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NUCLEAR ROCKETS

Herbert F. York and Arthur T. Biehl

April 26, 1955

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NUCLEAR ROCKETS

Herbert F. York and Arthur T. Biehl

University of California Radiation Laboratory
Livermore Site

April 26, 1955

ABSTRACT

A systems analysis is made of a class of nuclear-propelled rockets in combination with chemical boosters. Various missions are considered including the delivery of 5000-lb payload 5500 nautical miles, the placement of a satellite in an orbit about the earth and the delivery of a payload to escape velocity.

The reactors considered are of the heterogeneous type utilizing graphite fuel elements in a matrix of Be or hydrogenous moderator. Liquid hydrogen and ammonia are considered as propellants. Graphical results are presented which show the characteristics and performance of the nuclear rockets as the design parameters are varied.

It should be emphasized that this report is not in any sense intended as a handbook of rocket parameters; it is intended only as a guide for determining areas of interest.

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NUCLEAR ROCKETS

Herbert F. York and Arthur T. Biehl

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April 26, 1955

I. INTRODUCTION

This report describes several families of reactors for use as nuclear rocket heat exchangers. The reactors differ from others heretofore considered for this purpose in that they are heterogeneous reactors composed of graphite fuel elements in a matrix of some other better moderator material. Be, BeO and H_2O are considered as moderators. Although H_2O is perhaps not a feasible moderator, for the purpose of this report it may be considered to be representative of other hydrogenous materials which remain solid or liquid at higher temperatures. In the case of BeO, and, to a lesser extent, Be, a portion of the energy production and heat transfer may take place in these materials.

As will be developed in greater detail below, the reactor weight range covered is from 200 to 4000 pounds; the specific power range of interest is from 10 to 50 Mw/ft^3. Total initial nuclear rocket weights varying from about 70, 000 lb down to a total of 5000 lb are considered. The higher weight mission is for ground takeoff with NH_3 fuel, a low specific power and a 5000-lb payload. The 5000-lb mission involves an acceleration to 0. 9 orbital velocity by the contemplated ATLAS missile.

A typical design involves the delivery of a 5000-lb payload (warhead plus re-entry cone) 5500 nautical miles by means of a 10 to 20 thousand pound nuclear rocket boosted to 0. 1 to 0. 3 of orbital velocity by means of a chemical stage. The reactor weight for such a design is a few thousand pounds and the power a few hundred megawatts. The pote[redacted] advantages of this system are the following:

1. These reactors, for the missions usually desired, (ICBM) are much lighter than those previously considered[1, 2], except for the LASL series[2] which falls within our weight range.
2. The reactors operate at a lower power density level in the graphite than those previously considered[1, 2]; about 20 Mw/ft^3 are considered as opposed to the order of several hundred Mw/ft^3. This implies that the gas flow passages can be larger. Thus, problems arising from the small size of the heat transfer passages, such as erosion, clogging and instability, are greatly relieved. In addition, it may be possible to use propellants, which otherwise could not be used because of the production of deposits that would clog the smaller passages.
3. By making use of the chemical boost system suggested by LASL, and because of the intrinsic light weight of these reactors, the total power required is also reduced. This means, among other things, that pump requirements are relieved and test difficulties are eased, perhaps to such an extent as to determine the feasibility. Note that booster-produced initial velocities not only reduce the propellant weight requirement for the nuclear stage but also reduce the total initial acceleration requirements of the second stage. Thus the power requirements of the reactor are reduced to a considerable extent by the use of a chemical booster.
4. The problems of control and stability are probably considerably easier in small heterogeneous reactors, due to the fact that there are large volumes within the reactor which are relatively cool. Also a larger fraction of the neutrons are thermal, in contrast with an all-graphite reactor of comparable size. The use of large cool volumes allows the use of mechanical controls which might not otherwise be feasible.
5. The mass of fissile material required is about the same as in the case of the large thermal graphite reactors and considerably less than in the smaller epithermal graphite reactors. This reduction factor varies from about 2 to 10 depending on which heterogeneous system is considered. This mass reduction may be most important in connection with the testing program.

6. As a disadvantage it may be mentioned that the systems considered here are not simple, straight-through flow systems, and will present somewhat more complex manifold and structural problems.

The purpose of this report is to calculate to a first approximation the various performance parameters of interest (thrust, weight, etc.) of motors and rockets using heterogeneous reactors, so as to compare these results with the various possible missions of interest and thus determine the area of interest for an experimental program. All quantities are thus calculated to first order (meaning to within about 35%), and then second order corrections are noted. The reason for this is that there are too many parameters involved to do otherwise; for example, the volume taken up by gas passages in the reactor cannot be determined without knowing the power level required in advance, and hence the average density of the reactor is uncertain within small limits at the beginning. The minimum total thrust and power required cannot be known unless total weight of the rocket is known, which means that the total mission and chemical boost must be specified in advance. Thus, in order to keep this study general, such effects are considered in the first approximation only, except when it is believed they have an effect in excess of about 35% on the particular performance characteristic being discussed.

Section II of this report discusses the reactor calculations and characteristics; Section III discusses various missions and the requirements they introduce; and Section IV describes the total nuclear system.

II. THE REACTORS

A schematic of the reactor type considered is shown in Fig. 1. The upper part of this reactor consists of a heterogeneous system consisting of rods of graphite embedded in a moderator of some other material such as Be. The fissions take place entirely (or, perhaps mostly) in the graphite. The propellant flows first through holes in the Be and between the Be and graphite, and then through holes in the graphite. As a minimum, several percent of the energy will be deposited in the Be by the various penetrating radiations.

