N92-11094

LOW PRESSURE NUCLEAR THERMAL ROCKET CONCEPT (LPNTR)

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I am going to talk about the low pressure nuclear thermal concept. The concept initiator is Carl Leyse from INEL.

First, I will give you a little background and a description of the system. Then, I will discuss performance, mission analysis, development, critical issues, and some conclusions.

The low pressure nuclear thermal rocket has a number of inherent advantages in critical NTR requirements (see Figure 1). First of all, performance-wise, it looks as though we can get into the order of 1050 to 1350 seconds for specific impulse, and we think we can get up to six to one thrust-to-weight. Reliability is a difficult thing to project. If you had enough money you could test everything and make it reliable, but when you are starting, if you can eliminate some of your troublesome components, you have a better chance of getting there. And that's what we have done in our design concept. With safety, you also have the same issue. We took a look at some of the safety critical failures and saw how we stand relative to them. Have we gotten rid of the initiators for these? I think you will find the answer is yes. For versatility, we have gone to a multiple engine concept. We believe that one of the major requirements is a "two-engine-out" capability. We have met that with the concept we are going to propose. We are at a NASA technology readiness level of two. I think that "concept verification" is required.

We have done some trade studies at INEL on what a nuclear thermal rocket concept should be. The reason is that I am an old "Nervite." I have believed in it since the 1960s. In 1986, the Air Force gave me the opportunity to go back and study it again. Since I knew NERVA, we picked it out as our concept and I got results very similar to what Stan said. We showed about a 20 percent cost advantage in everything we did. However, the reaction throughout the contry was "20 percent isn't enough." So we started looking at how could we build a better mouse trap. We went through a series of trade studies. About the only ground rule we had was that we believed the solid core reactor was going to be the first one we developed. So we limited ourselves to the solid core reactors.

We set safety as our primary requirement. This meant eliminating inherently unsafe design features if possible (see Figure 2).

For performance, temperature is the name of the game. We want to be able to operate at as high a temperature as we can. We want favorable neutronics for the highest temperature fuel.

There are some that go beyond the zirconium such as Tantalum or Hafnium. They are lousy neutronically, but if we can get the neutronics correct, we can operate at higher temperatures. We tried to do that. If you look into where you lose a lot of your Isp in these things, it is the balance between flow and temperature. You are going to be limited by your maximum fuel temperature. If you come up with a concept where you can balance this nicely, you are going to gain a lot of Isp.

We looked into low pressure because, when we get up to 3,000 Kelvin, you get significant dissociation of hydrogen. There may be a real performance advantage when you get into that area.

In weight, you have heard a number of people say you should get at least six-to-one thrust-to-weight. So, we set that as a requirement. Reliability, at this stage of the game, boils down to simplicity. I will show you that we have a fairly simple concept.

With that we came up with our reference low pressure thermal reactor (see Figure 3). The concept was designed to maximize flow at low pressure and high temperature. In order to do that we came up with a radial outflow core.

If you look at NERVA and other concepts at low pressure, you reach critical flow at the exit of the core. In order to get a lot of core exit flow area, we went to the radial outflow. We have almost 50 percent flow area at the exit of the core. We can use virtually any kind of fuel that comes out of the fuel development program. We can use particles, plates, or whatever proves best.

An important feature would be that we can operate on tank pressure. We do not need a turbopump. We think we can operate with reactivity power control and eliminate the control drums.

The reference engine is an 11,000-pound thrust engine that weighs 1,840 pounds, (about a six-to-one thrust-to-weight). We are estimating a minimum specific impulse of 1050 seconds, with up to 1210 at full thrust. Then, low Isp is with a minimum of recombination, and the high Isp is with a maximum of recombination.

One of the unique features of the low pressure engine is that as you continue to drop pressure, you continue to get more dissociation, which increases Isp. We decided that if we took it as a good demanding objective, maybe we could get down to 20 percent full thrust. If you can do that, you get to a theoretical 1,350 seconds specific impulse.

The thrust level is too low for Earth escape, but it is useful for other manuevers. So we propose a dual function capability with one engine.

