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HIGH PERFORMANCE ULTRA-LIGHT NUCLEAR ROCKETS FOR NEO (NEAR EARTH OBJECTS) INTERACTION MISSIONS*

by

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Abstract

The performance capabilities and technology features of ultra compact nuclear thermal rockets based on very high power density (~ 30 Megawatts per liter) fuel elements are described. Nuclear rockets appear particularly attractive for carrying out missions to investigate or intercept Near Earth Objects (NEOs) that potentially could impact on the Earth. Many of these NEO threats, whether asteroids or comets, have extremely high closing velocities, i.e., tens of kilometers per second relative to the Earth. Nuclear rockets using hydrogen propellant enable flight velocities 2 to 3 times those achievable with chemical rockets, allowing interaction with a potential NEO threat at a much shorter time, and at much greater range. Two versions of an ultra compact nuclear rocket based on very high heat transfer rates are described: the PBR (Particle Bed Reactor), which has undergone substantial hardware development effort, and MITEE (MIniature Reactor Engine) which is a design derivative of the PBR. Nominal performance capabilities for the PBR are: thermal power ≈ 1000 MW thrust ≈ 45,000 lbsf, and weight ≈ 500 kg. For MITEE, nominal capabilities are: thermal power ≈ 100 MW; thrust ≅ 4500 lbsf, and weight ≅ 50 kg. Development of operational PBR/MITEE systems would enable spacecraft launched from LEO (Low Earth Orbit) to investigate intercept NEO's at a range of ~ 100 million kilometers in times of ~ 30 days.

INTRODUCTION

Major development efforts on nuclear thermal rocket propulsion have been carried out in the US and former Soviet Union since the 1950's, with a cumulative total expenditure of well over ten billion dollars (in current dollars). Although nuclear thermal rockets have not proceeded to the operational, or even the flight test stage, there has been extensive ground testing of nuclear rocket systems.

Nuclear thermal rockets offer the potential for a major increase in performance as compared to existing chemical rockets, which have essentially matured technologically with only marginal improvement likely. Using pure hydrogen propellant, nuclear rockets can achieve specific impulses (lbs of thrust per lb of mass per second) of ~ 1000 seconds, as compared to only ~ 425 seconds for H_2/O_2 rockets and ~ 250 seconds for solid propellant rockets.

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The higher specific impulse of nuclear rockets offers the potential for much greater operational velocities. For equivalent engine thrust/weight ratios, and the same mass ratios and payload weights, a nuclear rocket would achieve 2 to 3 times the ΔV (velocity increment) achievable with chemical rockets. This translates into much higher terminal velocities (a factor of 2 to 3 higher), or much greater payloads for a given terminal velocity, or some combination of the two.

Development efforts on nuclear rockets in the US initially focussed on the NERVA [Durham (1972)] System. NERVA was based on the use of uranium containing graphite or carbide fuel rods located in channels through a graphite moderator core. Hydrogen flowed axially down the multiple channels, exiting from the bottom of the core at ~2750 K. A number of NERVA type reactors were ground tested at the Nevada Test Site, at powers up to 5000 MW(th).

Because of its large size fuel elements, and the long axial flow path, the fuel element power density in NERVA reactors was constrained to be relatively low, on the order of 2 to 3 MW per liter. This constraint resulted in low thrust to weight ratios, on the order of 5 to 1, for NERVA engines. This feature combined with the large relatively heavy reactors dictated by the choice of moderator (graphite or zirconium hydride plus graphite), severely limited the potential usefulness of NERVA.

Development work on NERVA ceased in 1972 when no practical mission could be identified. R and D on NERVA type systems continued in the Soviet Union [Goldin (1991)] until the early 90's, when it too was canceled. The Soviet version used twisted ribbon type uranium - zirconium - niobium carbide fuel rods stacked along an axial flow channel inside a graphite moderated core. Fuel elements were tested at temperatures up to ~ 3000 K for periods on the order of one hour. Performance appeared satisfactory.

The Soviet type NERVA had the same low power density and heavy weight limitations of the US NERVA, however. Such nuclear rockets, while potential candidates for heavy lift type missions, e.g., manned journeys to Mars, do not appear promising for lightweight, high velocity applications, such as unmanned planetary scientific probes, or interaction missions with NEOs.

Work on a much higher performance nuclear rocket concept [Hatch (1960)], the Rotating Bed Reactor (RBR), was initiated at Brookhaven National Laboratory in the 1960's. The RBR nuclear rocket used small diameter (~ 400 micron) coated HTGR type fuel particles instead of large solid fuel rods. The particles were directly cooled by the flowing hydrogen propellant. Their much smaller size, and the consequent much greater heat transfer area per unit volume of fuel (~ 100 cm^2 per cubic centimeter of fuel bed) enabled much greater power densities than NERVA - on the order of 30 Megawatts per liter.

In the RBR, the fuel particles were held by centrifugal force inside a porous rotating cylindrical basket (~ 1000 rpm) through which the inlet hydrogen passed. After passing through the fuel bed, the hot H_2 exited through an outlet nozzle at the bottom of the rotating basket. An external moderator surrounding the annular fuel downscattered the released fast neutrons to thermal energies, where they then diffused back into, and were absorbed by the fuel bed.

The RBR development was at an early stage when the US nuclear rocket program stopped in 1972,

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with only cold flow, non-nuclear testing having been carried out.

Major US R&D on nuclear rockets resumed in 1987 on the Particle Bed Reactor (PBR), a derivative of the RBR. In the PBR [Powell (1985), Ludewig (1993, 1996)] the elements consist of fuel particles that are placed into annular packed beds held between two porous cylindrical "frits". Hydrogen coolant flows radially inwards through the outer "cold" frit at cryogenic temperature, then through the thin bed of fuel particles, and finally exits through the hot frit at ~ 3000 K. The hot hydrogen then flows out through the central hot channel to the rocket exit chamber and nozzle.

The PBR program was directed towards defense applications. Used as an upper stage on a standard booster in place of a conventional hydrogen/oxygen stage, it would lift into Low Earth Orbit (LEO) 3 to 4 times the payload that the conventional upper stage could.

Development of the PBR proceeded successfully until 1993, when the program was terminated due to the ending of the Cold War and the PBR mission. Major technical advancements to that point included the development of fuel particles capable of operation at 3000 K, along with hot and cold frits and other reactor hardware. Full size PBR fuel elements were thermally hydraulically tested at 2500 K; these tests demonstrated the capability for 30 MW per liter power density in transient blow down experiments. Nuclear critical performance, including critical mass and 3D power distributions, was verified in a zero power critical assembly of the PBR. Tests of a PBR fuel element were also carried out in an operating reactor. The PBR nuclear engine appears very attractive for planetary exploration and NEO interaction missions, because of its low weight (~ 500 kg) and high specific impulse (~ 1000 seconds).

The PBR design and hardware development was guided by the goal of a high thrust (~ 45,000 lbsf) engine for heavy lift launch applications. Planetary and NEO mission launched from LEO orbits, however, do not require high thrust capability. Removing this constraint enables further major reductions in engine weight, since core size is no longer determined by the requirement for high thermal powers (~ 1000 MW for the PBR) but only by the requirement that the core be critical. This allows a considerably smaller, lighter reactor.

A new concept for an ultra compact nuclear engine is described in this paper, termed the MITEE (MIniature ReacTor EnginE) nuclear rocket. MITEE is a derivative of the PBR, achieving comparable power densities, on the order of 30 MW per liter of fuel element. However, its total power is much lower than the PBR (~ 100 MW compared to ~ 1000 MW for the PBR). Its total weight is also much lower (~ 50 kg compared to ~ 500 kg for the PBR).

The MITEE engine appears very attractive for accelerating small light payloads from Earth orbit to ultra high velocities, i.e., several tens of kilometers per second. At a velocity of 35 kilometers per second for example, the payload could travel 100 million kilometers in a month. Probes could reach the outer planets in a few years, rather than decades, and interaction misions with asteroids and comets could occur at long ranges, i.e., ~ 1 AU, instead of close-in to Earth.

Figure 1 illustrates an overview of nuclear rocket projected capabilities. The MITEE engine would appear to be the end of the line for nuclear rockets, since the lower limit to its weight will be determined by criticality considerations, and it would use the lightest possible materials of construction.

The remainder of this paper describes the PBR and MITEE engines in greater detail, together with their technology issues and requirements.

THE PBR ENGINE

Figure 2 shows the basic construction of the PBR reactor [Ludewig (1993)]. The small diameter (~ 400 microns) fuel particles are contained between two porous thin cylindrical tubes, an outer "cold frit", and an inner "hot frit". Cold (~ 100 K) H_2 coolant flows radially inwards through the annual packed particle bed; after exiting from the hot frit, the hot (~ 3000 K) H_2 turns and flows out through the central flow channel to the outlet chamber and exhaust nozzle.

The annular fuel elements are arranged in a surrounding matrix of moderator made of a beryllium structure with hydrogenous inserts (polyethylene or ^7LiH). The full reactor core typically contains 19 or 37 fuel elements, depending on the desired power level. The complete PBR engine (Figure 3) includes the reactor, exhaust plenum chamber, nozzle, turbo pump, turbo pump exhaust, structure and thrust vector controls.

