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FISSION FRAGMENT ASSISTED REACTOR CONCEPT FOR SPACE PROPULSION-- FOIL REACTOR

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Well, I am not the salesman that Mr. Zubrin is, nor the poet that Mr. Kirk is, but I think we have a reactor concept that will be intellectually stimulating and fun. It is called the foil reactor in the agenda, but I will be referring to it as a fission fragment assisted reactor concept for space propulsion. And as Mr. Kirk said, the idea is not new, it is just a collection or combination of ideas that have been around for quite sometime.

What we want to do (Figure 1) is to fabricate a reactor using thin films or foils of uranium, uranium oxide and coat them on to substrates. We would make these coatings so thin as to allow the escaping fission fragments to directly heat a hydrogen propellant. This idea is not new. In 1958, Bussard and Delauer mentioned a concept of similar nature in their book; however, they didn't investigate it very much in depth.

At Sandia we have been studying this idea of direct gas heating and direct gas pumping in a nuclear pumped laser program. In this program we are actually using fission fragments to pump lasers. And to show you that I am stealing ideas, I actually have one of their vugraphs that fits very nicely in this talk (Figure 2).

In this concept two substrates are placed opposite each other. The internal faces are coated with thin foil of uranium oxide. The foils are so thin that a large fraction of the fission fragments escape into the gas. The gas is chosen so it will be excited by escaping fission and emit light to provide light amplification. This method of pumping a laser does indeed work.

We have taken another idea for our concept from the particle bed reactor. In the particle bed reactor porous frits are used to control the flow to the fuel element. For the foil reactor, we will also use substrates that are porous. However, our substrates will be coated with thin films of uranium oxide. The gas flows to the substrate into this folded flow reactor, and it comes down and flows through, and heats up through this substrate, which will pick up approximately 2,000 or 2,300 degrees Kelvin. Then, in the exit plenum between the foils, a large fraction of energy is being directly deposited, and will heat the gas another thousand degrees. So our gas temperatures are much, much hotter than our substrate temperatures and we would do the same thing on the other sides. The one thing we have to optimize is the spacing between the plates so you don't get a lot of heat transfer back to the substrates.

We selected a hydrogen propellant pressure of 1000 psia. To stop the fission fragments that travel through the plenum between the foils, you need approximately two centimeters of hydrogen at this pressure. However, we are proposing a system which uses five centimeters. This spacing was selected to minimize the heat conduction or heat transfer back to the substrates. There exists a large technology base (Figure 3) that supports this concept of direct gas heating, and most of it comes from the nuclear pumped laser program called FALCON, which stands for Fission Activated Laser CONcepts. These experiments are being performed at Sandia, and in conjunction with experiments at INEL.

We already have experimental verification for the amount of energy and the number of fission fragments that escape foils, as a function of foil thickness. I will show you the vugraph supporting that in a minute. Since we are doing experiments, we have to develop technology to coat UO_2 on a variety of substrates (Figure 4), including stainless steel, aluminum, alumina, and beryllia. The technology to make coatings is available, but we do need to advance the technology, especially to place them on porous substrates.

Figure 4 shows a scanning electron micrograph of a uranium oxide coating placed on an alumina substrate. We have made these types of coatings on both aluminum oxide and beryllium oxide ceramics.

In our experiments (which are transient experiments), we have verified that one can heat gases at least 1,000-1,500 degrees above the substrate temperature. In these experiments the power densities are approximately 17 kilowatts per square centimeter of foil surface area. This is 17 times higher than the power densities that we are proposing for the nuclear propulsion concept described here.

Let me show you that we really do know how much energy is getting out of these foils as a function of foil thickness (Figure 5). This figure shows the energy escape fraction as a function of foil thickness. The diamond marks are actual measurements. With a three micron foil, you can get about 20-21 percent energy release fraction. We are proposing, in this concept, to work between the one and two micron foil thickness; thus we would expect to see fission fragment escape fractions (in terms of energy) of, say 24 to 30 percent. The squares on the figure show you the actual particle escape fraction, and that's important because it tells the number of the fission fragments that are lost out the exhaust of the reactor.

If you make a reactor out of a coated porous substrate and assemble these fuel elements to make a nuclear driven rocket engine out of this type reactor geometry, what does it get you (Figure 6)? We feel like this gives us enabling technology that is well beyond what is feasible with current designs. The major advantage of this approach is that the propellant gas is much hotter than the structure, approximately a thousand degrees hotter. As a consequence we also get very respectable Isps; 800 to 1,000 seconds for very low substrate temperatures. Here is an example. A 2,000 degrees Kelvin substrate temperature allows one to obtain a gas temperature of 2,700 degrees and an Isp of 836 seconds. I believe we did this calculation for one and a quarter micron foil thickness.

This reactor is very big, it's very dilute, so it can be run at very high power levels to obtain tremendous thrust; 600 thousand pounds or more. It's a lot of thrust.

How would you make a reactor out of this? What we proposed is to place the foil-coated substrates into an annular geometry as shown in Figure 7. The gas flows down in the narrow gap between these plates. There is a three millimeter gap between the plates. Cold, dense hydrogen gas flows down, turns the corner in both directions and flows through the beryllia substrates, which we assume to be porous and have a one to two micron coating of uranium oxide. The gas flowing though the substrates heats up 2,000 degrees. Once the gas reaches the exhaust channels the escaping fission fragments heat the hydrogen up another thousand degrees.

Figure 8 shows a cross section of one fuel element module. Each module a is approximately 36 centimeters in diameter and 4 m long. The module is a self-contained pressure vessel that uses carbon-carbon for the containment boundary (Figure 9). One would assemble these modules in a hexagonal or a square lattice to form a reactor. Each module uses the beryllium oxide as a neutron moderator and as the porous substrate upon which the uranium oxide is coated. At the exit end of the module the pressure vessel is shaped into a nozzle which could, if needed, be transpirtation cooled. The weights (engine masses) that I will show include the fuel and all the structure, including the nozzle at the bottom.

About a hundred of these modules are required for the reactor to have sufficient criticality. It is a big system (Figure 10); about four meters tall and four meters in diameter. Figure 10 shows fewer modules than a hundred, but this is just a schematic to illustrate the concept.

Because the fuel is so dilute, a substantial reflector is required (Figure 11). The reflector should be somewhere between 75 centimeters and a meter thick. A wide choice of reflector materials can be used. You can use heavy water, but that is heavy. You can use beryllium, which works quite well, but also it is about as heavy as heavy water. A nearly ideal material to use would be liquid deuterium, but we feel the power required to keep the deuterium liquid would be too high. So we are proposing a new material; deuterated methane. With fairly low pressures and pumping powers you can compress it and keep it liquid. For a fuel module that uses a two micron foil thickness, you need only three-quarters of a meter of deuterated methane to reflect enough neutrons back into the reactor to have sufficient criticality margins.