If you take a look at this particular concept, the main structural part is a large central area that is probably steel or some neutronically favorable material. It is surrounded by two berylium structures with a series of holes in them. The flow enters the nozzle and cools the nozzle and pressure vessel. It enters the center cavity of the reactor and blows radially outward, through the fuel modules.

Now, you notice we have a very short nozzle exit cone. One of the advantages of low pressure is that the heat flux is greatly reduced. As a matter of fact, it is about a factor of 50-to-one less than the high pressure NERVA engine. Thus, you can have a very short exit cone and lose very little heat going out the nozzle.

We flow around this way: we come in to the center of the core and then exit through our fuel elements (see Figure 4). Reactivity control comes by running hydrogen down into the center. We have a large center cavity, and fill it with hydrogen for reactivity control.

I might mention that NERVA demonstrated that you could operate with reactivity control fixed. The drums were fixed and could run a complete startup, full power hold, and complete shutdown on reactivity feedback (no control drum movement).

NERVA also demonstrated that with your control drums full-in, you can get enough reactivity in to go critical, despite the fact that you had the control drums in. Therefore, we think it is a very desirable option to eliminate them. If you look at the safety analysis report, almost all of it was addressed to what you do about control drum roll out and all the associated problems.

Our fuel bed assembly is very similar to the particle bed that Brookhaven has been proposing (see Figure 5). Cold hydrogen comes in, flows through the core structure, and flows through a fuel bed. In this concept you have particle fuel, a hot frit, and a cold frit. You also have a reflector area beyond the fuel bed. You can substitute fuel plates for the particles. We don't operate at a high power density. We plan to operate at 3-4 MW/L and the plates would have sufficient heat transfer surface.

The fuels that people are considering, carbides in particular, are ceramics. At the time of the NERVA program, there were many problems fabricating fuel forms. If there is one thing we have learned a lot about since the days of the NERVA program, it's how to fabricate ceramics. So, I think there is a good possibility that we can come up with some rather novel fuel forms with new fabrication technologies. I would even propose that we have carbide-carbide composites. I would propose a carbide-carbide composite might be a very viable way to make plates. The concept can use plates or particles or whatever type of a fuel form you come up with.

At the end of the NERVA program, we are projecting the capability to operate at 3,200 Kelvin. They were planning on doing that with zirconium carbide or uranium carbide composites. I suggest that you look at tantalum carbides that have approximately a 600 to 700 degree advantage over zirconium. There are also ternaries that may be able to operate at higher temperatures (see Figures 6 & 7).

In other words, if you pull out one of the old data points, there are some hafnium tantalum carbides that are higher than the tantalum carbide by itself. If you use melting point as a figure of merit and assume the structural properties will go with it, you have the potential to operate greater than 3,600 Kelvin, if you can design it to handle the unfavorable neutronic properties of the tantalum carbides and the hafnium carbides.

Figure 8 shows that once you get up to the higher temperatures, there is performance advantage for operating at low pressure. The capability to operate at 3000 K did not exist when NERVA was being developed and there was no reason to consider operating at low pressure.

But with this capability to operate at higher temperature, you begin to show the possibility for substantial improvements in performance if you can operate at low pressure.

First, we have done a preliminary neutronic study (see Figure 9). This particular one was done on a reactor OD of 1.2 meters. It's a little bit larger than our reference, with a core OD of one meter and 50 percent exhaust flow area. The basic flow is through the fuel element as shown on the right.

We have a zirc hydride sleeve on the outside; a very small one (one millimeter) to improve our moderation. We had a cold section (but actually it's not that cold) of uranium zirconium carbide particles, then we went up through the hot section of the uranium hafnium carbide. We used hafnium 180. The reason we used hafnium 180 is that the code was set up with hafnium 180 properties, so it was an easy way to make our first run using this isotope.

The significant point is that we did get a K effective greater than one. We had a fuel loading of a half gram of uranium 235 per cc. It indicates that we could operate at higher temperatures if the structural properties of the fuels were adequate. There is no data on these materials at present.