Detailed PBR engine designs were carried out for a wide range of parameter space, including power level, fuel element diameters, fuel element pitches, moderator composition bed power density, number of fuel elements. The neutronic analysis utilized the explicit geometry Monte Carlo (MCNP) code with point cross sections to accurately model the all aspects of the reactor in 3 dimensions. Table 1 lists the design parameters and features for a typical 1000 MW design.

The time dependent neutronic behavior of PBR engines was also modeled in detail, including transient power response during fast startup, control requirements, and temperature stability. 3D power distributions were obtained for all points in the fuel elements and moderator.

The neutronic analyses were validated by carrying out a series of critical experiments in a zero power version of the PBR. The experimental results for K_{eff}, temperature coefficient, 3D power distribution, and other reactor parameters agreed very closely with analytical predictions.

The power density performance of the PBR was experimentally validated by an extensive series of transient blowdown tests on hot PBR fuel elements (the elements did not contain fissile fuel). The elements were first heated to high temperature, (~ 2500 K) and then subjected to a full flow blowdown with cold inlet high pressure H_2. Hydrogen heating rates equivalent to particle bed power densities of 30 Megawatts per liter were measured during the transient blowdown phase. Individual single elements were tested, along with a multi-element assembly (7 elements) that was representative of the central portion of 19 element PBR core.

Major accomplishments in the PBR materials development program included the fabrication and testing of coated fissile fuel particles capable of operating in 3000 K high pressure hydrogen for long periods; high strength coated graphite and carbon-carbon hot frits that could operate in high pressure

3000 K hydrogen for long periods; and porous aluminum cold frits that enabled precise control of local H_2 inlet flow, so that local H_2 flow rates could be optimally matched to the 3D axial, azimuthal, and radial variations in nuclear power generation rates.

Along with the materials development program, a PBR hardware component development effort was also carried out. This included a lightweight, high temperature H_2 turbo pump that utilized a small portion of the hot outlet H_2 flow for drive power; a coated high temperature carbon-carbon nozzle; and a lightweight, high strength carbon-carbon pressure vessel.

At the close of the PBR program, the first of a planned series of PBR nuclear fuel elements was undergoing tests in the Sandia ACRR reactor. This test (NET-1) demonstrated the generation of hot H_2 coolant from a particle bed fuel element. Following completion of the NET tests, it was then planned to operate a 7 element test reactor (PIPET) at the Nevada Test Site. Following the successful demonstration of full power density (30 MW per liter), full temperature (3000 K) PBR fuel elements in PIPET, it was planned to carry out the ground test of a complete PBR engine. All testing was to be carried out in a fully contained system, with zero release of fission products to the environment.

While the overall objective of developing an operational PBR engine was not achieved, due to termination of funding in 1993, the program was very successful. Over its 6 year period, it resolved the major technical unknowns that were issues at the start of the program, and developed the materials, the neutronic and mechanical design, and many of the components required for the operational engine. If the program had continued, it appears likely that the target date for testing a flight capable engine in the late 90's would have been met.

THE MITEE ENGINE

Towards the close of the PBR project, Brookhaven National Laboratory (BNL) was investigating modifications to further reduce the size and weight of the PBR rocket. These included incorporating fissile fuel into the hot (the afterburner concept) and cold frits, a hydride spike (inside the hot gas channel), the "sock" reactor (nested frits containing fuel), and moderator with fuel inclusions. These approaches substantially reduced size and weight. However, due to the termination of the PBR program, there was insufficient time to fully investigate their true potential and to develop self-consistent reactor designs.

Based on these earlier studies, a new concept for a ultra compact and lightweight nuclear rocket is now proposed, termed MITEE. Figure 4 illustrates the basic MITEE concept. In contrast to the PBR, which utilized a relatively large single pressure vessel, the MITEE core consists of a set of hexagonal pressure tubes, each containing an outer shell of moderator and an inner cylindrical fuel element. The H_2 coolant flow is radially inwards through the cylindrical fuel element, with cold H_2 entering the outer surface at low temperature ~ 100 K) and exiting the inner surface at high temperature (~ 3000 K).

Unlike the PBR, where the fissile fuel was contained in small individual fuel particles (~ 400 microns in diameter), in MITEE, the fuel is contained as fibers or particles in metal thin plates of perforated matrix composites that form the multi-layered annular cylindrical fuel element. As in the PBR, there is a central hot gas channel, down which the hot H_2 flows to exit the reactor.

In contrast to the PBR, however, the MITEE hot gas channels do not exit into a common large hot gas plenum and a single throat/nozzle unit. Instead, each pressure tube has its own individual nozzle (Figure 5) which exhausts to space. The combined thrust from the assembly of nozzles then provides the total engine thrust. This arrangement results in a much simpler and lighter reactor.

As shown in Figure 4, the core is made up by assembling a number (probably either 19 or 37) of the pressure tube elements. The core is surrounded by a row of pressure tubes that contain only reflector material.

Table 2 compares the main features of the PBR and MITEE. H_2 exit temperature, specific impulse and power densities are simliar, with the principal differences between the two types of reactors being the nature of the core, the power and thrust level, and the overall weight.

Two versions of MITEE appear possible:

- MITEE-1 with a solid moderator (lithium hydride or polyethylene)
- MITEE-2 with liquid H_2 moderator.

Table 3 compares the principal features of the moderator for the MITEE-1 and MITEE-2 designs. The liquid H_2 moderator has by far the lowest density; however, its core size will be substantially larger, as will be discussed shortly, which will tend to narrow the differences in the overall weights for the various reactor designs. Because of the low temperature, the effective thermal diffusion length in liquid H_2 will be significantly smaller than that for room temperature water ($L \sim 2.5$ cm). This will tend to require a larger number of pressure tubes (e.g., 37 for liquid H_2 compared to 19 for the solid moderators). To some extent, the enhanced absorption for low temperature neutrons in cold hydrogen will be compensated by the reduced scattering cross section of para-hydrogen, which will tend to increase the value of L and offset the increased absorption cross section.

The annual MITEE region, shown in Figure 6, would have 3 zones: 1) an outer zone of a beryllium metal matrix composite with graphite fibers that were loaded with UC_2 or UO_2 particles or whiskers, 2) a middle zone of a molybdenum metal matrix composite with UO_2 particles or whiskers, and 3) an inner zone of a tungsten metal (separated tungsten -184, to reduce the effective neutron absorption cross section) matrix composite with UO_2 particles or whiskers.

Table 4 gives nominal properties and operating temperatures for the 3 fuel forms. To first order, each zone would have the same ^{235}U loading per unit volume. The magnitude of the actual loading would be determined by the fuel volume required to meet the desired power output, and the required critical mass. The maximum achievable fuel loading per unit volume probably will be on the order of 3 g/cm^3 (including the gas flow channels in the metal matrix). For a midrange reactor of 75 MW with a power density of 25 MW/Liter, this corresponds to a maximum achievable M_{235} of 75/25 (3), or 9 kg, of uranium. Based on critical data, this appears to be more than will be required.

The metal matrix zones consist of multiple thin perforated plates (probably arranged as a spiral wrap for each of the 3 metal zones) through which the H_2 coolant flows. For weight estimation purposes, the plates are assumed to have 20% hole area. In addition, the metal matrix composite is assumed to be 80% metal and 20% U-235 fuel. Summing up the effective density factor in Table 4, the average metal density in the fuel region is equal to 0.4 + 2.26 + 2.66 = 5.35 g/cm^3. Thus, a fuel region volume of 3 liters would have a total metal weight of 3 x 5.35, or about 16 kg.

MITEE reactor weights can be estimated as follows. The critical core volume of homogeneous water moderated spheres is ~ 10 liters if an infinite water reflector is used [A 5 cm thick water reflector approximates an infinite reflector], with a corresponding critical mass of approximately 1 kg of U^{235}. The 10 liter core volume corresponds to a radius of $R_C^\star$ = 13.4 centimeters.

The critical core radius using alternate hydrogenous moderators (i.e., LiH, polyethylene, or liquid H_2) will scale as

$$R_C = R_C^\star \left(\frac{n_{H20}}{\bar{n}_H} \right) \left(\frac{1}{f_{\text{mod}}} \right) \qquad \textbf{(1)}$$

Where

$\bar{n}_H$ = effective H atom density in moderator (cf. Table 3).

f_{mod} = volume fraction of moderator in core.

and the corresponding core volume is given by

$$V_C = V_C^\star \left(\frac{n_{H20}}{\bar{n}_H} \right)^3 \left(\frac{1}{f_{\text{mod}}} \right)^3 \qquad \textbf{(2)}$$

Where the value of f_{mod} is given by

$$\begin{aligned} f_{\text{mod}} &= \frac{V_C - V_{Metal\ Matrix} - V_{Hot\ Channel}}{V_C} \\ &= 1 - \frac{\left(V_{MM} + V_{HC} \right)}{V_C} \end{aligned} \qquad \textbf{(3)}$$

For a nominal (75 MW) MITEE reactor, V_{MM} ~ 3 liters at a power density of 25 MW/Liter, and V_{HC} ~ 1 liter, so that

$$f_{\text{mod}} \cong 1 - \frac{4}{V_C} \qquad \textbf{(4)}$$

Where V_C is given in liters.