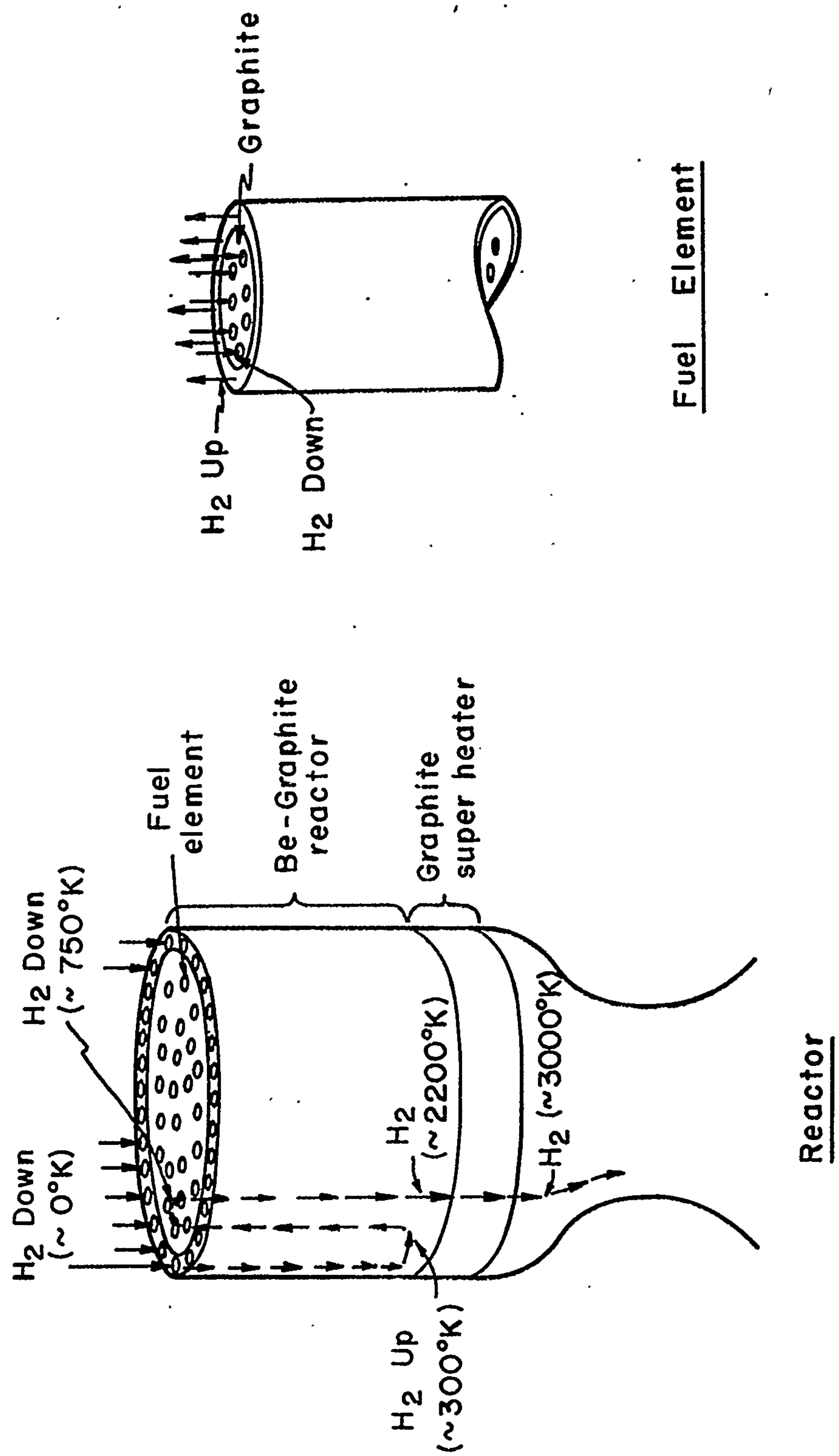

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Fig. 1 Schematic Diagram of Proposed Nuclear Rocket

The lower part is an all-graphite (U-impregnated as above) slab in which the final heating (superheat) is done. This slab is, roughly speaking, an exponential pile placed next to a critical reactor. In the calculations that follow, the weight of this slab was taken as one-half the weight of the graphite in the upper part of the reactor. The gas temperatures at the various points might be, for example, 750°K on entering the graphite rods, 2250°K on entering the bottom slab, and 3000°K on leaving the slab. The criticality estimates have been made considering the upper section alone and in a pristine condition. The reflector action of the lower slab is thus a reserve for the difference between the "cold and clean" condition and the "hot and dirty" condition. Another obvious design, but one which is harder to calculate in the general case, is that in which the fractional cross sections of the two systems change continuously from one end of the reactor to the other.

The reactors were calculated as if they were homogeneous, using the curves in R-259[3] (see Fig. 2). The reactors chosen were in the range in which the critical radius for the single-moderator cases were very insensitive to the amount of fissionable material - i.e., that region in which about 35% of the neutrons are thermalized to 1/40 ev. The values chosen for the radii of the normal-density, one-moderator systems were taken as 67 cm for graphite, 30 cm for Be, and 15 cm for H_2O. Under these circumstances then, the critical radius of the mixed system in terms of the critical radii for the two pure moderator systems was taken as

$$\frac{1}{R} = \frac{\eta_{Be}(1-f)}{R_{Be}} + \frac{\eta_c f}{R_c} \qquad (1)$$

where f is the fraction of the total volume of the reactor occupied by graphite including its voids and the η's are the ratio of the densities of the materials (as reduced by the average void volume). This equation is not exact, but fits several fixed points. A factor of 1.3 was used as an allowance for the nonspherical volume of the reactor. R, η, and f thus determine the weight of the total reactor.

In the calculations of critical size the graphite has been assumed to contain 33% void ($\eta_c = 0.67$), the Be to contain 10% void ($\eta_{Be} = 0.90$). For hydrogenous reactors it was assumed that the H_2O contained 25% voids