The next two figures show schematics of the reactor (Figures 11 & 12). In our design the reflector covers the circumference, and the top of the reactor. No reflector is used on the bottom or exit end of the engine. Since the reflector is so thick, an external shield is not required. This 0.75 m reflector can reduce the gamma radiation dose rates by about four orders of magnitude. Consequently, all the weights that I will show you include our reflector/shield.

Let me summarize the key features of this concept (Figure 13). I have already talked a little bit about the size; a hundred modules, four meters in diameter by four meters tall. We are assuming a two micron foil thickness, which gives us an efficiency of 24 percent for the energy going directly into the gas. We need 30 kilograms of uranium oxide fuel to go critical. If you sum up all the weights, including some seven tons put in for pumps and control, you end up with 42 tons. This is big, but you also have a lot of thrust.

The power densities are low; about 300 watts per cubic centimeters. This is equivalent to a surface flux of a thousand watts per square centimeter. For reference purposes this power density is a fourth of what NERVA had. Total power is 13 gigawatts. Two percent of this power is deposited in the reflectors. This presents a problem. We have to cool that reflector, and so we are going to take some penalty for providing a cooling system. I will talk a little bit more about that in a minute.

In spite of the large reflector, the thrust-to-weight ratio is still quite respectable. It is six and a half, even for a huge reactor.

Continuing to examine Figure 13 and the key features, one sees we are limiting the maximum surface temperature to 2,700 degrees Kelvin. This is a good hundred degrees below the melt temperature of beryllia, and 400 degrees below the melt temperature of uranium oxide. Our gas temperatures are 3,400 degrees Kelvin and this and gives us an Isp of 940 seconds. For the design we proposed, we do not have a large expansion ratio nozzle. This is because we are limiting the diameter of the nozzle to the diameter of the module. One can conceive of grouping modules to increase the expansion ratio to a 100 to 1 or 200 to 1.

We have done some scoping calculations to estimate the dose rates (Figure 14). Because we have so much hydrogen propellant between the reactor and the crew habitat, which is placed at a hundred meters away from the reactor, we don't expect significant dose rates until the last burn, when the last 30 meters of hydrogen above the reactor are expended. Even though the average dose rate is high, we have so much thrust that our burn times are short. Because of the tremendous thrust, the burn time is only 11 minutes for the Mars to Earth Burn, and a short 3 minutes for the Mars to Earth burn. The cumulative dose is 4.5 Rads.

We thought a little bit about what some of the safety features of this reactor concept or rocket concept are. Figures 15 lists both advantages and disadvantages. The major advantage is that the structure is much cooler than the propellant; about a thousand degrees cooler. Additionally, the hot surfaces are limited to very, very small surfaces on the substrates. Only the outer 20 microns are hot. The rest of the materials are cool because they are bathed in cold hydrogen.

Another advantage is that the fissile inventory is low, 18 to 30 kilograms. We have redundancy, because of the large number of self-contained pressure vessels in each module. We have very short burn times, three to ten minutes for each one of the burns; as a consequence, we have total burn times of 22 minutes. So we are running at low temperatures and not running very long.

I don't know if you want to include this as an advantage or disadvantage, but it is such a large dilute reactor that it would more than likely break up on re-entry or impact. In case of impact, criticality is not a problem, if it's an impact into water. It is difficult to make this reactor go critical, so immersion in water has a negative K-effective affect. Just about anything you do to this reactor is going to make it go subcritical.

The hydrogen worth itself is negative. The hydrogen has a negative $4 worth for the whole reactor core. Over a single module it is about 4 cents, so loss of hydrogen from a single module results in 4 cents positive reactivity. This will result in a rapid power transient. You could easily deal with the resulting power increases. We also think that you could provide enough fuel modules in the reactor design so that if you lost all the hydrogen and the fuel from the fuel modules you could still go critical.

An additional safety feature is the low power densities. If power to flow mismatches did occur, the heat-up rates would be relatively slow. And in addition, since it is difficult to find sources of large positive reactivities, large energetic accidents should not occur. Thus the core design naturally provides slow accident progressions.

I think you can summarize all of these advantages into three major titles:

(1) We have increased reliability because of the lower temperatures and modularity.

(2) It is tolerant to power-to-flow mismatches. A significant power-to-flow mismatch, would vaporize the uranium oxide surface and blow that out the back end; however, you could still be critical; and

(3) The design inherently leads to graceful failure modes. You shouldn't be able to destroy the reactor through energetic reactor reactivity-induced accidents.

The major disadvantage is a perceived disadvantage. We are throwing a lot of fission fragments out the back end of the reactor in the exhaust plume. Another disadvantage is that the reactor design has a low structural mass and is quite large. It may be difficult to withstand the required loads.

A significant effort is required to learn how one might design a reactor or rocket of this concept. An additional penalty or disadvantage is that a significant amount of equipment is required to cool the reflectors.

In some aspects, losing fission fragments out the exhaust has a positive effect. About half of our fission fragments are gone. That's why I pointed out the particle escape fraction earlier. As far as the crew is concerned, having lower fission product inventory is a benefit.

What are some of the key technology issues (Figure 17)? You have to remember we have taken this idea from the nuclear laser program, and there we are trying to get all the energy we put in to the gas back out as light. If we get light out of this excited hydrogen, it is going to heat up our substrates and the concept isn't going to work; so we need to make sure that we test the concept of directly heating hydrogen with fission fragments. We have to try hydrogen in the SNL laser experiments to find out if we get significant quantities of light out. We think the answer is no, because hydrogen is a symmetric molecule. If you want to make a laser, you use $C0$ or $C0_2$, which is an asymmetric molecule. Additionally, our experience indicates that most of the excitation energy will end up as thermal energy if we have high gas pressures and high temperatures, which we do.

We think the physics is in our favor here, but we don't know. We have to test it. Also we need to study dilute system critically. Nobody has spent much time on this or reported on it, although we scoped it out a bit. We also need to study reactor structural designs for large dilute systems. Again, this hasn't been done. And finally, we need to learn how to fabricate porous frits and ceramics. They could be made from the beryllioxide as I mentioned, but there is no reason why we couldn't use carbon porous frits with zirconium carbide or uranium carbide overcoatings. These materials would increase our temperature capabilities.

We have investigated techniques to coat solid substrates, but we haven't coated porous materials. Once you can do these things, we need to study its integrity. How much of the hydrogen erosion would occur on the fuel and substrate? What kind of maximum thermal gradient can be tolerated before we start popping off or flaking off fuel. And we need to take a really good look at the reflector cooling, at how much it weighs and how one would go about cooling the reflector. We don't think you can push cool hydrogen down into the liquid or the deuterated methane to cool it, because hydrogen is poison to this reactor. So you have to pump methane out of the reactor to some sort of heat exchanger up above the reflector.