Iterating, the values of f_{mod}, R_C, and V_C shown in Table 5 as a function of the choice of MITEE moderator are obtained. The critical mass of uranium is approximated by

$$M_{25} = M_{25}^{\star} \; x \left(\frac{R_C}{R_C^{\star}} \right)^2 ; \; M_{25}^{\star} \sim 1 \; kg \qquad \textbf{(5)}$$

The critical mass depends on the square of R_C rather than the cube, since the lower moderator density partially off-sets the larger core volume. [The relationship in equation (5) assumes that the ratio of hydrogen atoms to uranium atoms remains fixed.]

Moderator, fuel, metal matrix, reflector, and total weights are shown in Table 5 for the 3 MITEE designs. Interestingly, all three designs have approximately the same total weight, that is, about 50 kg. This is a result of the lower density liquid H_2 moderator having a larger core and heavier reflector, even through the density of the liquid H_2 moderator itself is much lower than the density of the solid moderators.

Given this situation, MITEE-1 with the solid lithium hydride moderator appears to be the best choice. It is more stable and easier to cool than polyethylene. By operating at a high moderator temperature, neutron absorption by hydrogen will be much less than with the liquid H_2 moderator, so that the core looks more like a homogeneous reactor than a heterogeneous one. It also enables the use of fewer fuel elements (e.g., 19 instead of 37), without having excessive neutron absorption in the moderator.

The heat transfer area in the perforated metal matrix sheets is calculated by taking the surface area of the holes through the sheet. This neglects the additional heat transfer from the surface of the sheet, and thus underestimates the actual heat transfer capability of the metal matrix fuel form. Figure 7 shows the heat transfer area as a function of hole diameter for the case where 25% of the sheet surface area is penetrated by holes. At a hole diameter of 1.5×10^{-2} cm (6 mils) the heat transfer area is 67 cm^2/cm^3, comparable to the surface area in PBR beds.

Figure 8 shows a proposed construction for the layered array of perforated sheets. The gas flow holes through the sheets are located in a grid of slightly depressed lines formed in the sheets. When the sheets are layered together, the raised zones prevent closure of the holes in the sheets. Gas exiting through the set of holes in one sheet has no problem in flowing to, and entering, the set of holes in the next sheet.

This flow arrangement helps to mix the gas flow between sheets, and reduces the chance of thermal instability. The first sheet in the multi-layer stack (the "cold frit") will have smaller holes so as to distribute and match the H_2 flow to local variations in the radial, axial, and azimuthal nuclear power distributors.

Table 6 gives nominal design parameters for the MITEE-1 engine with LiH moderator. The ^{235}U

loading is not given, since it will have to be determined by MCNP calculations. Based on this initial examination, the MITEE-1 reactor will weigh approximately 50 kilograms. The weight of the turbo pump (~ 10 kg) assembly has not been included. Further optimization of the reactor is expected to reduce its weight somewhat, allowing the total engine weight to be about 50 kilograms.

UTILITY OF THE MITEE ENGINE FOR NEO INTERACTION MISSIONS

We now consider the quantitative advantages of the MITEE engine over a chemical rocket for a typical "terminal interception" of an NEO on collision course with Earth. Terminal interception, as its name implies, differs from what is termed "remote interdiction" where the orbit of a colliding NEO is well known several periods prior to the collision, and deflection of the NEO can be effected at an early time. The Earth-crossing asteroids may eventually become subject to remote interdiction, but not long-period comets which may visit the Earth only once. At this writing, only a small fraction of even the "well-behaved" Earth-crossing asteroids have been found. Thus, for some time to come, both comets and asteroids will be subject to "terminal interception."

Considering now a case involving terminal interception, Figure 9(a) shows an earth-crossing NEO on collision course with Earth, represented in heliocentric coordinates. The orbit of the NEO is elliptic around the sun. Transformation of the coordinates from heliocentric to geocentric, as shown in Figure 9(b), makes the problem very nearly one-dimensional, if we confine our attention to terminal interception, i.e., to a time scale of about one month. (Note: The one-dimensional analysis would certainly be inappropriate if we considered interaction time scales corresponding to the period of the NEO or the period of the Earth, i.e., one year.)

If we now view the interception as a one-dimensional problem, we can illustrate the interception graphically on a time vs. radial-distance-from-Earth plot, as shown in Figure 10. The abscissa is the time scale, represented in days prior to impact, with "D" as the day of predicted impact. The graph illustrates a case where an impacting NEO is discovered at a distance R_L from Earth on a date T_L days prior to impact. At the same time that the NEO is discovered, an interceptor is launched to interrogate/deflect/destroy the NEO. The slopes of the two lines representing the motions of the NEO and the interceptor correspond to their respective slopes. The interception occurs at T_I days before impact at a distance of R_I from the Earth.

A graph such as Figure 10 can be used to illustrate the advantages of a nuclear rocket such as MITEE. In Figure 11 we show a comparison of the nuclear and the chemical rocket for two different situations: 1) The NEO velocity is moderate compared to the interceptor velocity, and 2) NEO velocity is larger than or comparable to the interceptor velocity. The first might correspond to an Earth-crossing asteroid, whereas the second corresponds to a very long-period comet. The latter typically have closing velocities of about 55 km/sec. The conclusions that can be drawn from Figure 11 are:

1. Nuclear rocket is always better than chemical because interception occurs at a larger distance.

2. The advantage of the nuclear rocket is greatest when the NEO closes at a high

velocity. These NEOs are likely to be long period comets, which will probably be discovered only a short time prior to impact.

The analysis described above was used for a numerical example of the interception problem. Assume that a long-period comet is discovered to be on a collision course with Earth 30 days prior to impact. The comet has a closing velocity of 55 km/sec. Interception is considered via a chemical rocket and a nuclear rocket.

The interceptor powered by a chemical rocket has a terminal velocity of 7.5 km/sec. The interceptor reaches the comet 3.6 days prior to impact, when the comet is at a distance of 17,000,000 km from Earth. If the vehicle carried an explosive device it would have to impart a lateral velocity of 20.6 m/sec to the comet to miss the Earth.

For the interceptor powered by a nuclear rocket, the situation would be as follows. The terminal velocity of the interceptor is 15 km/sec. The interceptor reaches the comet in 6.4 days prior to impact, when the comet is at a distance of 30,000,000 km from Earth. If the vehicle carried an explosive device it would have to impart a lateral velocity of 11.5 m/sec to the comet to miss the Earth. The advantage of the nuclear rocket is clearly evident from this example.

CONCLUSIONS

Ultra compact nuclear engines offer the potential of achieving extremely high ΔVs of NEO intercept and rendezvous missions, using light-weight spacecraft. Total ΔVs of 30 to 40 km per second appear possible using an ultra-compact MITEE engine. The total weight of the MITEE engine is projected to be approximately 50 kilograms, with a thrust level of ~ 2000 kilograms force. The MITEE engine could accelerate a 50 kilogram payload to a flyby velocity of 35 km/second based on a total spacecraft takeoff weight of 3 metric tons.

The MITEE engine is an advanced lightweight version of the PBR nuclear engine, for which an extensive development program was carried out during the period 1987 to 1993. During the program, the neutronic and thermal hydraulic performance of the PBR was experimentally validated, with demonstration of fuel element power densities of 30 Megawatt power densities. Hardware for the PBR - fuel particles, moderators, frits, etc. - were also developed and demonstrated.

The MITEE engine appears to be of excellent promise for NEO interaction missions, and would intercept and rendezvous with NEOs at much longer ranges than would be possible with chemical rockets.

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Table 1

Design Features and Parameters for a 1000 Megawatt PBR Nuclear Engine

Power level	=	1000 MW
Mixed mean outlet temperature	=	3000 K
Average fuel bed power density	=	40 MW/Liter
H_2 chamber pressure	=	70 Atm
Number of fuel elements	=	19
K_{eff}	=	1.18 (criticality constant)
Specific impulse	=	950 seconds
Fuel element pitch/diameter ratio	=	1.5
Frit mass	=	29 kg (aluminum cold frit, coated carbon-carbon hot frit)
Fuel bed	=	56 kg
Moderator	=	159 kg (beryllium - polyethylene)
Grids	=	100 kg
Core total	=	345 kg
Pressure vessel	=	45 kg (carbon - carbon)
Balance of plant	=	647 kg (turbo-pump, thrust vector control, nozzle, propellant management system, and instrumentation)
Thrust to weight ratio	=	31

Table 2

Comparative Features of the PBR and MITEE Nuclear Engines

Feature	PBR	MITEE
Type of construction	Single pressure vessel	Assembly of multiple individual pressure tubes
Type of nozzle	Single nozzle	Multiple nozzles - one for each pressure tube
Fuel form	Coated particles (~ 400 μ diameter)	UC/C or UO_2 particles or fibers in thin metal matrix composite plates
Heat transfer to H_2	Packed bed of fuel particles	Perforated metal matrix plates
Weight	~ 500 kg	~ 50 kg
Power level	~ 1000 MW	~ 50 to 100 MW
Power density in fuel zone	~ 30 to 40 MW/Liter	~ 20 to 30 MW/Liter
Thrust, lbsf	~ 45,000	~ 3000 to 4000
H_2 exit temperature (mixed mean)	~ 3000 K	~ 3000 K

