. It can be seen that the longitudinal strain far exceeds the tangential strain; however, both exceed the elastic limit (for the range considered) and thus are in the region of plastic deformation. Up to about 700 pounds per square inch, the longitudinal strain is constant with chamber pressure, because the hot-wall temperature is constant. Beyond this, there is a rapid increase in longitudinal strain because of the rapidly increasing hot-wall temperature. The value of longitudinal strain (0.0165) indicated for pressures under 700 pounds per square inch absolute is typical of that encountered in the Inconel X nozzles currently under development for NERVA. Thus far, none of these nozzles has proved satisfactory, and it is quite possible that nozzle technological improvement is required even if low chamber pressures are to be utilized in the advanced nuclear rocket.

The effect of chamber pressure on exhaust-nozzle length and weight for the 15,000-megawatt engine is shown in figure 7 for nozzle expansion ratios of 25, 50, and 100. Included for reference are points that indicate the lengths of the NERVA (6 ft) and the M-1 (21 ft) exhaust nozzles.

Changes in nozzle weight and length with reductions in chamber pressure are relatively minor down to a pressure of about 1000 pounds per square inch absolute; below this value, they increase at a rapidly accelerating rate. The rapid weight increase is a result of the constant tube-wall thickness (0.0090 in.), which, in turn, is necessitated by longitudinal strain considerations. If fabrication techniques can be devised to alleviate the longitudinal strain, appreciable weight reductions might be realized at the lower pressures. Even with current technology, however, the nozzle weights at a chamber pressure of 500 pounds per square inch absolute do not appear excessive when it is considered that the higher area ratios provide greater impulse.

Of perhaps greater significance is the size of the nozzle, because it not only affects engine weight but influences interstage structure weight as well. At a chamber pressure of 500 pounds per square inch absolute, a 25:1 conventional nozzle would be about 20 feet long, whereas a 100:1 nozzle would be about twice that or 40 feet long. Thus, if low chamber pressures and high area ratios are to be employed, serious consideration should be given to unconventional, folded, or multinozzle arrangements.

A preliminary look at a graphite reactor for a 15,000-megawatt engine indicated that it would weigh about 12,000 pounds (excluding the shield) and that the weight would be essentially unaffected by chamber pressure. The shape or volume of the reactor, however, probably would be affected by pressure level, with the lower pressures requiring larger diameters. Inasmuch as larger diameters will mean a larger and heavier shadow shield, it was decided to take a quick look at this component. This look indicated that the weight of a shadow shield for a 15,000-megawatt engine will vary from about 5500 pounds at a chamber pressure of 1500 pounds per square inch absolute to about 8000 pounds at a chamber pressure of 500 pounds per square inch absolute. Inasmuch as the change in shield weight is only 2500 pounds, this effect is considered to be insignificant.

. Another factor to consider is the effect of diameter on reactor controllability. As the diameter becomes larger, it becomes increasingly difficult to control the reactor by means of a simple peripheral rotating-drum control system. One method of handling this situation would be to use sliding control rodes dispersed throughout the core or more complex "island type" control drums. Another method would be to operate at higher pressures thereby permitting smaller diameters. It is to be emphasized that these considerations plus many others must be taken into account in the optimization of the reactor and propulsion system.

The variation of the sum of the weights of the reactor, the nozzle, and the turbopump with chamber pressure for the 15,000-megawatt engine is presented in figure 8 for the three nozzle expansion ratios previously considered. (The weight of the shield is not included.) It should be recognized that although these three components are the principal constituents of a nuclear rocket, items such as the interstage structure and impulse trade-offs associated with cycle and nozzle selection could also influence the selection of the optimum chamber pressure. For both cycles and the nozzle area ratios considered, the minimum combined reactor, nozzle, and turbopump weights occur at about 500 pounds per square inch absolute chamber pressure. Variations in chamber pressure from about 300 to 1000 pounds per square inch absolute, however, do not have an appreciable effect on the combined weights because of the compensating effects of the turbopump and the nozzle. The higher weights required for the topping cycle are a result of the higher pump pressures that this cycle requires. For the range of chamber pressures considered (500 to 1500 psia) the difference in weight is not too great and is more than compensated for by the higher specific impulse obtained.