The critical tests to verify such a proposed concept are closely related to the key issues (Figure 18). We need physics experiments. This should require a couple years of work, which have to be performed in-pile, so it's fairly expensive, $5 million. We need scoping studies for dilute system criticality, reflector cooling, and structural design. Again, I estimate it will take a team of people about two years and $5 million.

Additionally, we need technology development. We need to learn how to build porous substrates either out of beryllioxides or carbides. We need to learn how to make coatings, again, with oxides or carbides. And we need to study and test the integrity of these uranium and zirconium carbide coatings.

We need component testing. Ideally these should be channel-type tests, i.e. tests where you would have one of these coated substrates assembled to mock-up a fuel module. You would like to test them at prototypic power, temperature and flow rates. Unfortunately there aren't any reactors around that can meet the desired flux levels that you need. Two candidates would be HFIR reactor and Advanced Test Reactor. I am not sure of the accuracy of these numbers, but it is in this range. I believe we can only get about 50 to 100 watts per square centimeter power density on the surface of such a reactor. There is another reactor being proposed for the nuclear pumped laser program and this reactor might be available in 1995. If this reactor is built, you might be able to get up about 400 watts per square centimeter. If this test reactor is built, you might be able to get up about 400 watts per square centimeters. If this test reactor existed, one would need about $20 million in two years worth of module testing experimentation.

Then finally you need systems integration, site preparation, engineering fabrication, and facility operation. My total numbers here are in the same range as everybody else's, 1.2 to $2.4 billion. The cost depends on whether you want to go first class, or do it a little cheaper, or on how many people are involved.

How would you ground test such a thing (Figure 19)? Shooting fission fragments out the back end would not be acceptable. What we are proposing is that one could overcoat the UO_2 films with sufficient amounts of zirconium carbide or another material to stop the fission fragments so they don't get out, and to do this to all the modules except one. Then for the coated modules we would propose a closed 13 gigawatt loop heat exchanger. It's no small item, but probably is within reason, because you have 33 gigawatt nuclear power plants. Then, in that one module, you could run it as an open loop at about 130 megawatts. You would have to vent the exhaust through a scrubber. So this one scheme could be used for testing.

Now, I am a nuclear engineer, not a rocket scientist, and I feel rather uncomfortable putting up Figures 20-23. We have tried to make an estimate of what the IMLEO would be as a function of thrust-to-weight, and I believe we are roughly in the category shown. We are expecting Isps of about 900 or 950 seconds, so we are predicting an IMLEO of about 450 metric tons including shields. We think this compares favorably with the NERVA baseline.

What are the mission options (Figure 23)? I think we have a variety of them. Because we have such high thrust you can carry more propellant, and you can make much shorter trip times if you can get the propellant up there. You can take more cargo as another option, but again, you have to take more propellant. You could also carry extra modules or extra equipment to add redundancy.

We think this concept might be ideal for a freighter because if has so much thrust. In fact, it has so much thrust it might be a problem to humans on board. Coming back from Mars, you have several G's of acceleration. You might be able to use it for earth-moon freighting, perhaps distant planetary exploration or cargo ships to Mars.

As to the burnup, we think this thing might even be reusable, because it has such low temperatures and it would be limited only by burnup.

Let me conclude. I've listed a few of the advantages (Figure 24) of this technology. In general, however, we feel that if you look at all solid-core nuclear thermal rockets or nuclear thermal propulsion methods you are going to find they all look pretty much the same. They look good compared to the chemical approach, but within themselves they vary 10, 20, 30 percent; small percentages. So we think you are going to have to make your decision based on something else. We feel that something else could be, and should be, safety or reliability. We feel that this reactor has higher potential reliability. It has low structural operating temperatures, very short burn times, we think there are graceful failure modes, and it has reduced potential for energetic accidents. If you do have a failure on the ground or anywhere else, you are not likely to kill people or damage equipment through energetic accidents or energetic explosions, and we could increase the redundancy through modularity.

In conclusion, going to a design like this would take the NTP community part way to some of the very advanced engines designs, such as the gas core reactor, but with reduced risk because of much lower temperatures.

Fission Fragment Direct Heating Concept

Fabricate a Reactor from thin Foils of Uranium coated on substrates to allow escaping fission fragments to directly heat H_2 propellant

Bussard and Delauer (1958)
Nuclear Pumped Laser Tests (FALCON)

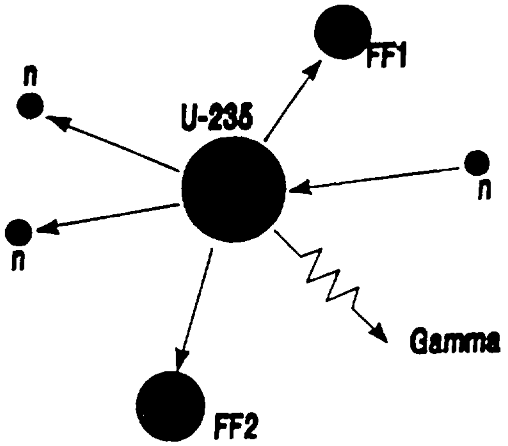
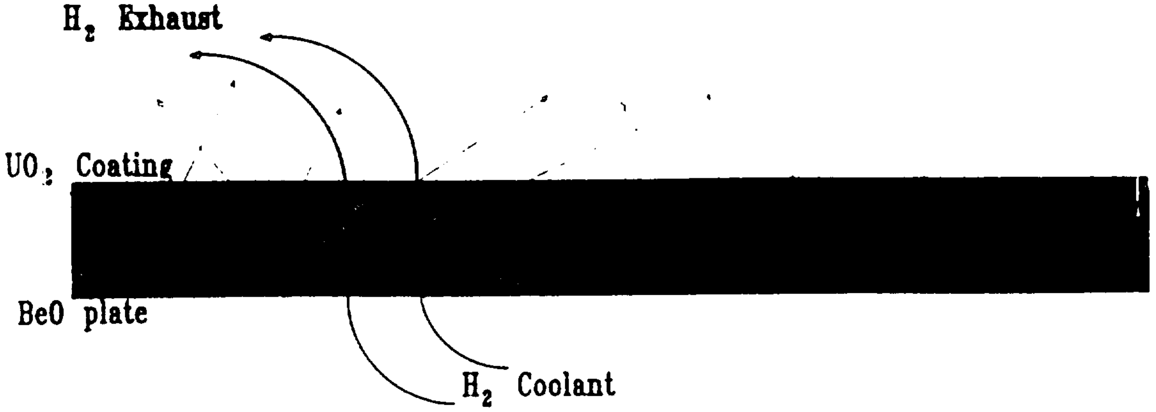