Table 3

Principal Features of MITEE-1 and MITEE-2 Moderators

	MITEE-1		MITEE-2
Feature	LiH Moderator	Polyethylene Moderator	Liquid H_2 Moderator
Moderator form	LiH particles in Be-Graphite metal matrix composite	Polyethylene melted into Be-Graphite honey-comb pressure tube	Liquid H_2 inside Be-Graphite pressure tube
Moderator maximum temperature	~ 700 K	~ 400 K	~ 30 K
Volume fraction of moderator	~ 0.8	~ 0.8	~ 0.9
H_2 density in mod material, cm^{-3}	6.2×10^{22}	8.4×10^{22}	4.2×10^{22}
Effective H_2 density, cm^{-3}	5.0×10^{22}	6.5×10^{22}	3.8×10^{22}
Effective mass density of mod/Be-G mixture, g/cm^3	1.02	1.14	0.24

Note: Be-Gr mass density = 1.8 g/cm^3

Table 4

Nominal Properties and Operating Temperatures for Metal Matrix Fuel Forms

Parameter	Be Matrix	Fuel Form MO Matrix	W Matrix (separated W^{184})
U-235 form	UC_2/C fibers or UO_2 particles or UO_2 whiskers	UO_2 particles or UO_2 whiskers	UO_2 particles or UO_2 whiskers
Matrix melting point, K	1557	2893	3643
Matrix maximum operating temperature, K	1200	2300	3000
Matrix density, g/cm^3 (100% density factor, U^{235})	1.8	10.2	19.3
Effective density of metal in fuel zone, g/cm^3 (20% holes and 20% U^{235} by volume in matrix)	1.08	6.12	11.58
Fraction of fuel region occupied by fuel form	0.40	0.37	0.23
Effective density of metal in fuel region, g/cm^3	0.43	2.26	2.66

Table 5

MITEE Reactor Dimensions and Weights as a Function of Moderator Type

Parameter	MITEE-1		MITEE-2
	LiH Mod	Poly E Mod	Liquid H_2 Mod
$\bar{n}_H$, atoms/cm^3	5×10^{22}	6.5×10^{22}	3.8×10^{22}
Metal matrix volume, Liters	3	3	3
Hot channel volume, Liters	1	1	1
f_{mod}	0.85	0.77	0.92
R_C, centimeters	18.8	16.2	23.1
Core volume, Liters	27.5	17.5	51.1
Moderator volume, Liters	23.5	13.5	47.1
Moderator weight, kg	24.0	15.4	11.3
Metal matrix weight, kg	16	16	16
U^{235} weight, kg	~ 2	~ 2	~ 3
Total core weight, kg	42	33.4	30.3
Reflector thickness, cm	7.5	7.5	7.5
Reflector volume, Liters	48.4	37.9	68.3
Reflector effective density, g/cm^3 (Liquid H_2 + Be-G)	0.25	0.25	0.25
Reflector weight, kg	12.1	9.5	17.1
Total Reactor Weight, kg	54.1	43.9	47.4

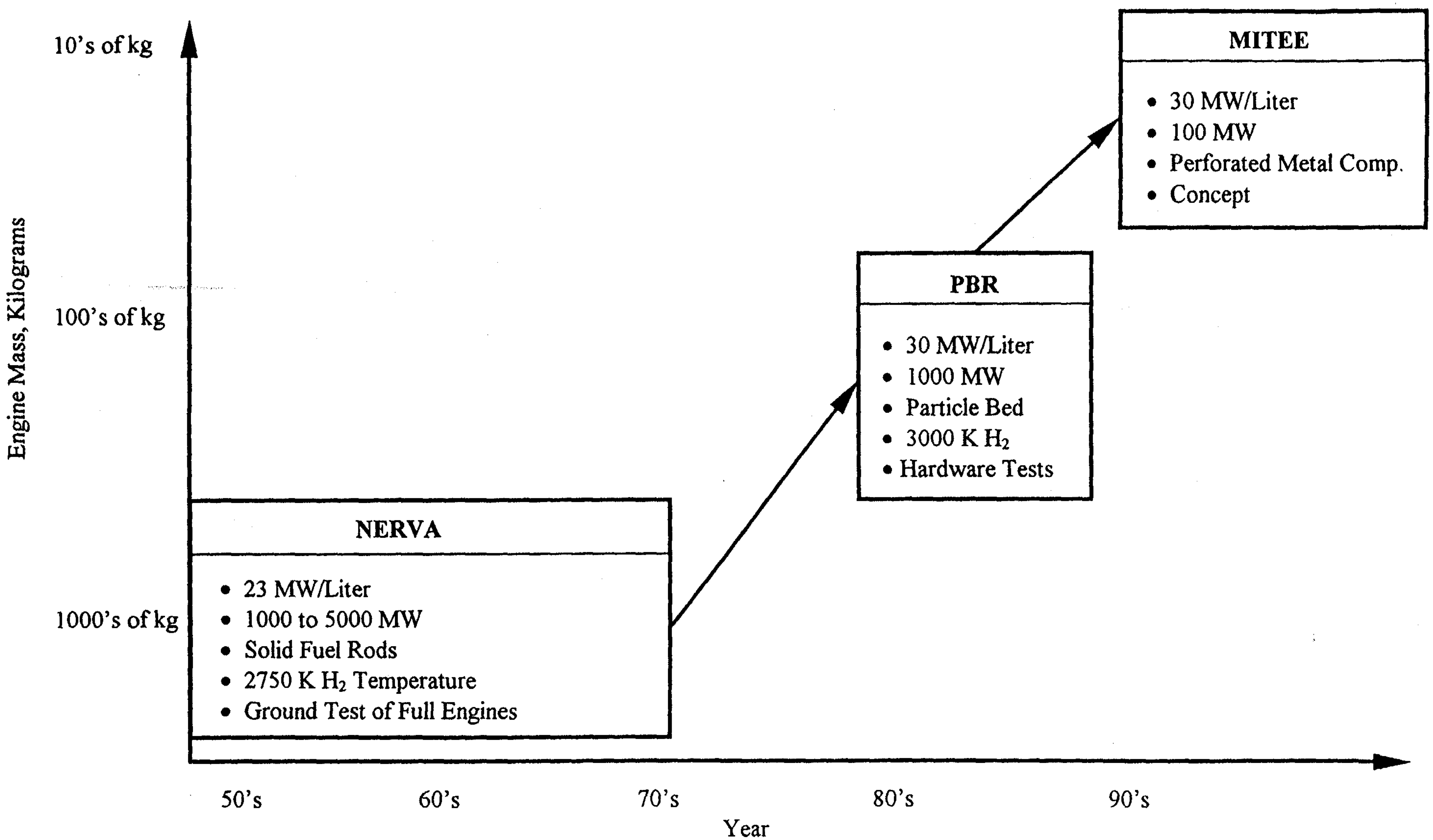
Table 6

Nominal Design Parameters for MITEE

- 75 MW reactor power
- 3000 K exit temperature
- 25 MW/Liter average power density in metal matrix
- 19 fuel elements (hexagonal shape)
- 37 cm core diameter
- Radius of hot gas channel = 0.685 cm
- Total H_2 flow rate = 1.67 kg per second
- Outer radius of metal matrix region in fuel element = 1.35 cm
- Be matrix volume fraction = 0.40
- Mo matrix volume fraction = 0.37
- W matrix volume fraction = 0.23 (Tungsten - 184)
- Moderator volume fraction = 0.85
- Core moderator composition
    - 80% LiH ($\rho = 0.82$ g/cm^3)
    - 20% graphite-Be (70% Be, 30% graphite)
- Core moderator temperature = 700 K
- Reflector composition
    - 90% liquid H_2 ($\rho = 0.07$ g/cm^3)
    - 10% graphite-Be (70% Be, 30% graphite)
- Hole volume fraction in metal matrix = 0.25
- Hole diameter = 1.5×10^{-2} cm (6 mil)
- Exit temperature from metal matrix zone
    - 1200 K from Be matrix
    - 2300 K from Mo matrix
    - 3000 K from W matrix