This preliminary study of some of the variables and components of a 15,000-megawatt nuclear rocket engine suitable for a possible manned Mars mission has indicated that the selection of the cycle and the engine design chamber pressure will probably not be determined by engine weight considerations (if the chamber pressure falls in the range of 300 to 1000 psia), but more probably by reactor control and nozzle heat transfer, stress-strain, and size considerations. The selection of the optimum cycle and design pressure is quite a complex problem with many interrelated variables that undoubtedly will be influenced by technological developments of the future. This being the case, it is desirable that a continuing and more detailed study be pursued.

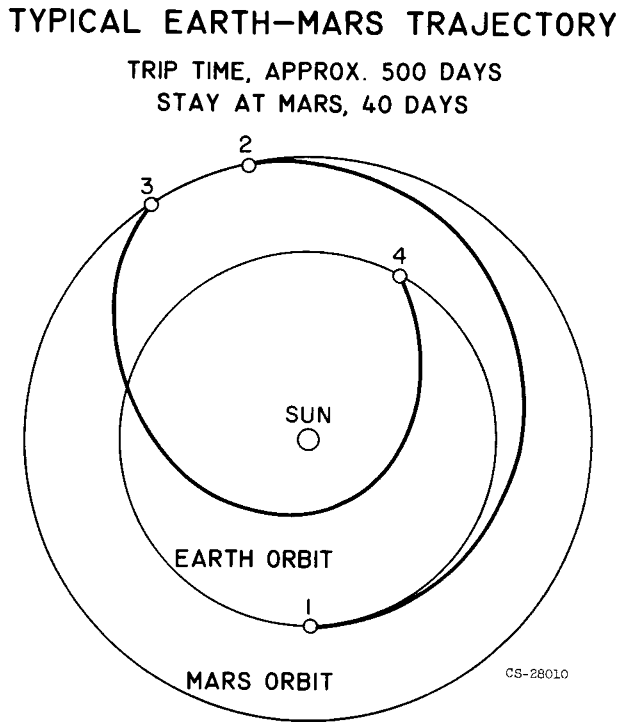

Figure 1

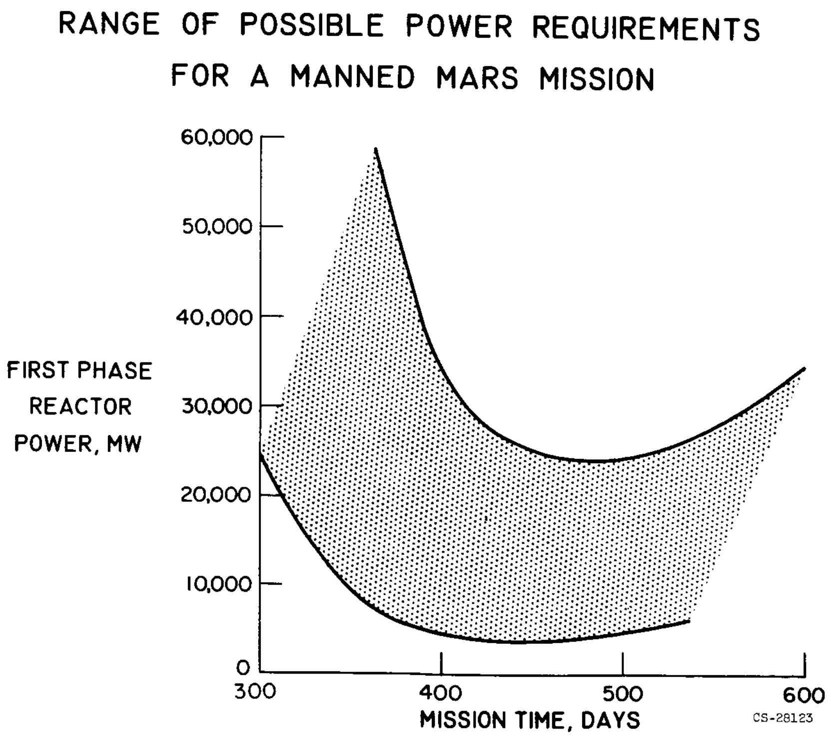

Figure 2