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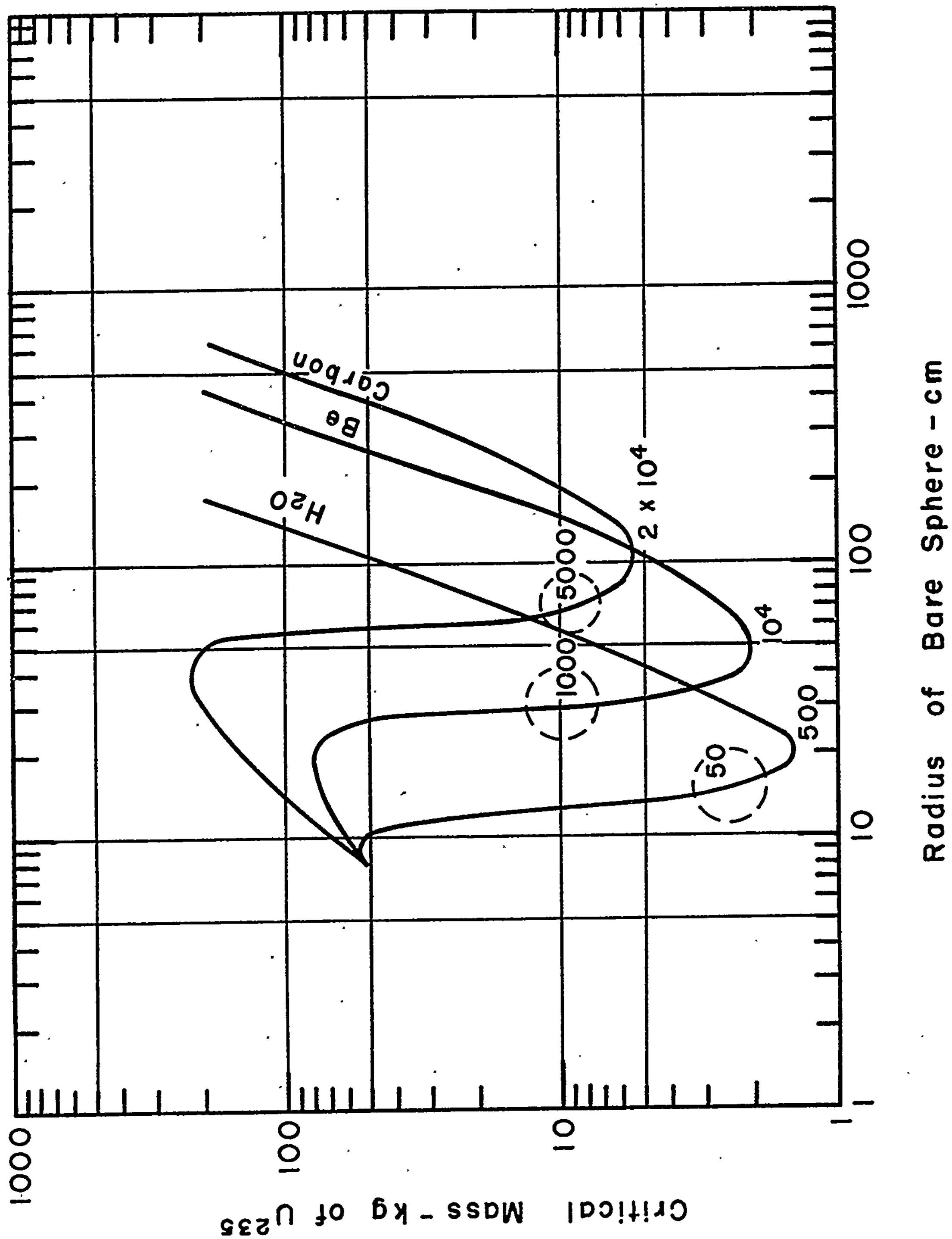

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Fig. 2 Critical Mass of U^{235} Systems. (From R-259[3], p. 3)

(η_{H_2O} = 0.75). The densities (for computing weights) were taken as $\eta\rho_o$ for graphite and Be, and 1.33 $\eta\rho_o$ for the water to allow for the container structure weight. The total motor weight (reactor + pumps + piping + nozzle + support + pressure shell) was taken to be equal to 1.5 times the reactor. This, from discussion with engineers, is perhaps low for the higher power systems, and high for the lower power systems. Also, this ratio appears to be somewhat low for the lightest weight reactors, and, perhaps, high for the higher weight reactors, but a constant ratio seems more nearly correct than a constant additive. Note that this method of calculation does not yield values for the amount of critical material needed. The amounts, however, will be between those for the two pure moderators considered, multiplied by a factor about equal to the reciprocal of the density ratios.

The thrust that can be produced by such an engine is given by

$$T = \frac{2P}{I_{sp}} \tag{2}$$

where P is the power produced in the reactor and I_{sp} is the specific impulse of the propellant. Figure 3 is based on these two equations and gives the thrust of the various reactors considered vs their total weight. The numbers along the curves are the volume fraction of graphite, including holes. The power density assumed was 20 Mw per cubic foot of graphite, with an additional allowance for one-third of the power originating in the Be, but with no extra allowance for the power in the H_2O. The specific impulse was assumed to be 800 seconds. A specific impulse near 800 seconds should be obtainable using hydrogen propellant at 3000°K. The specific impulse for an ammonia system was assumed to be 400 seconds, yielding double the thrust shown for the same power density.

If the specific impulse requirement is lowered to 600 or 700 seconds, then temperatures in the range of only 1400° to 2000°C are involved. In this case a material such as tungsten might serve suitably as the heat source and transfer material, with Be or other material serving again as the moderator. This type of reactor is not considered in detail in this report.