Figure 1

Overview of Nuclear Rocket Capabilities



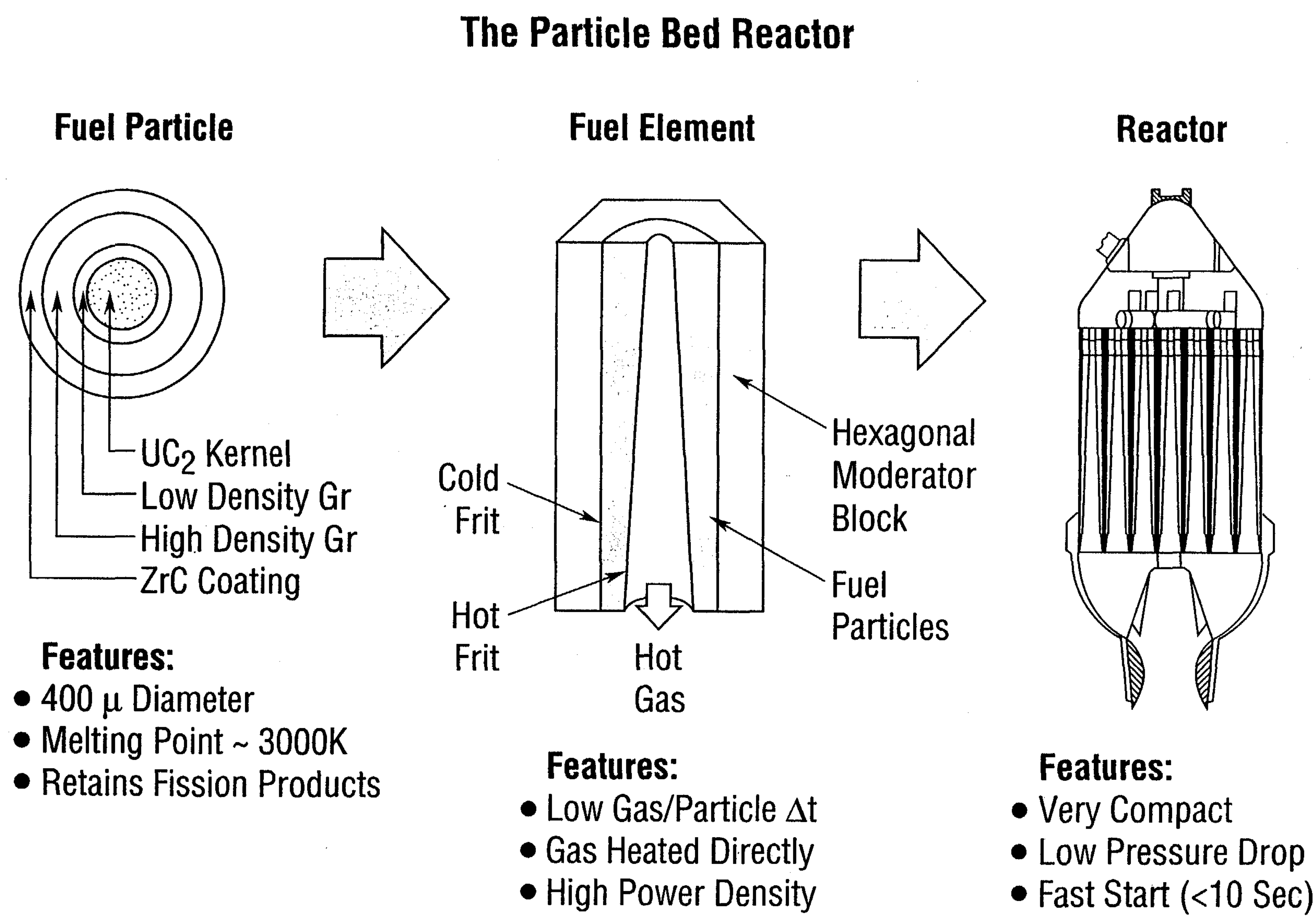

The Particle Bed Reactor
Fuel Particle
Fuel Element
Reactor
UC2 Kernel
Low Density Gr
High Density Gr
ZrC Coating
Features:
• 400 μ Diameter
• Melting Point ~ 3000K
• Retains Fission Products
Cold Frit
Hot Frit
Hot Gas
Hexagonal Moderator Block
Fuel Particles
Features:
• Low Gas/Particle Δt
• Gas Heated Directly
• High Power Density
Features:
• Very Compact
• Low Pressure Drop
• Fast Start (<10 Sec)