Figure 1

FISSION FRAGMENT DIRECT GAS HEATING



SECTIONED FOIL SHOWING COOLANT FLOW AND FISSION FRAGMENT HEATING OF EXHAUST

Figure 2

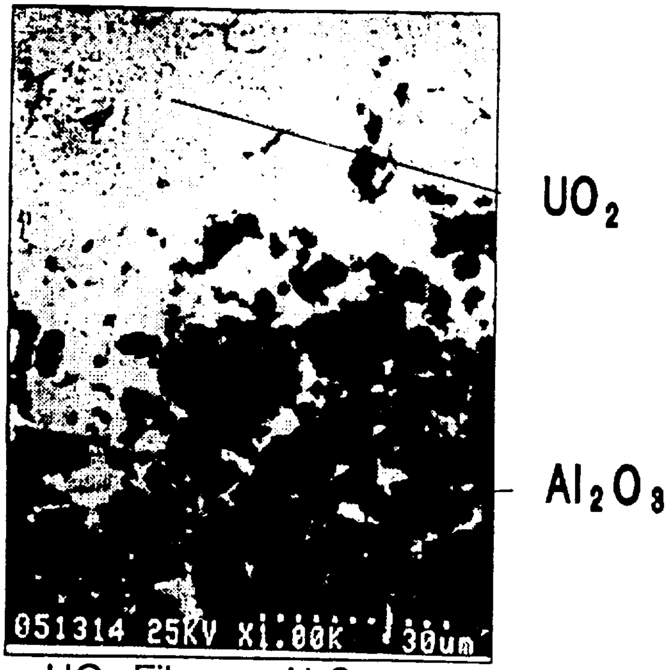
Existing Technology Base

Nuclear Pumped Laser Experimental Program
(FALCON at SNL & INEL)

- Experimental verification of fission fragment energy escape fraction versus UO_2 foil thickness
- Coating technology of UO_2 films on metalic and ceramic substrates exists, and is being advanced
- Experimental verification of direct gas heating well above substrate temperatures (> 1500 K)

Figure 3

Coating Technology



UO_2 Film on Al_2O_3

Figure 4

C 4

Comparison of Measured and Calculated FF Energy Release Fraction Versus UO_2 Foil Thickness

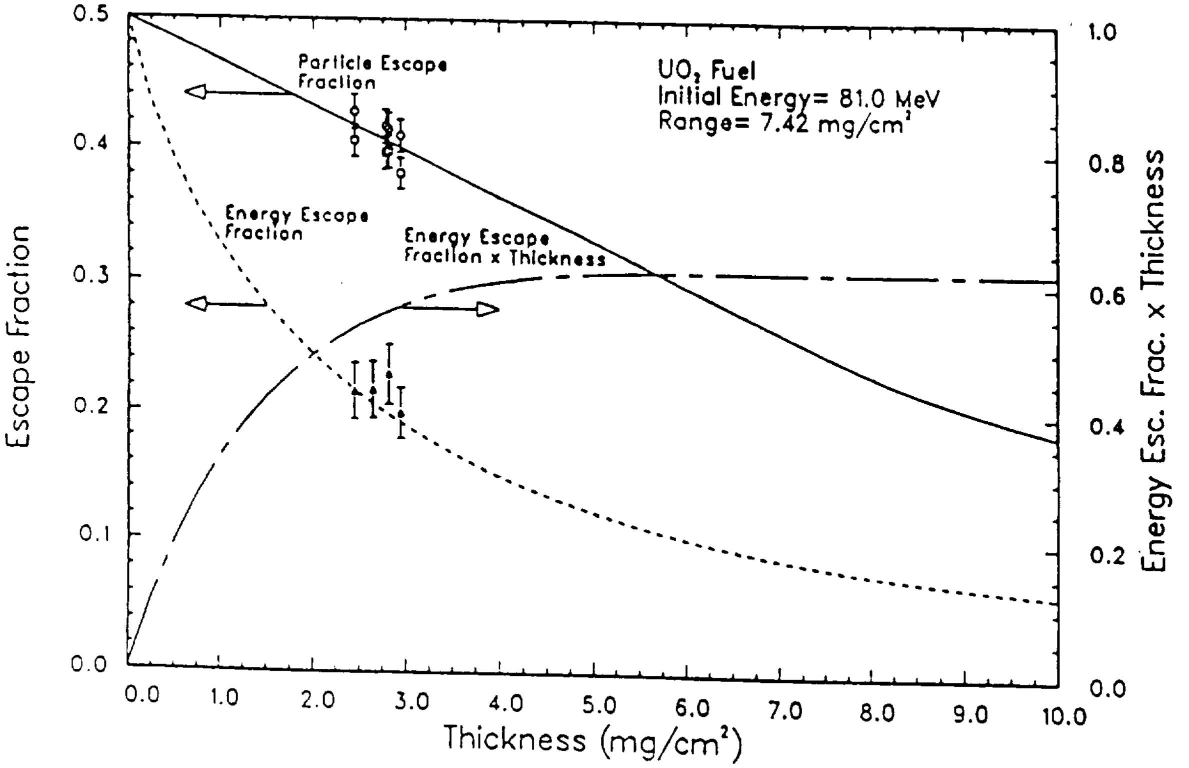


Figure 5

Advantages of Direct Gas Heating "Enabling Technology"

- Cool Structure ,Hot Gas T_{gas} -$T_{substrate}$ = ≈ 1000 K
- Operating Conditions provide good ISP and High Thrust

$T_{substrate}$	T_{gas}	ISP	Thrust
2000 K	2700 K	836 sec	686,000 lbf
2300 K	3100 K	898	633,000
2500 K	3370 K	937	604,000
2700 K	3630 K	975	578,000
3000 K	4040 K	1030	545,000