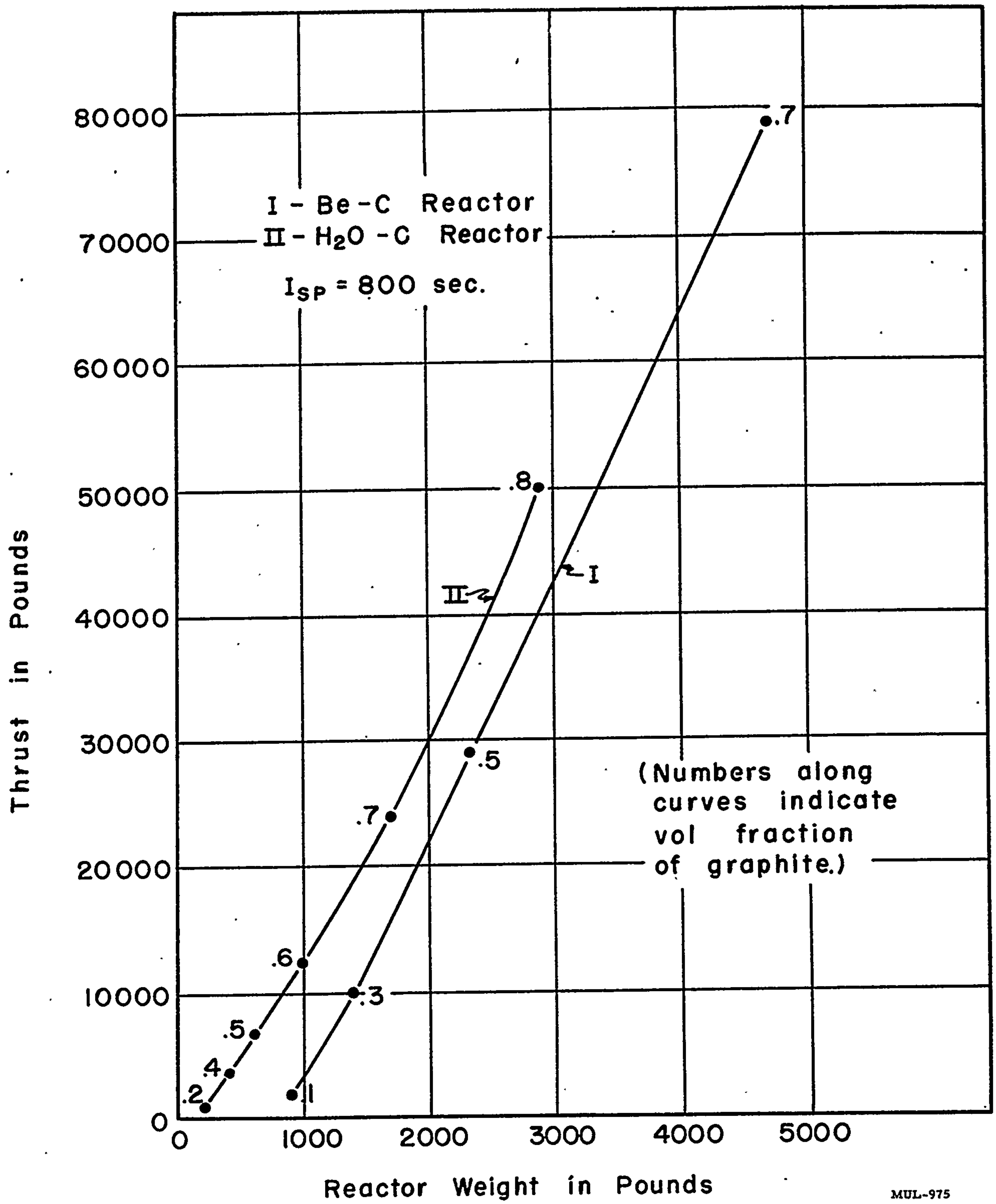

Fig. 3 Thrust vs Weight for 20 Mw/ft^3 of Graphite in Reactor

III. MISSION

In order to calculate the weight of the entire nuclear rocket, we must know how much payload is to be delivered where. The weight and initial velocity of the nuclear rocket in turn determine the thrust needed, and the range of specific power densities allowed then determines the volume of graphite needed in the reactor and thus the factor f (ratio of graphite to moderator volumes), which in turn controls the motor weight. We are thus again in a regime where there are too many variables to solve all the parameters simultaneously while still keeping our calculations sufficiently general, so we again make judicious guesses to start with.

A rocket that starts from the ground and that is to have a range of 5500 miles must acquire a total velocity of 23, 000 feet per second, or about 0.9 of the orbital velocity of a satellite near the earth's surface (calculations are simplified when carried out in units of the orbital velocity, V_o, which equals 24, 000 ft/sec). As we shall show in Section IV, and as pointed out in LAMS-1870[2], if chemical booster rockets of approximately 100,000-lb weight are used to give the nuclear rocket a start, then, for the nuclear rockets we are considering, initial velocities of about $0.1V_o$ to $0.3V_o$ can be achieved, and so additional velocities of only $0.6V_o$ to $0.8V_o$ are required for an ICBM mission. If one wishes to use a combination of ATLAS, as now contemplated, plus a nuclear rocket for producing a satellite, then additional velocities of as little as 0.1 are all that the nuclear rocket need add. In this case, however, the velocity change is so small that the nuclear rocket has little advantage over the chemical rocket unless further accelerations are wanted later, such as for reaching higher orbits or for returning to the surface at reduced speeds. We see from arguments such as these that we are interested in systems that give velocity changes between $0.1V_o$ and $1.0V_o$, with the main interest centered about $0.6V_o$ to $0.8V_o$.

If one assumes that tank weight is proportional to fuel weight, where tank weight also includes unusable fuel weight and the like, then the total weight, W, of a rocket is given by

$$W = L \left\{ 1 + \frac{e^{x} - 1}{1 - \frac{K}{1 + K} e^{x}} \right\} \qquad (3)$$

where

L = motor weight + payload weight

$$x = \frac{\text{velocity change required}}{\text{exhaust velocity of fuel}}$$

K = ratio of tank weight to fuel weight (it is this factor which puts the limit on how fast a one-stage rocket can go)

This equation neglects both gravitational attraction and centrifugal forces. The correction factors for both of these terms depend on the details of the orbit path, the initial thrust-to-weight ratio of the rocket, and the boost velocity. Detailed calculations of several special cases have been made. For example, the above equation underestimates the fuel requirement by about 20% in the case of a rocket boosted to $0.2V_o$ by a chemical system, and accelerating on from that point with a thrust-to-weight ratio of 1 at an angle of 25°. For a rocket starting from the ground and following an appropriate orbit (in which the angle with the vertical varies) the correction is about 20% for a thrust-to-weight ratio of 1.35. These figures are from a forthcoming report by C. E. Leith.

Figure 4 gives three cases of W/L ratios. The lowest curve is calculated for I_{sp} = 800, and a tank-to-initial-fuel-weight ratio of 15% (K = 0.15). Preliminary engineering estimates made here, and comparisons with other estimates, indicate that this figure is reasonable. The middle curve is for I_{sp} = 400 and a K value of 0.05, since these fuels are assumed to be non-cryogenic. The upper curve gives the same thing for a chemical rocket having a net I_{sp} = 150. The value is low for liquid fuels and perhaps high for solid fuels, but this approximate value is sufficiently accurate to allow an estimate of the booster-produced velocity when the booster weighs from two to six times the nuclear rocket weight. This range of weight ratio factors is seen to result in initial velocities of between approximately $0.1V_o$ and $0.3V_o$, thus leaving a velocity of $0.6V_o$ to $0.8V_o$ to be achieved by the nuclear rocket.