Fig. 2

PBR Engine Description

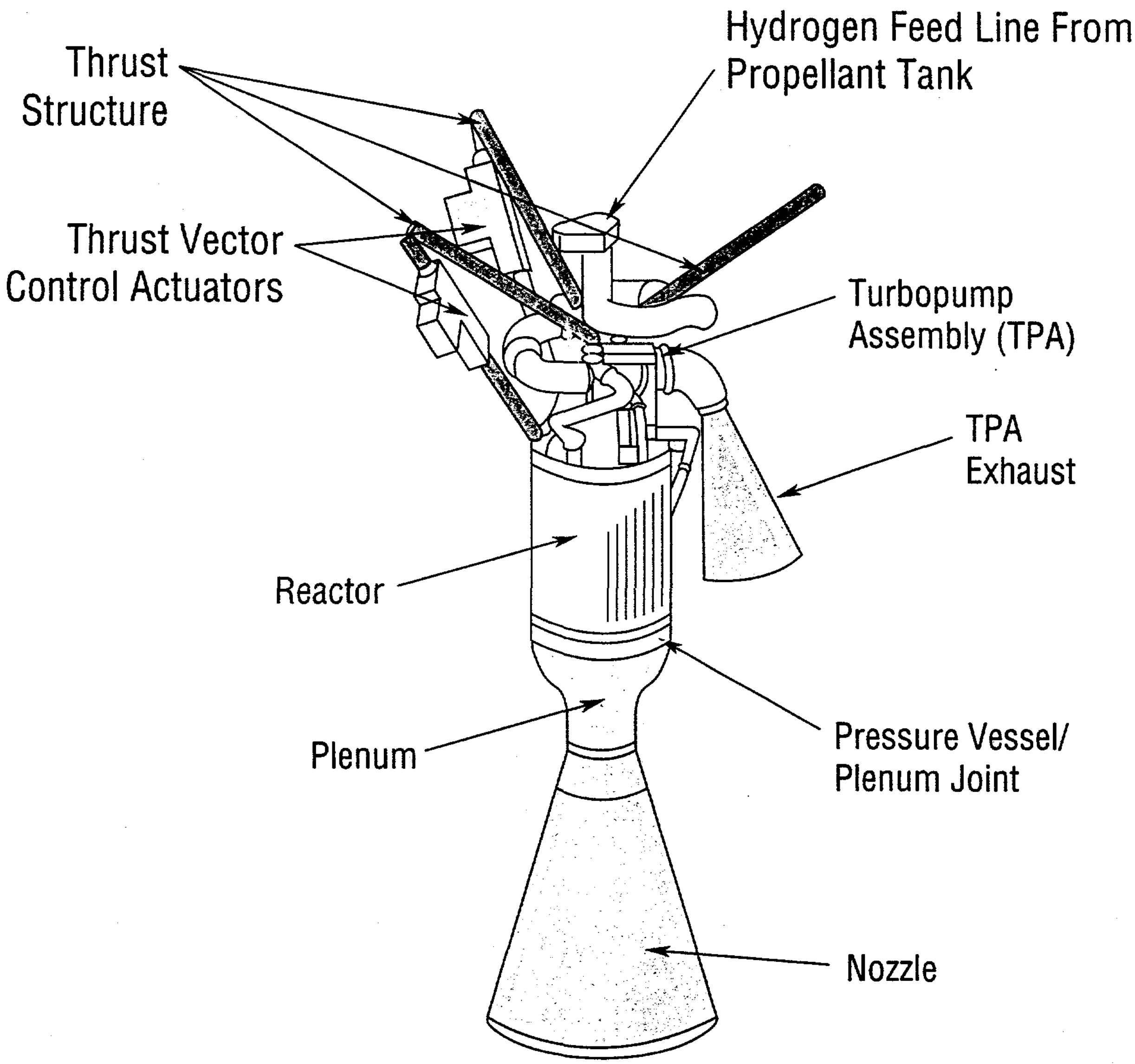


Fig. 3

Ludewig 9/96 judy

The MITEE (MIniature ReacTor EnginE) Concept

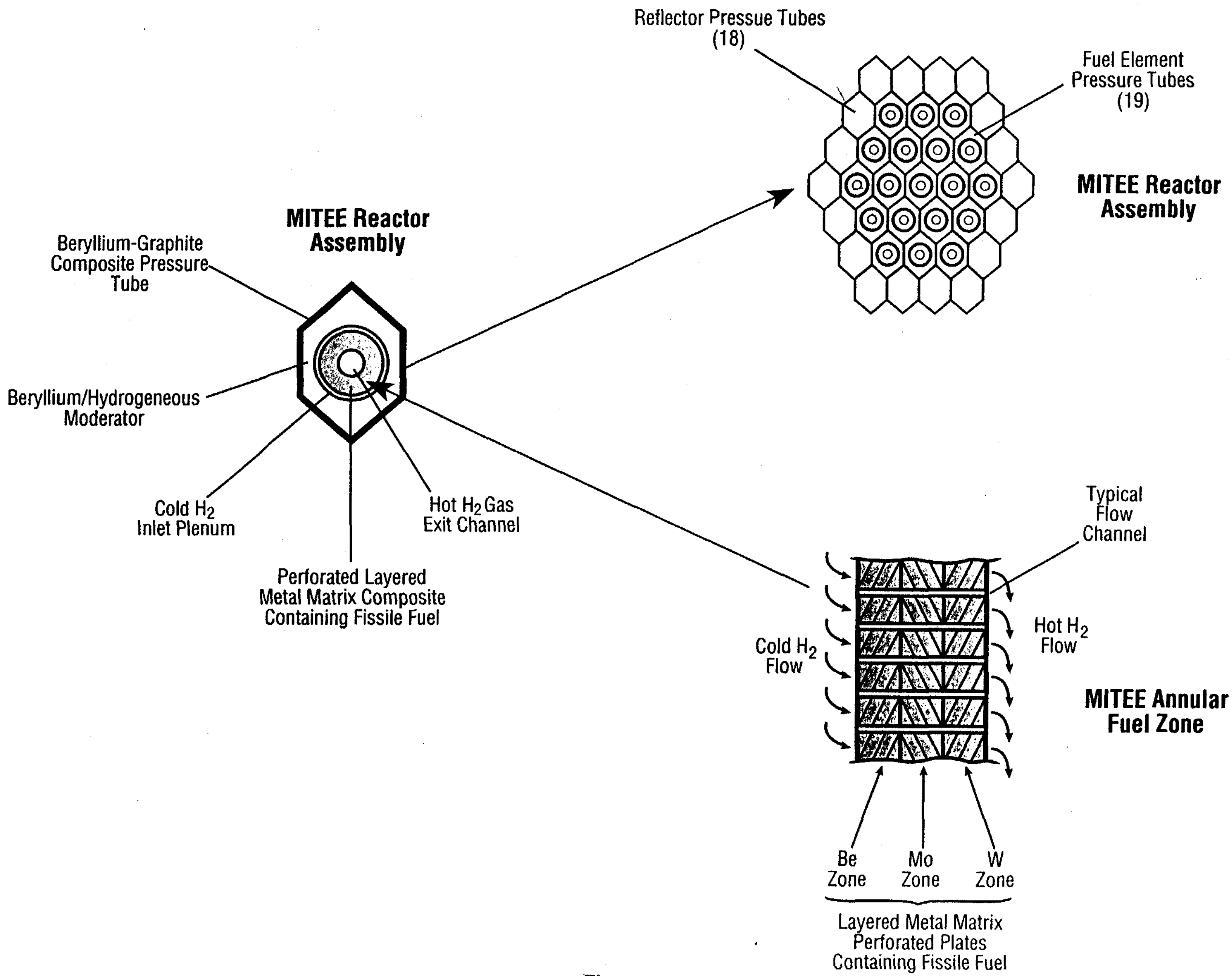


Fig. 4

Powell 1. 9/96 judy

MITEE Pressure Tube and Exit Nozzle

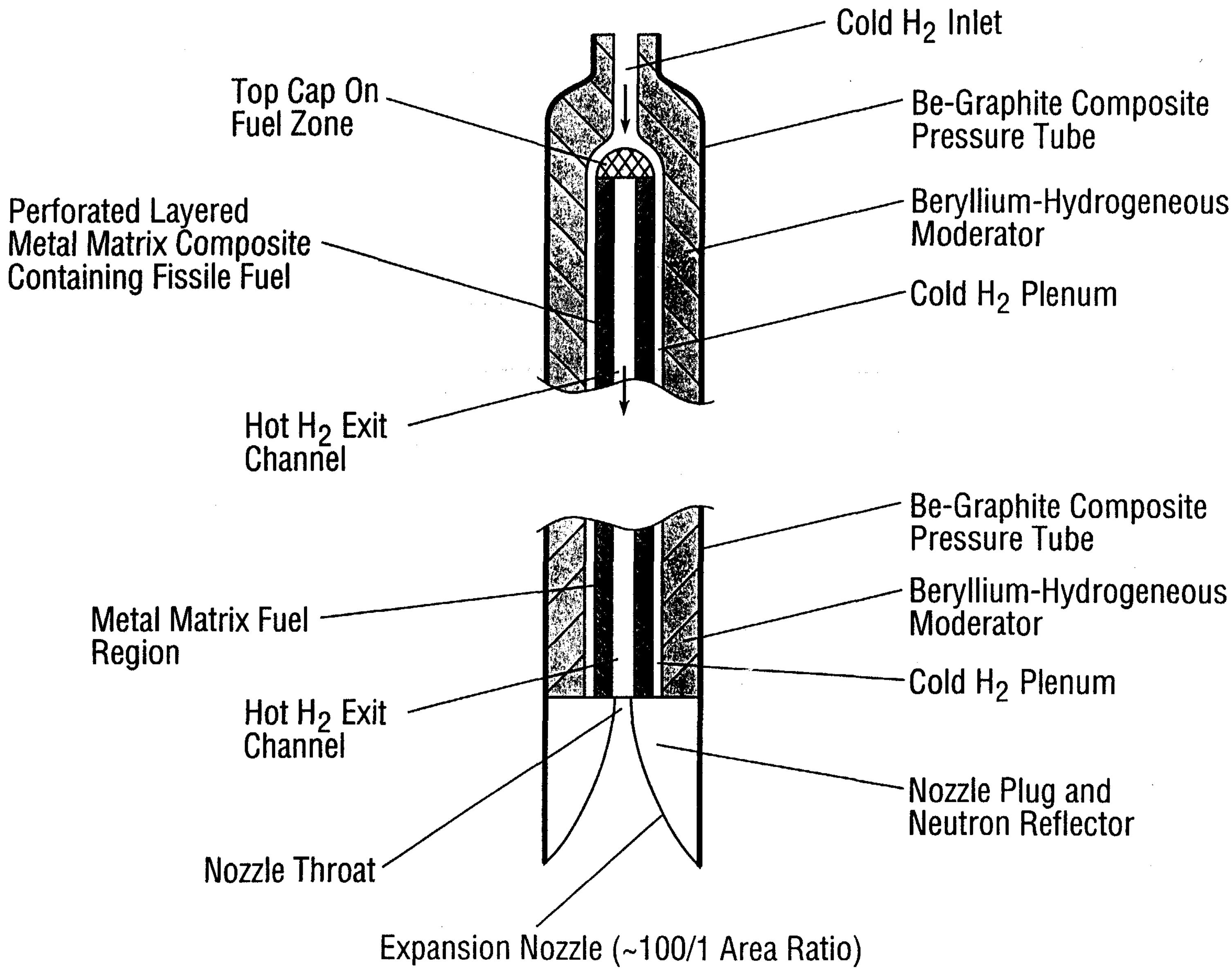


Fig. 5

Powell 2' 9/96 judy

MITEE Fuel Region