Figure 6

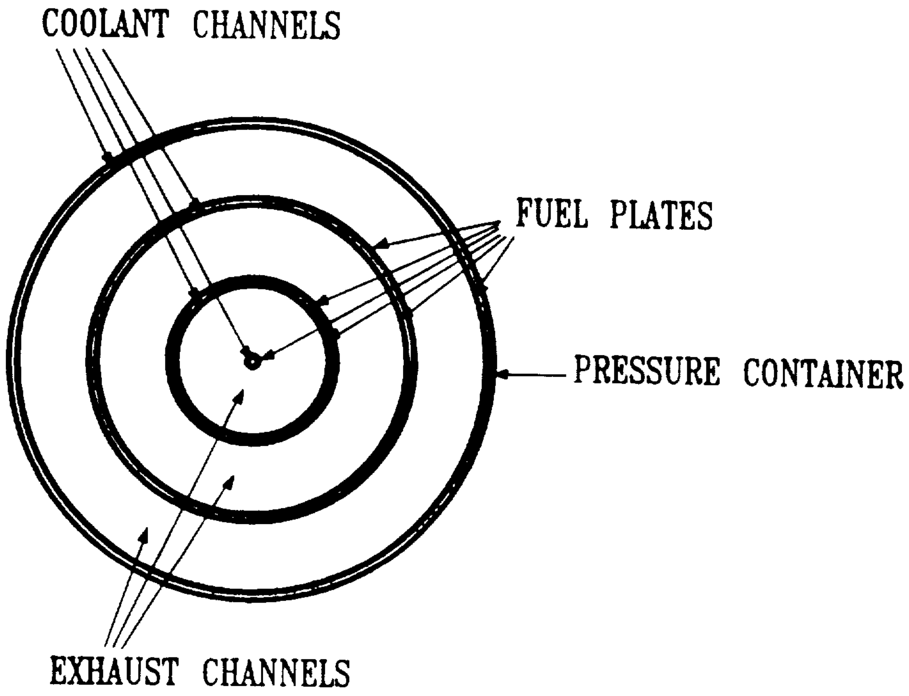
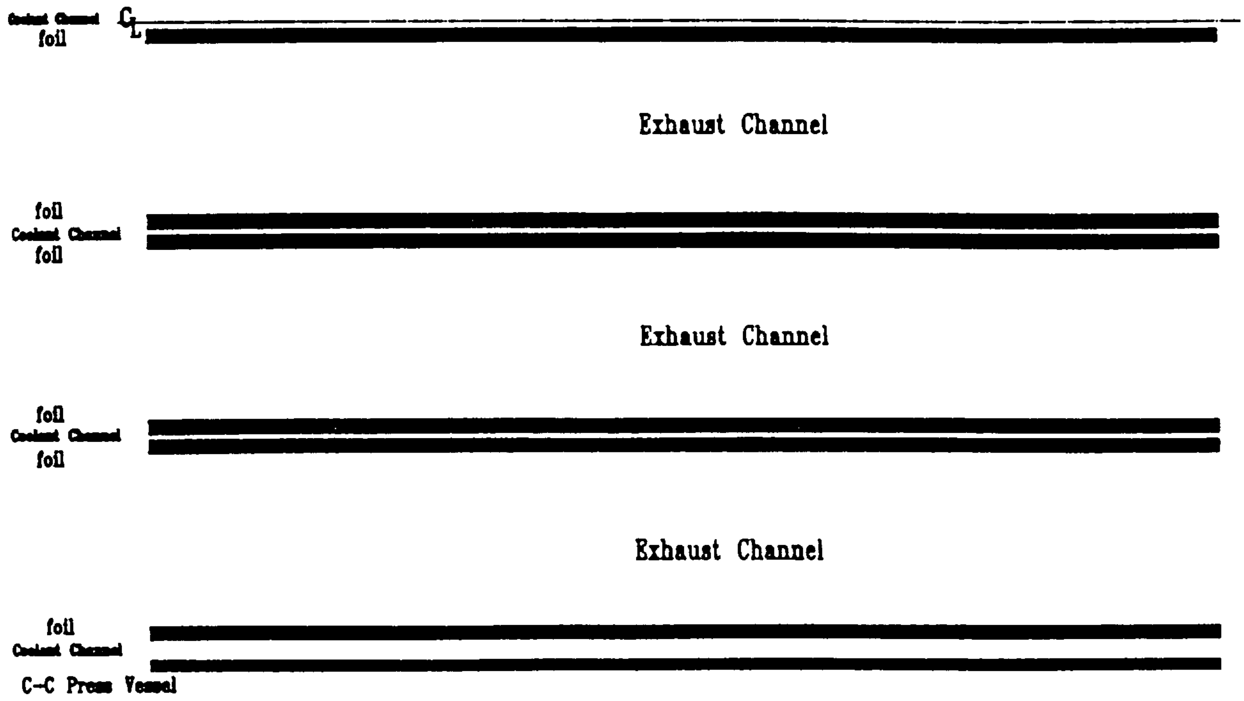
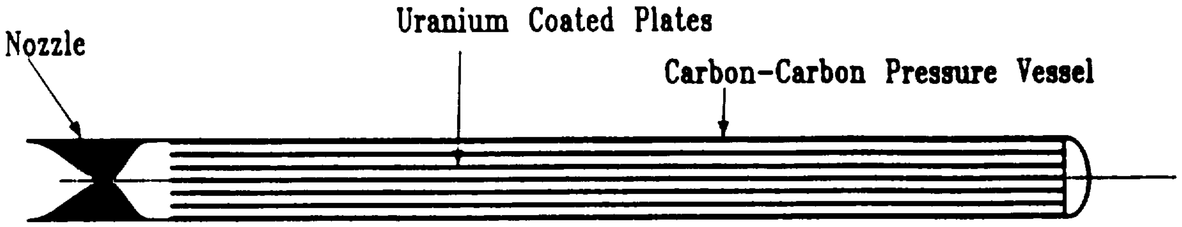