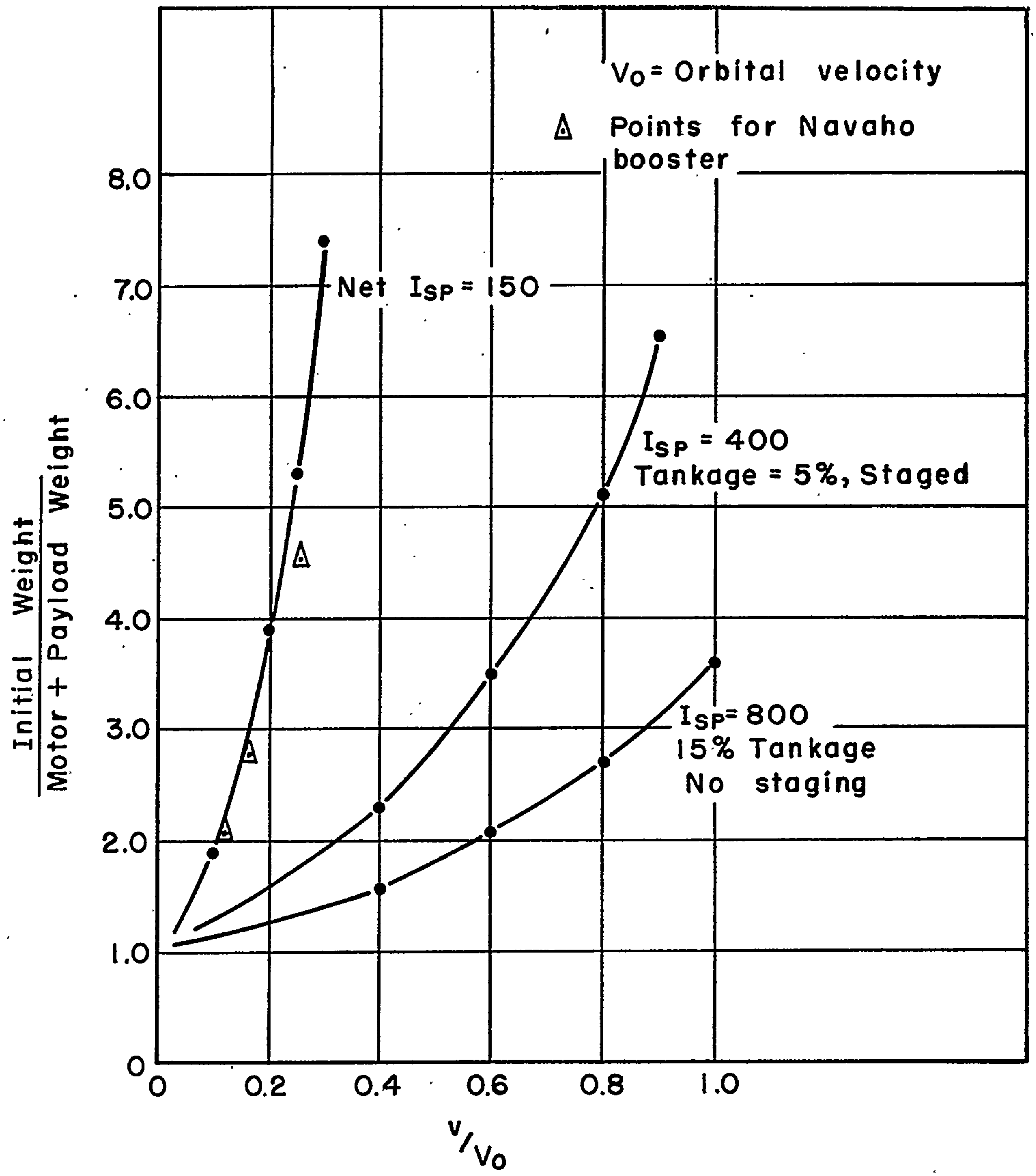

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Fig. 4 $\frac{\text{Initial Weight}}{\text{Motor + Payload Weight}}$ vs $\frac{v}{V_o}$

IV. NUCLEAR SYSTEM

If we now combine the results of Sections II and III and make some assumptions concerning payload weight requirements, we can now calculate both the total weight of a nuclear rocket and the power density required for various values of the parameter f, the ratio of graphite volume (including holes) to reactor volume. Figure 5 is a plot of power density required to give a thrust-to-weight ratio of unity plotted against total rocket weight for a number of different missions. The numbers plotted along the curve are the values of f used. All calculations are for Be-moderated systems. The mission in curve I is to take a 5000-lb warhead and give it a velocity increase of $0.7V_o$ using $I_{sp} = 400$ fuel. Curve II is for 5000 lb, $0.7V_o$, $I_{sp} = 800$. Curve III is for 5000 lb, $0.1V_o$, $I_{sp} = 800$.

The striking thing about these curves is that they all have relatively sharp bends in region where $f = 0.4$ to 0.5. As one goes to lower values of f, the power density requirement rises rapidly with only a slow decrease in weight; as one goes to higher values of f, the weight increases rapidly with only slight decreases in power density. For values of $f = 0.5$, the power densities are in the range 10 - 20 Mw per cubic foot for $T/W = 1$ (the power density is linear in T/W) and the weights range from 20,000 to 40,000 lbs. For $f = 0.4$, the power densities vary from 20 to 30 Mw per cubic foot and the weights vary from 18,000 to 36,000 lbs.

If we now choose $f = 0.5$ as being a practical optimum for all cases, except in the heaviest system considered, where 0.4 may be better, we can calculate the power density and total nuclear rocket weight for various missions as a function of the velocity increase required. Fig. 6 gives curves of power density versus velocity gain for $I_{sp} = 800$, and 400 and for a payload of 5000 lbs. The rocket weight is indicated along the curve. Note that again we have not taken into account the fact that for the higher values of v/V_o, a thrust-to-weight ratio of greater than unity is needed, thus increasing both power and weight requirements. At $v/V_o = 0.9$, the power increase must be between 1.25 to 1.50 and the weight must be about 20% greater.