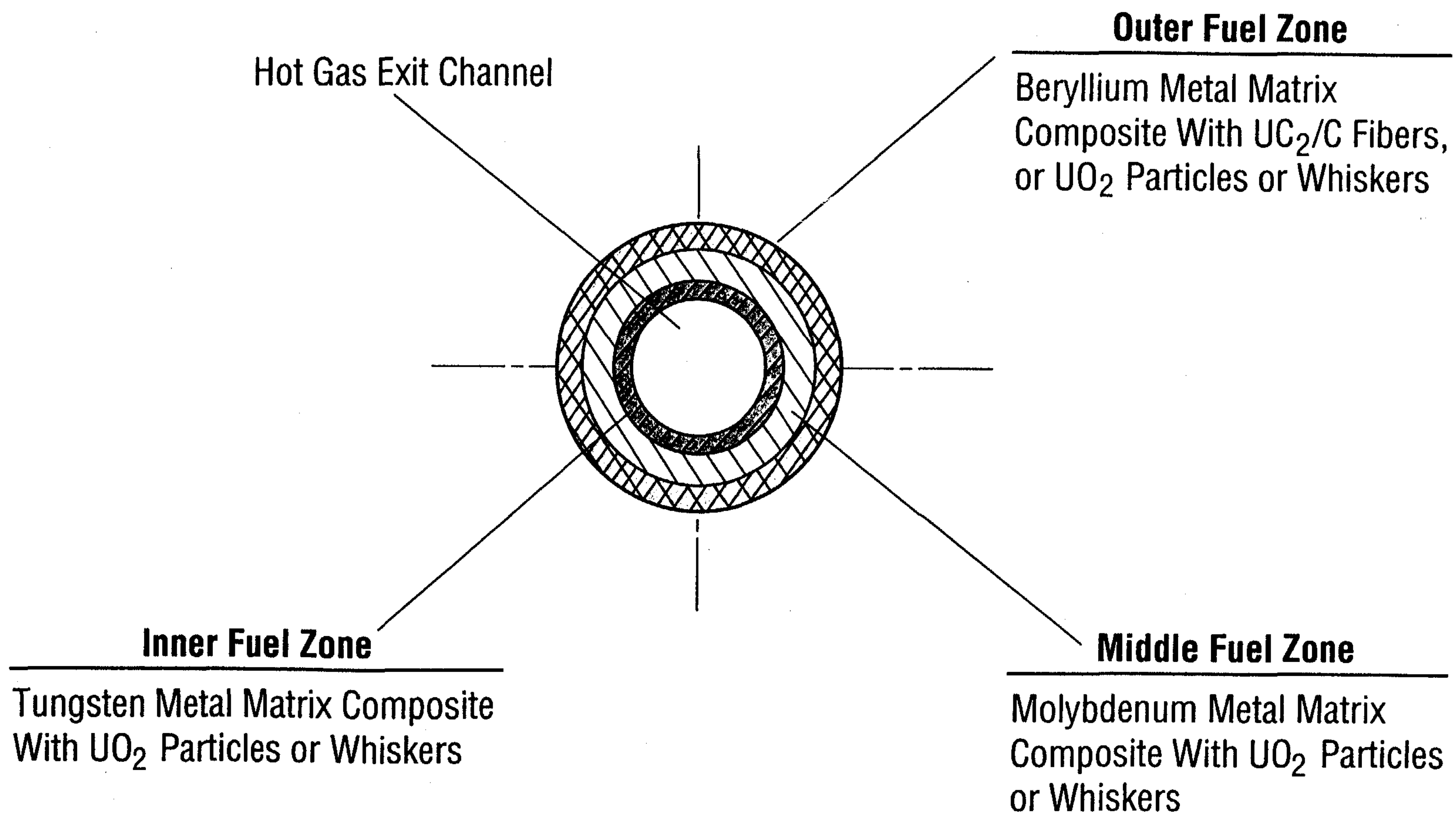


Fig. 6

MITEE Heat Transfer Area In Metal Matrix As A Function of Hole Diameter

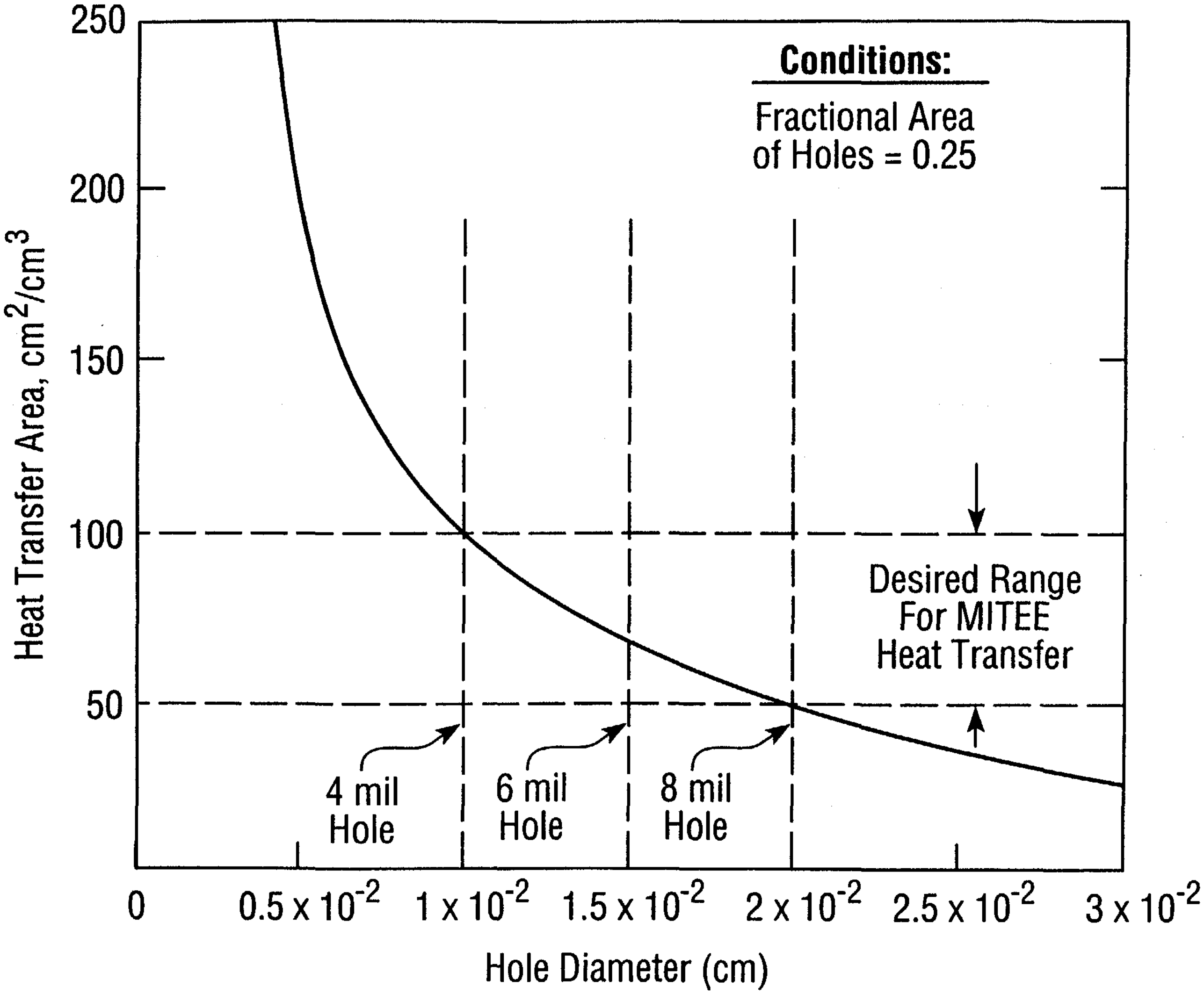


Fig. 7

Construction of Multiple Matrix Sheets

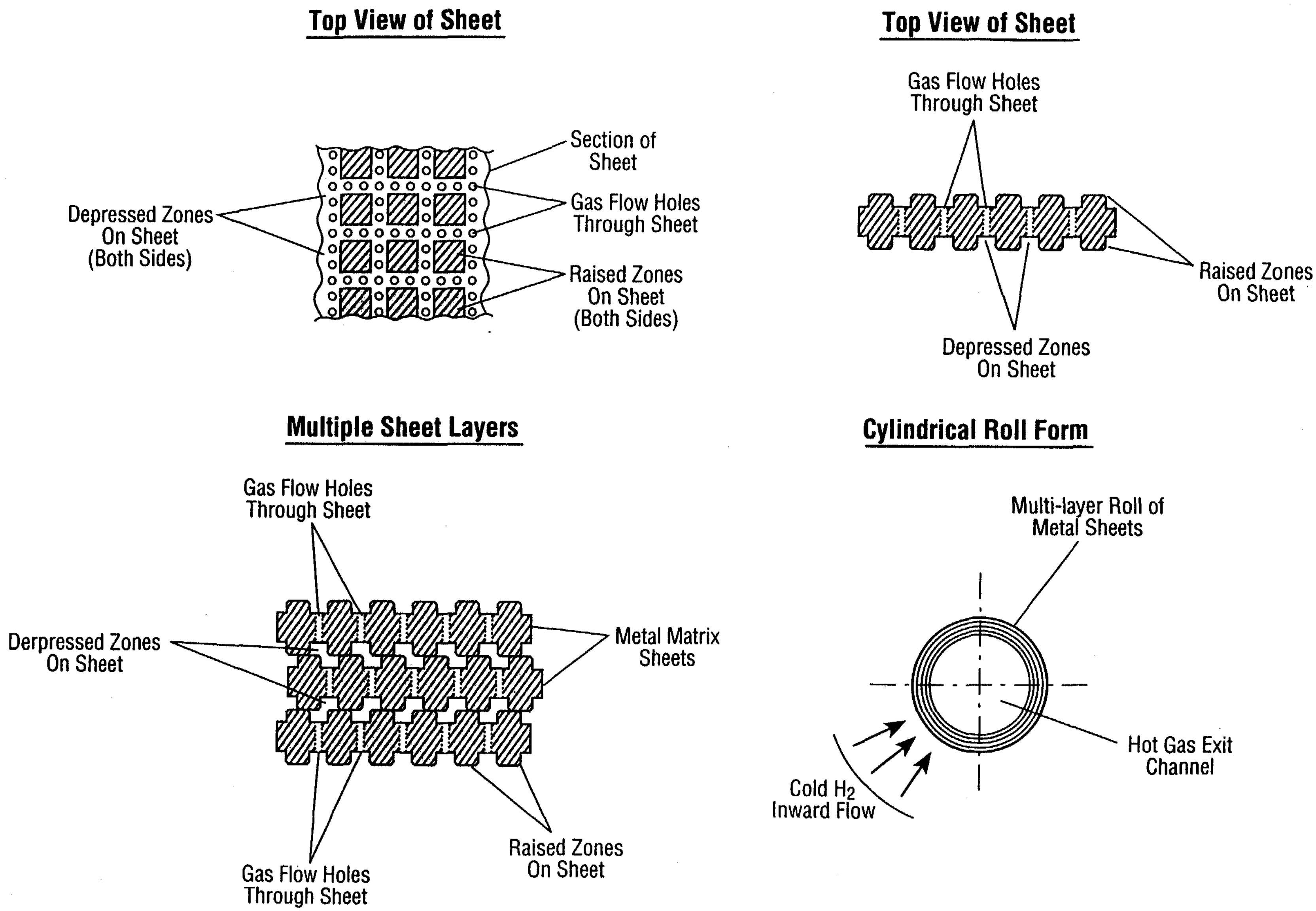
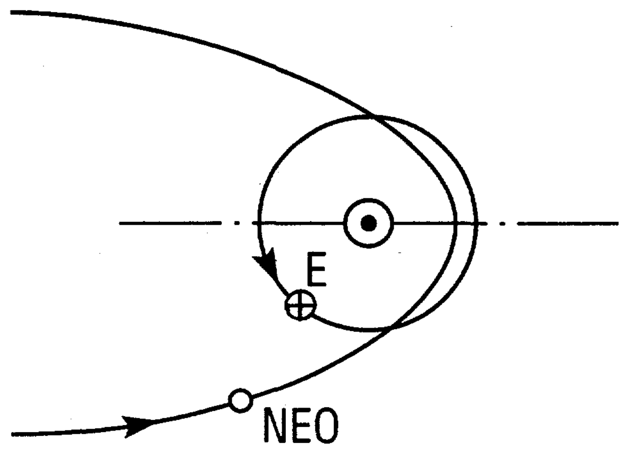
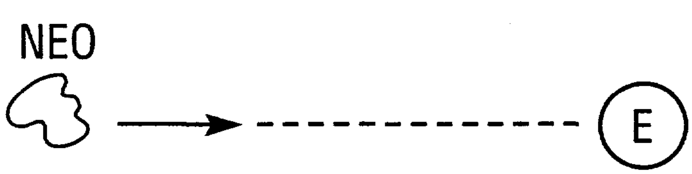