Figure 7



CROSS SECTION OF FOIL REACTOR MODUAL SHOWING PRESSURE VESSEL, FOIL, AND CHANNEL ARRANGEMENT

Figure 8



CROSS SECTION OF REACTOR MODULE SHOWING FUEL, PRESSURE VESSEL, AND NOZZLE ARRANGEMENT

Figure 9

Schematic of Direct Heating NTR

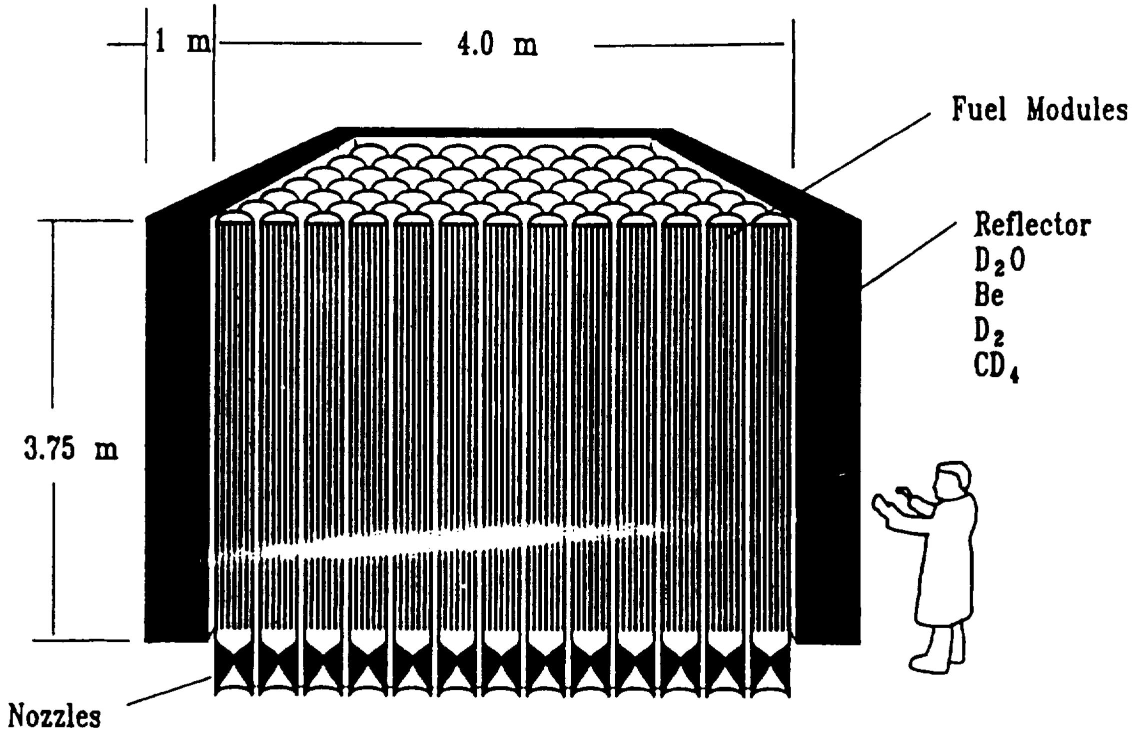


Figure 10

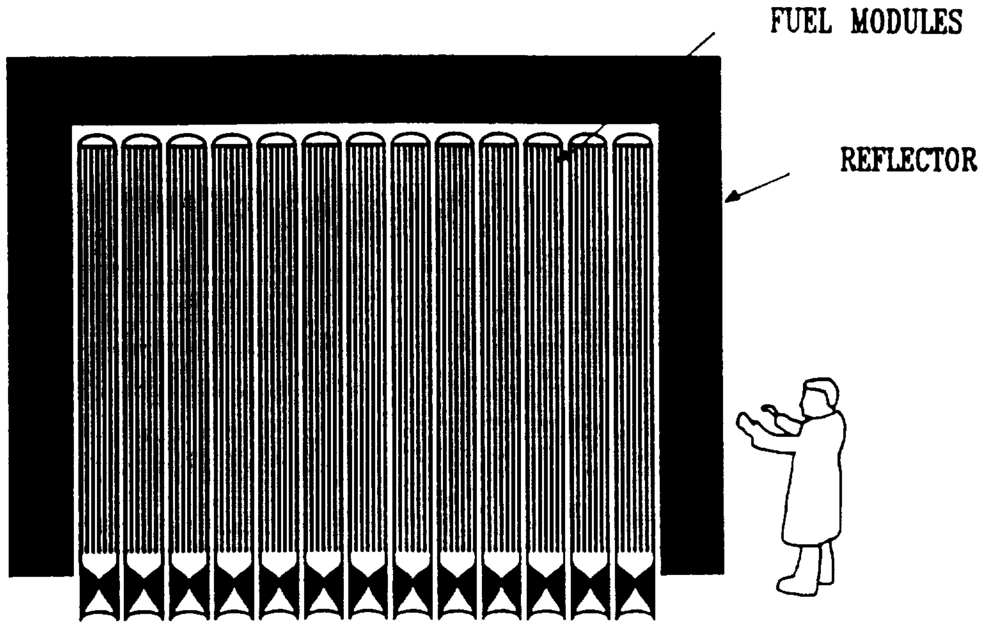


Figure 11

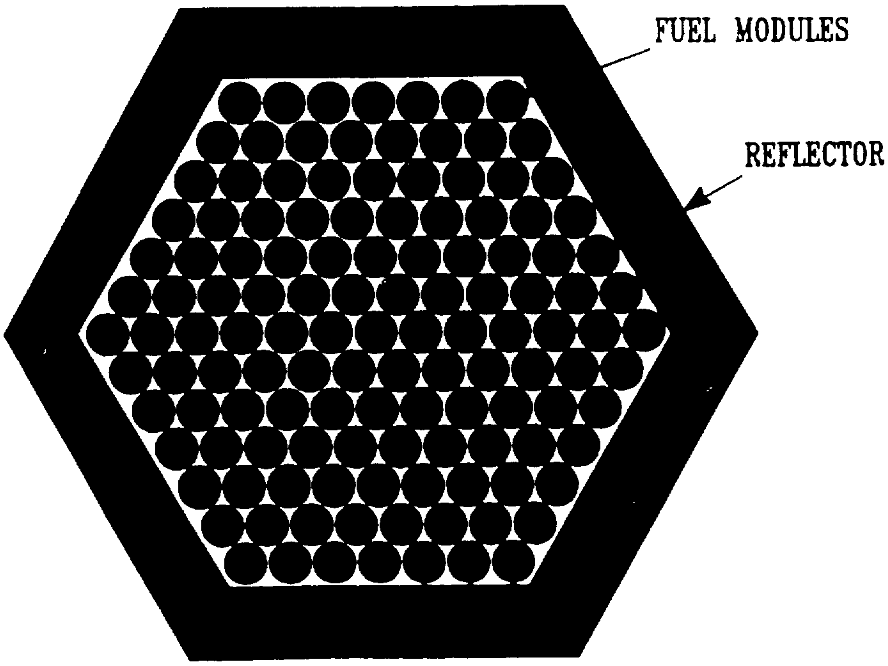


Figure 12

Key Features of Direct Heated NTR

Diameter	3.75 m
Height	4.0 m
Reflector Thickness	.7 m
No. Fuel Modules	100
Module Dia.	.358 m
UO_2 Mass	18-30 Kg
Mass	
Moderator (D_2O)	5 T
Nozzle Refl (Be)	3 T
Tube Wall (C-C)	2 T
Substrate (BeO)	7 T
Reflector (CD_4)	18 T
Pumps & Control	7 T
Shield (Not needed)	
Total	42 T

Power Density	310 W/cc 1000 W/cm^2
Power	13.3 GW
Reflector Power	2%
Thrust	600,000 lbf
Thrust/Weight	6.5

$T_{foil-max}$	2700 K	(4% Heat Transfer losses)	
T_{gas}	3400 K	(Dissociation not included)	
ISP	990 sec	Gas Exit Velocity	70 m/s
Nozzle Expansion Ratio	43.1	Gas Pressure	1000 psia
Foil Thickness	2 μm	Foil Efficiency	24%

Figure 13

Radiation Dose Rates and Shielding

Assumes No External Shield and only 1m of D_2 Reflector
13.6 GW power level and crew habitat at 100 m

Burn Number	Burn Time (sec)	Dose Rate (R/hr)	Dose(R)
1 **Earth to Mars** (60 m H_2)	690	0	0
2 **Mars Breaking** (30 m H_2)	420	0	0
3 **Mars to Earth** Shielding removed during burn (30 m -> 0 m)	190	86	4.5

Figure 14

Safety Features of Fission Fragment Direct Heating Concept

Advantages

- Structure much cooler than Propellant
- Hot surfaces limited to a very small volume
- Low Fissile Inventory (18 kg)
- Redundancy through self contained modular fuel elements
- Short Burn Times 3 - 10 minutes (22 minutes total)
- Almost certain breakup upon reentry or impact
- Subcritical up water emersion (k_{eff}=0.1)
- H_2 worth in module is negative (4 ¢)
- Loss of H_2 and fuel in a few modules; Still Critical
- Low Power Densities (300 w/cm^3)
- No energetic accidents are likely
- Slow progression during accidents