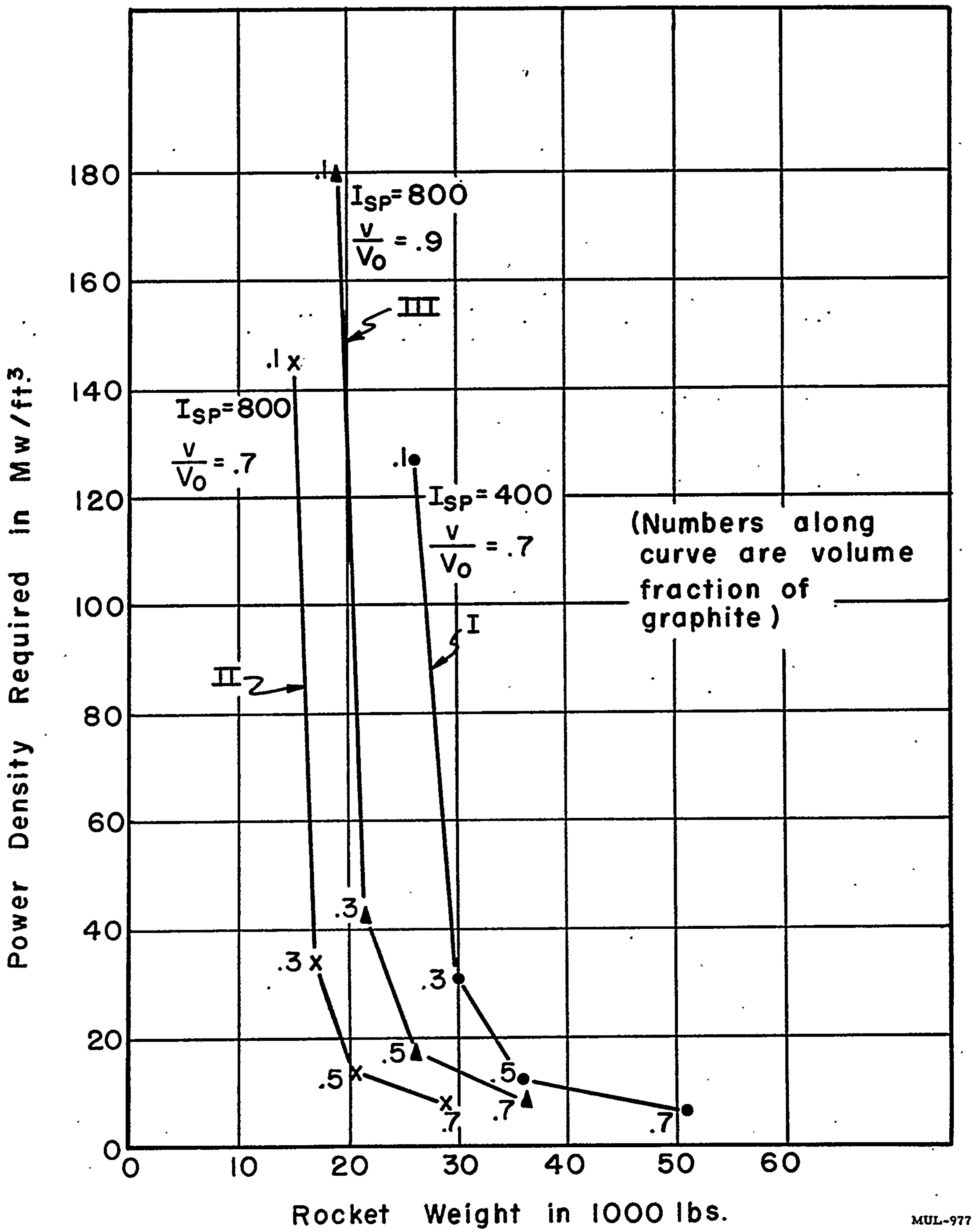

Fig. 5 Power Density vs Rocket Weight for Various Designs and Missions

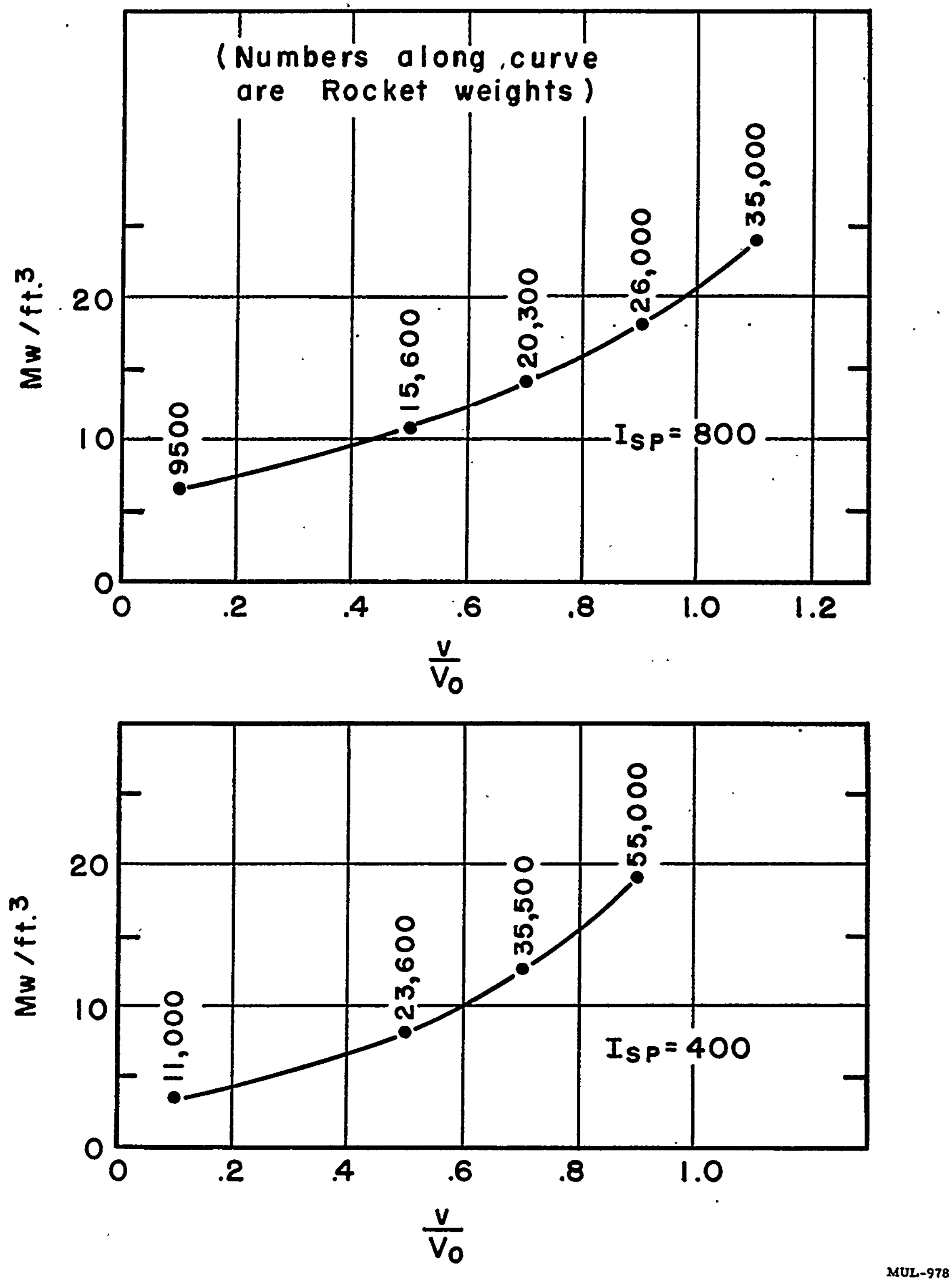

Fig. 6 Power Required vs Velocity Change

V. COMPLETE SYSTEMS

These last curves and the curve for W/L vs velocity gain for chemical rockets given in Fig. 4 can now be combined to give the total weight of booster plus nuclear rocket.

Figure 7 shows the weight of nuclear rocket necessary to achieve various values of v/V_o and the total weight of booster plus nuclear rocket necessary to boost the total velocity up to $0.9V_o$ for two cases: 5000-lb payload, I_{sp} = 800 and 5000-lb payload, I_{sp} = 400. Again we have not allowed for the additional weight required when taking off against gravity with low original thrust-to-weight ratios. This correction is about 20% for $v/V_o = 0.9$ for the cases of interest. We may also note here the effect of varying the I_{sp} of the chemical rocket. In the region where the velocity change of the nuclear rocket is to be about $0.7V_o$, we find that a variation of 20% in the chemical I_{sp} results in about a 15% change in total weight for a fixed nuclear rocket weight. A 20% variation in I_{sp} covers virtually all possibilities of interest.