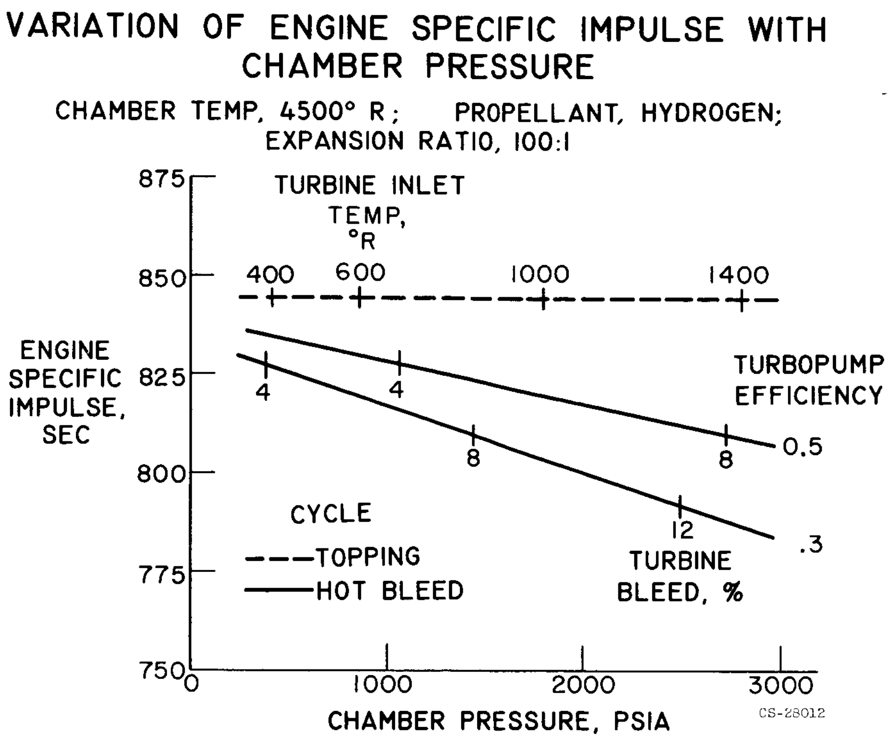

Figure 3

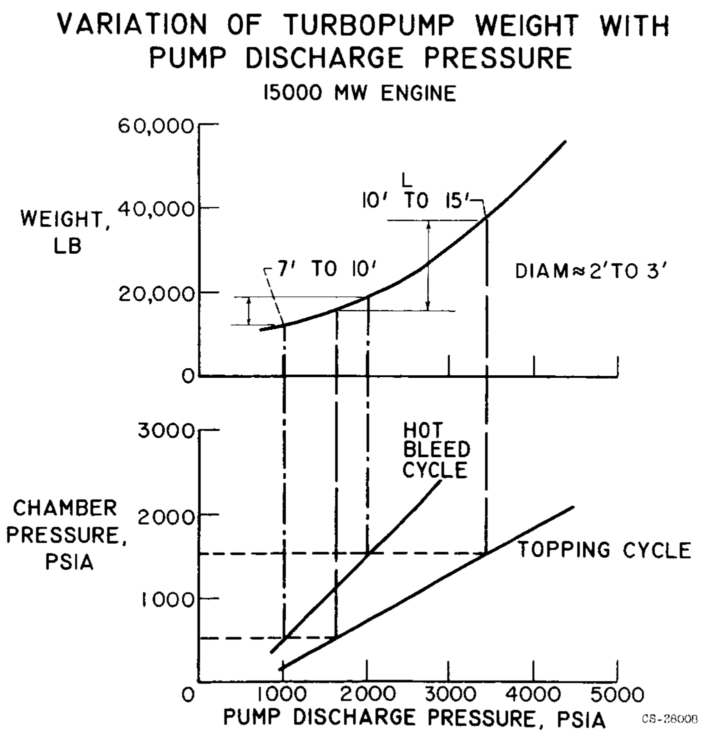

Figure 4

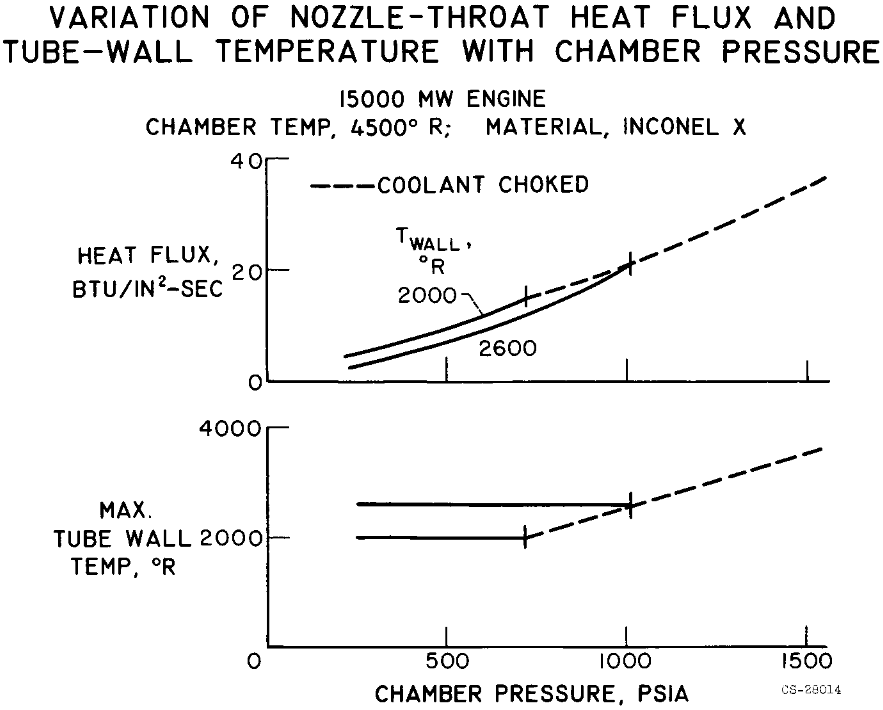

Figure 5

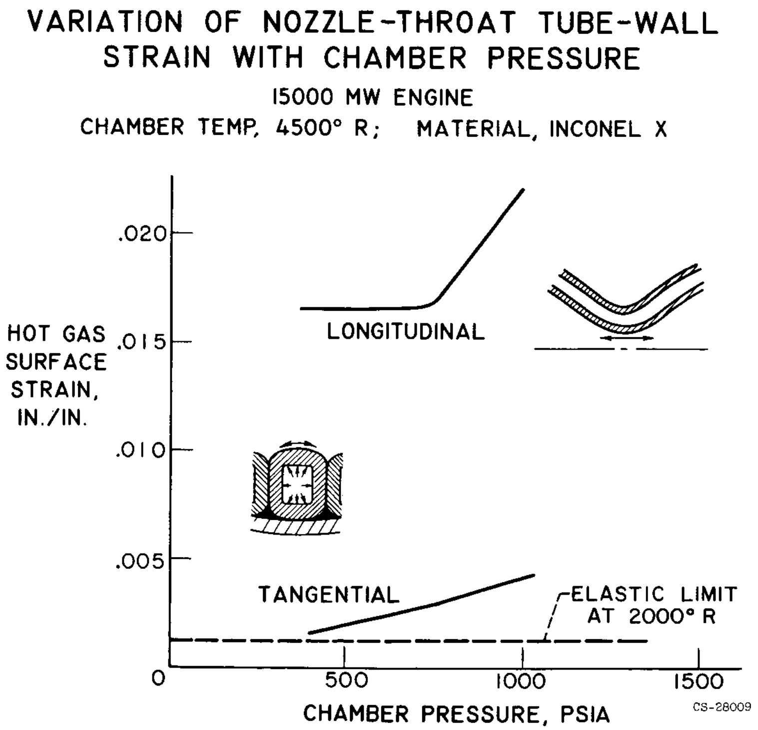

Figure 6

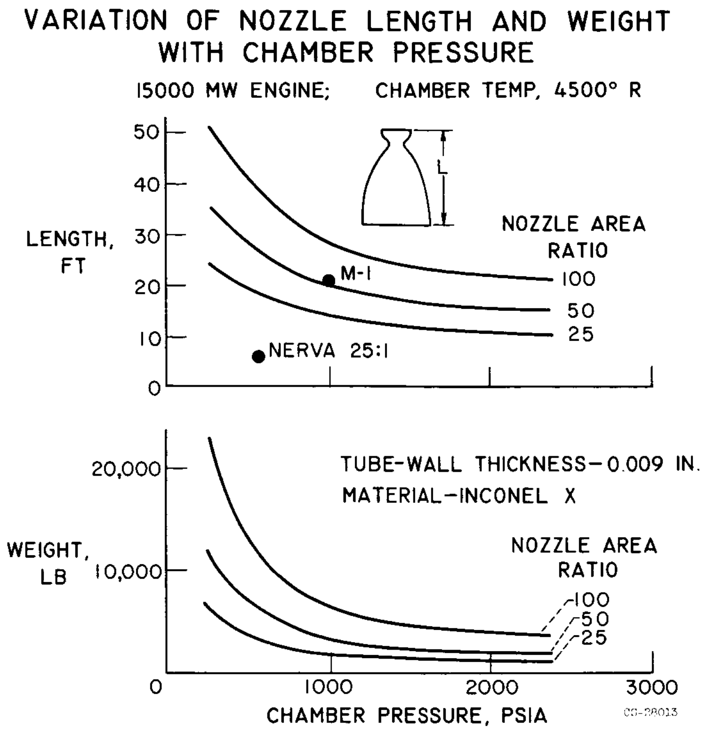

Figure 7

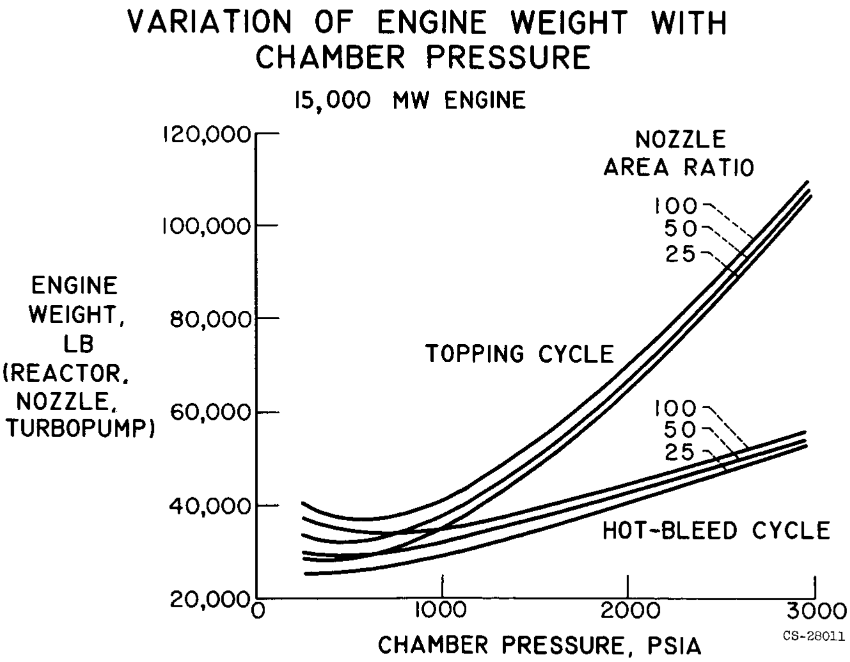

Figure 8