- Increased Reliability
- Tolerant to Power/Flow Mismatch
- Graceful Failure Modes

Disadvantages

- Fission Fragment escape in Exhaust Plume
- Low Structural Mass and Large Size
- Reflector Cooling Mass Penalty

Figure 15

Key Features of Concept

- Gas is Directly Heated by Fission Fragments
  - Cool Structure Relative to Gas/Propellant Temperature
  - Increases Reliability
- Large Dilute Reactor System (requires unique design)
- Moderator Flexibility (D_2O, Be, D_2 liquid or gas, CD_4)
- High Power and Thrust
  13 GW 600,000 lbf
- Fission Fragments Discharged to Space

Figure 16

Key Technology Issues

- H_2 Excitation Physics
- Dilute System Criticality
- Reactor Structural Design (large dilute system)
- Frit/Porous Ceramic Design and Fabrication
- Coating Technology
- Fuel Integrity
    - H_2 Erosion
    - Thermal Gradient
- Reflector Cooling

Figure 17

Critical Tests to Verify Technology

Category	Description	Time	Cost	
Physics	H_2 Excitation Radiation	2 yr	5	M$
Scoping Studies	Dilute Systems Criticality			
	Reflector Cooling			
	Structural Design	2 yr	5	M$
Technology Development	Substrate (BeO, Carbides)			
	Coatings (UO_2, {U,Zr}C)			
	Integrity (H_2, Temperature)	5 yr	60	M$
Component Testing	Channel Tests			
	-Prototypic Power,Temp,Flow			
	HFIR, ATR 50-100 W/cm²	2 yr	20	M$
	FALCON (FTR) 400 W/cm²	2 yr	20	M$
System Integration Tests	Site Preparation	5 yr	.2 - .5	B$
	Engineering and fabrication	15 yr	.8 - 1.5	B$
	Facility Operation	5 yr	.1 - .3	B$
		Total	1.2- 2.4	B$

Figure 18

Ground Testing

- Overcoat UO_2 films to prevent escape of fission fragments on all modules except one
- 13 GW closed loop with heat exchanger
- 130 MW Open Loop for one Module with Scrubber