Fig. 8

Coordinate Systems For Terminal Intercept Problem



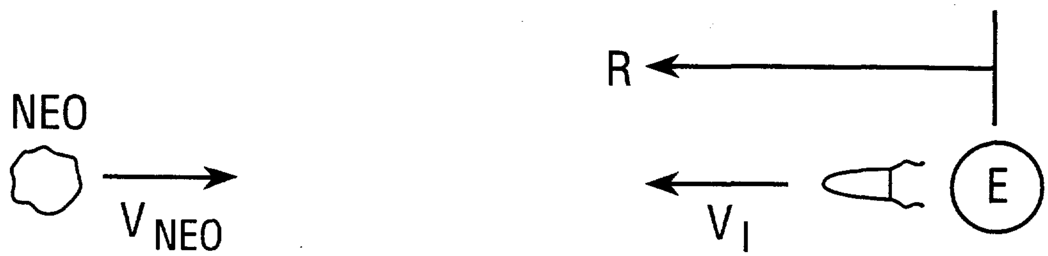
(A) Heliocentric Coordinates



(B) Geocentric Coordinates
(Time To Impact ~1 Month)

Fig. 9

Terminal Intercept Problem



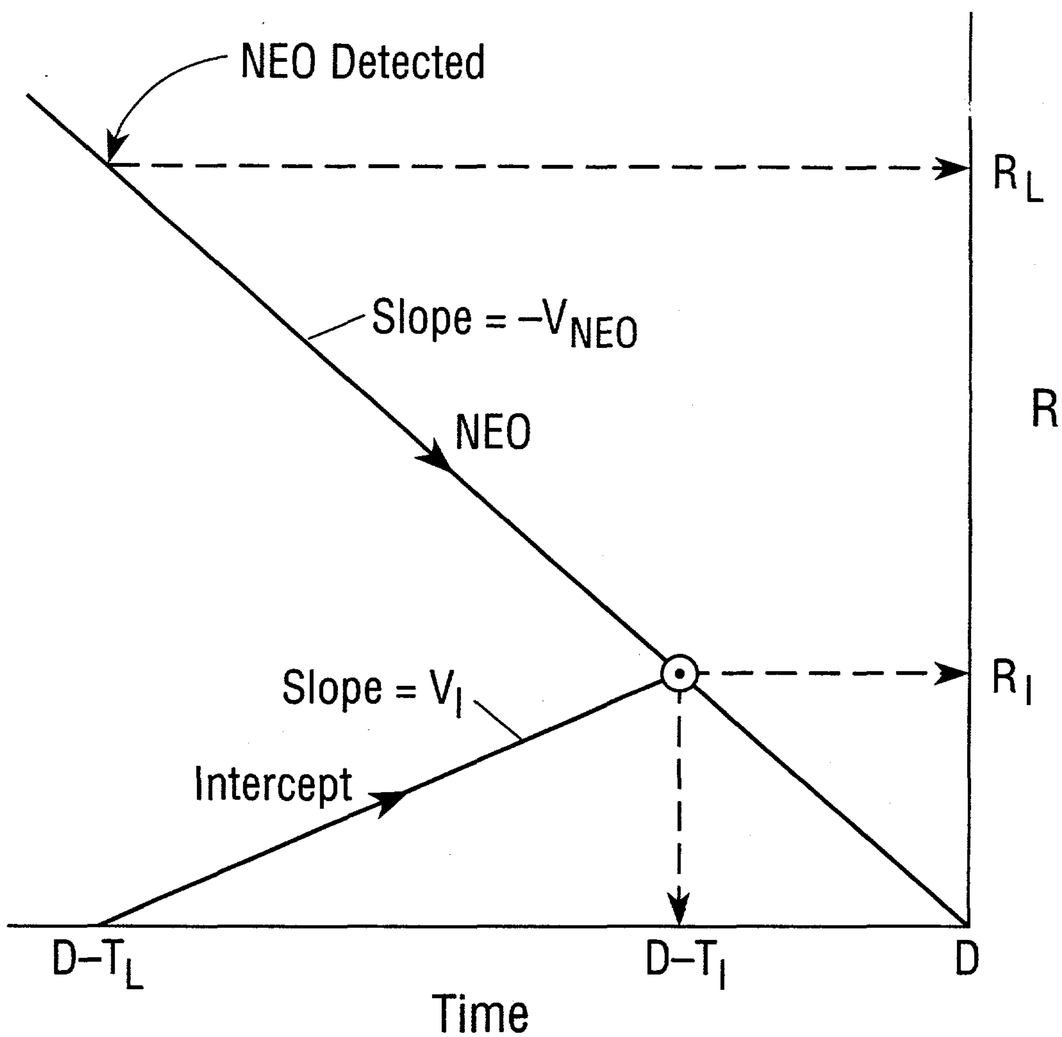


Fig. 10

Comparison of Chemically and Nuclear Powered Rockets

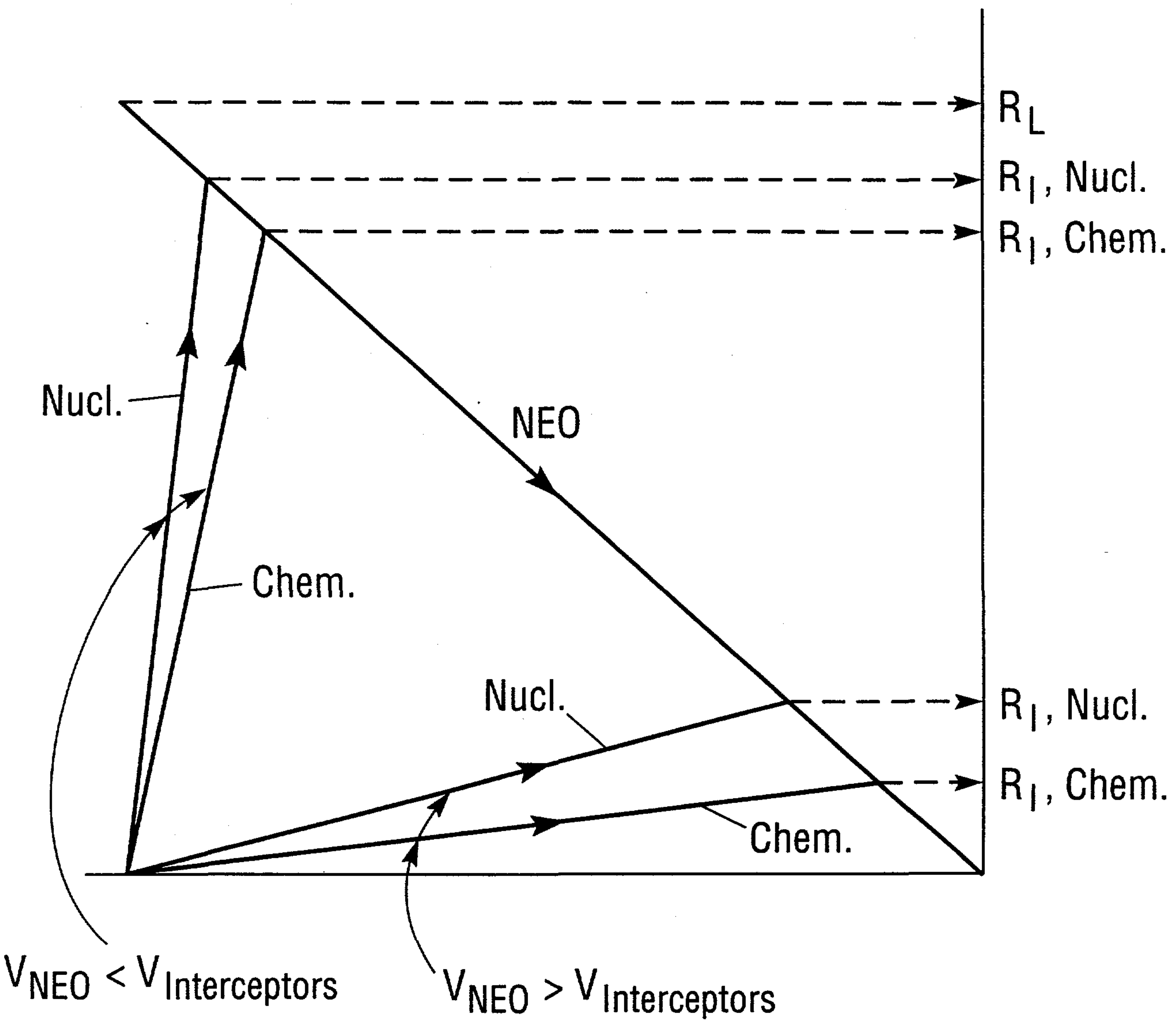


Fig. 11