The various plots accompanying this report have been made for particular circumstances as noted; in particular, all specific powers in Fig. 6 are thrust-to-weight ratios of unity, and fuel weights neglect losses in working against gravity. However, we can use these results as starting points for perturbation calculations for making estimates for specific missions. We shall consider here only three extremes of ICBMS missions, where in all cases we wish to deliver a 5000-lb payload to a point 5500 nm away.

A. Ground takeoff, hydrogen propellant, $f = 0.5$. The figures needed from Fig. 6 for such a mission are those for which $v/V_o = 0.9$. These give an initial weight of 26, 000 lb and a specific power of 18 Mw per cubic foot. These figures are, as pointed out above, for $T/M = 1$ and $g = 0$. For ground takeoff the optimum initial T/M is difficult to determine exactly but lies between 1.5 and 2.0. Under these conditions, approximately 30% extra fuel weight is needed, and since this rocket is about 70% fuel (including tank) the initial takeoff weight is

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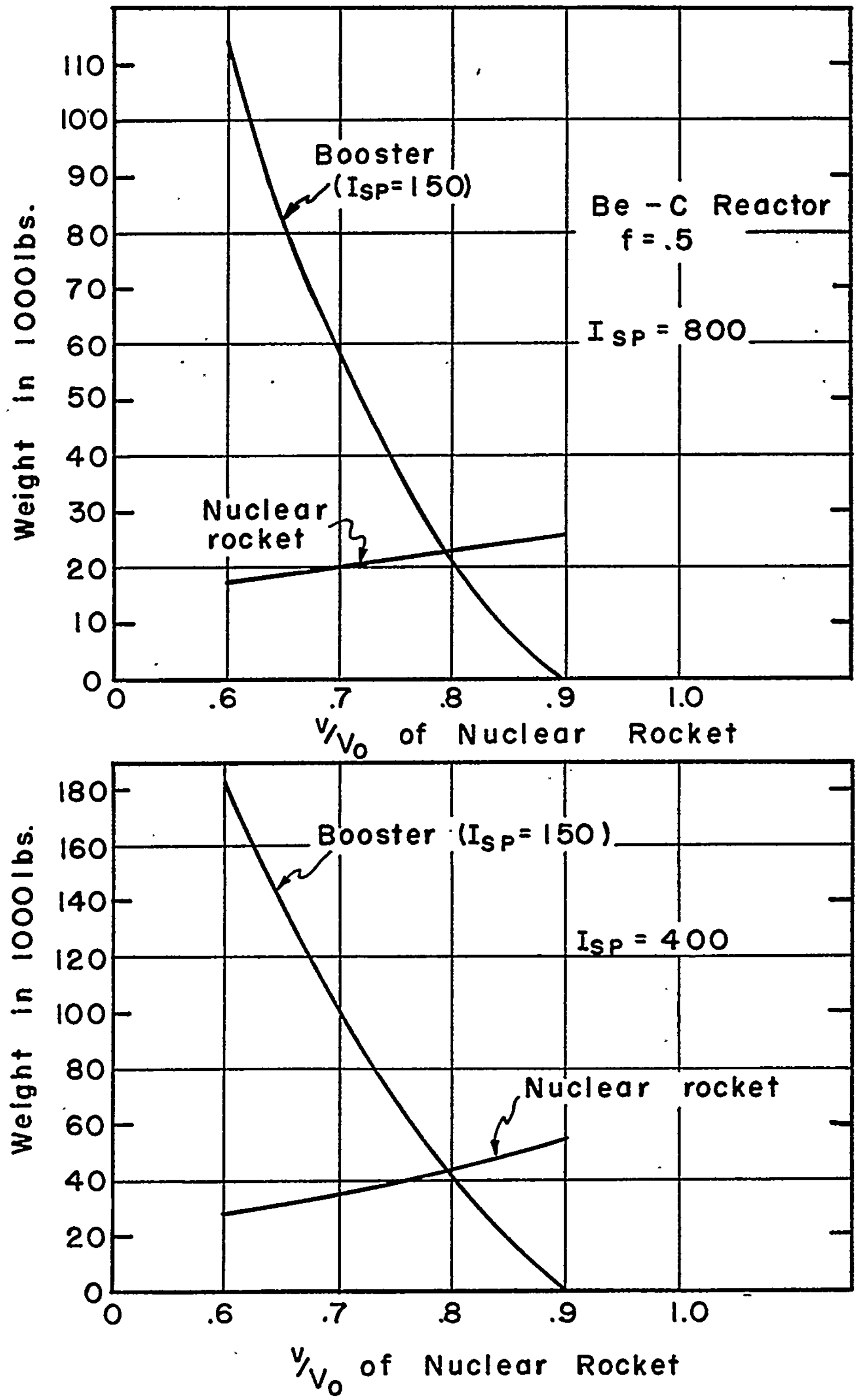