Figure 19

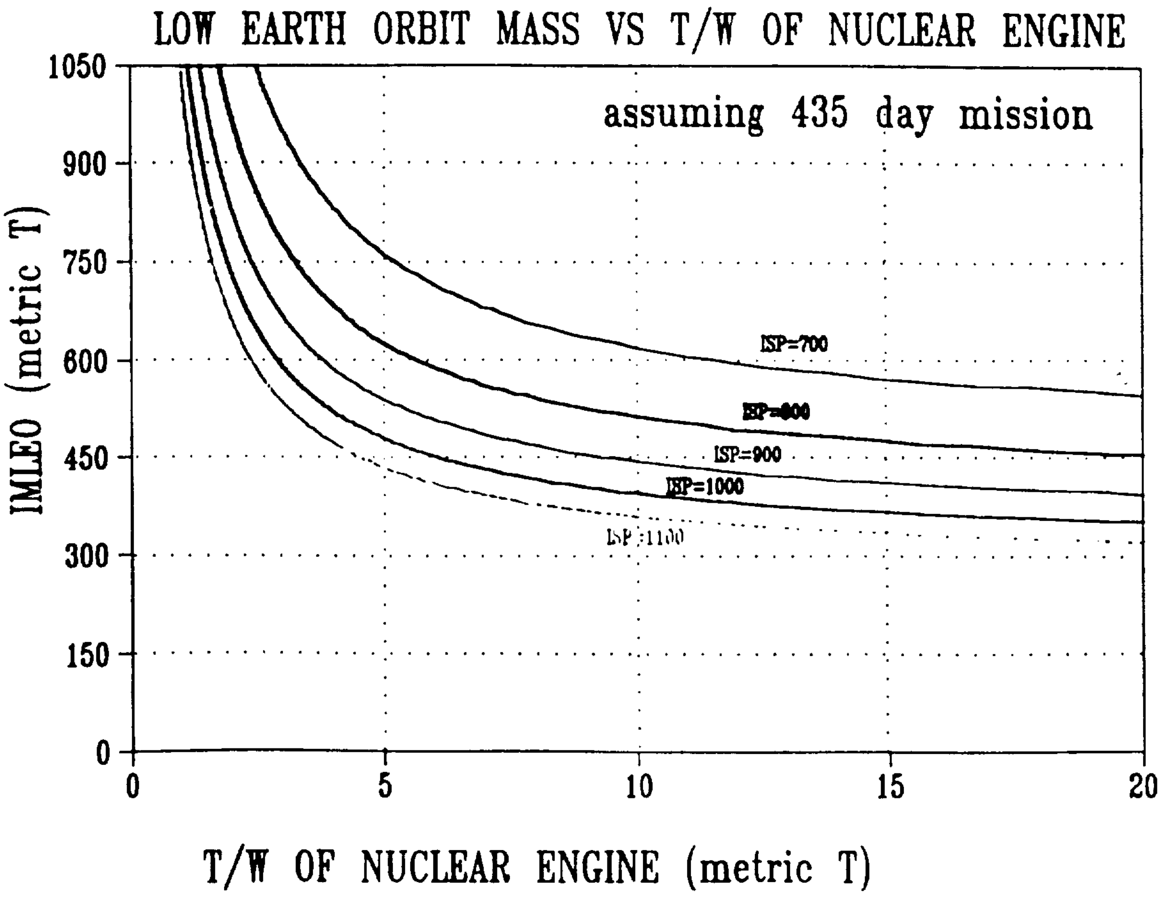


Figure 20

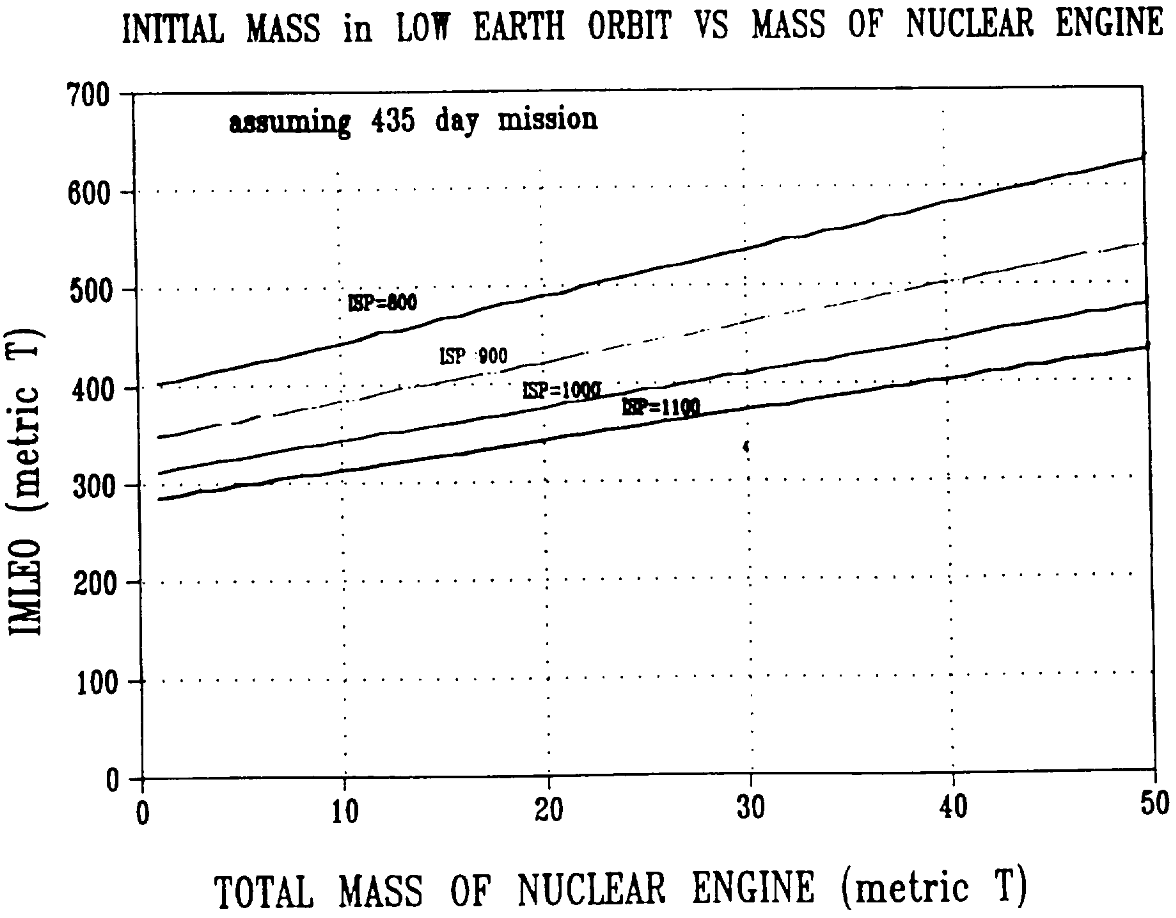


Figure 21

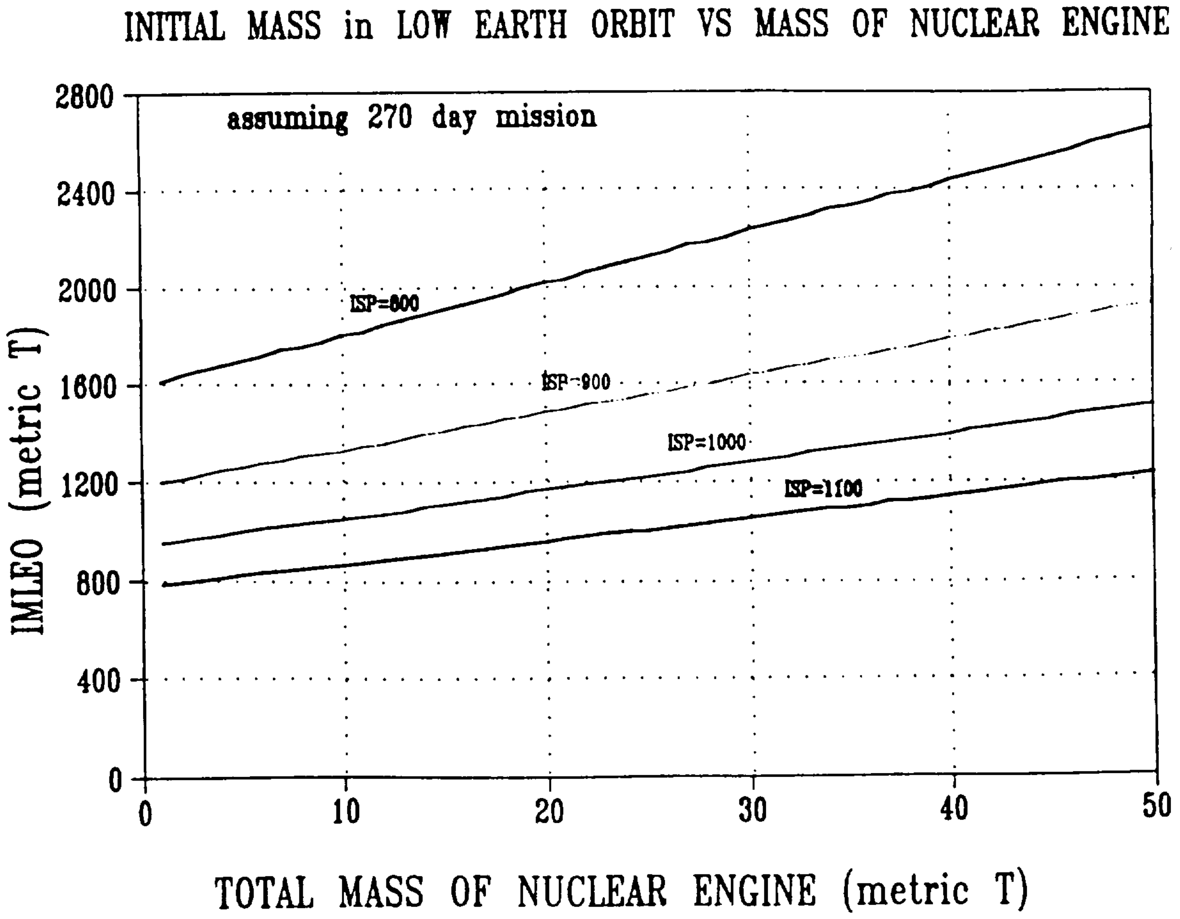


Figure 22

Mission Options

- High Thrust -> More propellant for shorter trip times
  - -> Carry more cargo
  - -> Carry extra modules equipment for redundancy
- Ideal for a freighter
  - Earth Moon
  - Planet Robotic Exploration
  - Cargo Ship to Mars
- Reusable -> Limited by burnup only

Figure 23

Advantages Direct Heating NTR over Baseline

"Conclusions and Summary"

- Compares favorably to baseline NTR for 435 day mission
  - 10% advantage for short 270 day mission

- Higher potential reliability
  - Lower Structure Operating Temperatures
  - Shorter Burn times (22 min.)
  - Graceful Failure Modes
  - Reduced Potential for High Energetic Accidents
  - Redundancy through modularity
- Part way to very advanced engines, but with reduced risk

Figure 24