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Fig. 7 Weight of Booster and Nuclear Rocket vs v/V_o of Nuclear Component

21% greater than shown. Therefore we get for this system:

$$W_T \approx 32,000 \text{ lbs}$$

$$P \approx 25 - 30 \text{ Mw/ft}^3 .$$

B. Boost to $v/V_o = 0.3$, ammonia propellant, $f = 0.5$, 5000-lb payload, 5500 nm. The figures needed from Figs. 6 and 7 for such a mission are those for $v/V_o = 0.6$. These give an initial nuclear rocket weight of 28, 200 lbs, specific power of 10 Mw per cubic foot, and (Fig. 7) a 183, 000-lb booster where $I_{sp} = 150$. With this big a boost to start with, T/M less than 1 will continue the mission, but extra weight of about 20% would be required at T/M = 1. At T/M = 4/3 this drops to 10%, so that the perturbed values are

$$W_T \text{ (nuclear)} = 31,000 \text{ lbs}$$

$$W_T \text{ (booster)} = 200,000 \text{ lbs}$$

$$P \approx 10 - 20 \text{ Mw/ft}^3 .$$

C. Boost to $v/V_o = 0.3$, ammonia-propelled, 5000-lb payload, 5500 nm, $f = 0.3$. The $f = 0.3$ systems were not carried through in detail in the last section, but by referring back to the beginning we can get this particular case. We find that the corresponding figures are

$$W_T \text{ (nuclear)} = 25,000 \text{ lbs}$$

$$W_T \text{ (booster)} = 160,000 \text{ lbs}$$

$$P \approx 30 - 40 \text{ Mw/ft}^3 .$$

As above, the power density can be cut about in half by reducing the T/M to 1 and increasing the weights by about 10%.

The hydride (H_2O, $(CH_2)_n$, Li^7H, etc.) moderated reactors have not been calculated for the same series of cases as for the Be-moderated systems. This is partly because it seems at first glance that they are intrinsically more difficult to build and because higher power densities are required for most cases of interest. However, an estimate of how they effect ICBMS performance is of interest. Referring to Fig. 3 we find that for the same specific power and total thrust the hydride reactor weighs between 0.5 and 0.8 of the weight of the Be reactor in the region of interest. Also, since the Be systems were generally considered as operating at about 20 Mw/ft^3, we see that if indeed a hydride reactor can be operated at 100 Mw/ft^3, the reactor weight is thus reduced to about 0.15 of that in the Be case. Further, since the Be motors are about equal to the payloads (3000 - 4000 lbs versus 5000 lbs), this means that the over-all weight of the system would be reduced to about two-thirds.

Hydride-moderated reactors furnishing low specific power may also be of interest in connection with satellite and other future missions which do not now have the status of ICBMS, however. As an example of this, we consider the hypothetical mission in which it is desired to put up a satellite having a payload of 5700 lbs and then to bring this satellite down again at a controlled time and place. By cross-checking the curves in this report, we find that this could be done by replacing the nose cone of the ATLAS by a nuclear rocket having a total weight of approximately 10,000 lbs, using a 300-lb hydride motor and containing 4000 lbs of fuel. Such an ATLAS warhead could be accelerated to about $0.8V_o$. The nuclear motor would then have to produce an initial change of $0.2V_o$ and would require a thrust-to-weight ratio of only 0.2 to achieve this. Sufficient fuel (presumably noncryogenic) would remain to bring the rocket back down to $0.9V_o$ or a little less, so that it would re-enter the atmosphere. The 5700-lb payload thus must include a re-entry cone capable of slowing the warhead down to a suitable velocity in the atmosphere for landing. The specific power in the reactor would be only about 20 Mw/ft^3 since the initial T/W requirement is only about 0.2.

Another hypothetical mission which is perhaps interesting is that in which the objective is to establish a satellite in a 24-hour orbit, i.e., an orbit such that the satellite remains over the same spot on the earth.

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Such a satellite would be at a height of about 21, 000 miles and hence would have about fifty times less resolution than for the usually considered satellite for the same telescope; it could, however, detect the movement of objects smaller than the resolution limit and so might be useful, though it is not our purpose to argue this point. If we again use 10, 000 lbs for the total system considered as an ATLAS warhead, we again start out with about $0.8V_o$. Reaching this orbit requires an energy equivalent to nearly $1.4V_o$, and so $0.6V_o$ must be added. If hydrogen is used as fuel, this requires a total weight-to-load ratio of 2.1. Thus, of the 10, 000 lbs, 4300 lbs are available for load, and if the 300-lb motor is used, 4000 lbs remain for payload as a satellite in such an orbit.

As a final mission, consider the case in which we start again with a 10, 000-lb nuclear rocket as a warhead for an ATLAS missile, and we wish to send this missile around the moon and recover its payload. On the way up we use hydrogen, and since the velocity we must add is $0.6V_o$, the total weight-to-load ratio for this part of the mission is 2.1. On the way down we use ammonia to slow down to $0.9V_o$ to allow for capture by the earth and re-entry. This velocity change is $0.5V_o$ and requires a total weight-to-load ratio of 2.9. Thus, the useful load is 10, 000 lbs divided by 2.1 x 2.9 or 1600 lbs. If we use a 300-lb motor there remain 1300 lbs for the payload, again including the re-entry gear.

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