Now, what does this mean in specific impulse? Go back to the 1960s data and get the King report where they talked about the equilibrium data (see Figure 8). What does hydrogen look like at equilibrium as it comes out? You find that around 10 psi chamber pressure operating at 3,500 K you are over 1,400 seconds in specific impulse.

When we started on this work, we had a data base in the old NERVA code. In other words, we did have a thrust cell when we ran the XE tests. We ran nozzle tests out in the old Aerojet test area. We had some specific impulse data.

With a computer code, you have a table of temperature and pressure and you can go to areas where you haven't tested; namely, you can go to high temperature and low pressure.

When we first did that, we got some very favorable results and we said that this looked like it was worth considering. When you pull out Bussard's old data, (he wrote the "Bible" of nuclear propulsion in the old days) and look at his data plots, you will find you are well over 1,200 specific impulse. Corliss had a similar plot, indicating up around 1,200 or so.

The present state-of-the-art kinetics codes that Rocketdyne ran (the ODK code -- we ran the TDK code) are chemical kinetic codes designed for burning LOX hydrogen. They do have a hydrogen recombination routine in them, but it was a very small part of what was in the code. If you strip out all the LOX hydrogen and just use what is left, you will obtain the results shown on Figure 9. We and Rocketdyne got similar results. But if you check the data base for these, you will find that in the area that we are talking, there really is no data. Therefore, you don't know what kind of performance you are going to get.

The second point I would make is that if you start to play around with these codes and change the shape of your nozzle, you will find your performance improves (see Figure 10). In other words, you need resonance time for the recombination of hydrogen to occur. If you can get the recombination, you can begin to get the large performance improvements. You may call them losses in a conventional nozzle, whereas they may be a gain to you in this case.

How do you design a thrust chamber and a nozzle to maximize the performance you can get out of a dissociated and recombined hydrogen system? This is the type of thing that I am referring to (see Figure 11). This is again taken out of Bussard's data. What it shows is in a core, when you get to high temperature and low pressure, you get up to a factor of 10 apparent augmentation in your heat transfer. What it really amounts to is that, on the wall you are dissociating the hydrogen; it takes a lot of energy to dissociate the hydrogen. It dissociates on the wall, goes back into the mainstream and then recombines and increases in temperature. The net effect is an increase in heat transfer.

Based on this type of data, and talking with most of the people we can find, it appears that when you come out of the core, you will be in equilibrium dissociation. The problem is, as you get into the nozzle and begin the supersonic expansion, do you get the recombination that goes with the lower pressure? This can amount to as much as 1,500 degrees Kelvin difference in your exit temperature at the maximum expansion point of the nozzle. So there is a real issue of how do you expand that nozzle? We have looked at a lot of novel concepts and I will just show you one here in Figure 12.

Some of the things that have been rejected in the chemical engines, such as expansion deflection nozzle, spike nozzles, and plug nozzles, all become candidates for reexamination to see what would be the optimum way to design a thrust chamber/nozzle for hydrogen recombination.

We have not considered any of those advanced nozzles for our baseline studies. We stuck with a rather conventional thrust chamber bell nozzle approach.

MASE says you may have a requirement of two engines out. So, to have two engines out and do this mission, we thought you had to start building small engines. We picked as our reference an 11,000 pound thrust engine. We limited ourselves to a launch envelope (diameter) of 10 meters. We went through some trade-offs between the pressure and the expansion ratio.

We assume you could control thrust alignment with engine thrust (see Figure 13). In other words, with a nuclear engine, you can run the thrust up and down to get thrust alignment with your seven engines. You would abort the mission with any failures during the perigee pulse phase. After you left Earth with your perigee pulses, you can have the partial thrust with any two engines' failure after you left. The advantage of this is you have no gimbals. And you can completely assemble this thing on the ground.

We believe the small engines are going to be easier to develop and ground test. This clustering arrangement can be used for both lunar and planetary missions. We think we have a very versatile engine with this concept.

Figure 14 is a cartoon of a tank arrangement. We have our seven engines, each with a shield above it and then an elongated tanks above that. We took a penalty and put in part of our shielding into the bottom of these tanks. In other words, we have extra propellant on board in order to cut down on the weight of the disk shield.

The advantage of this is that when you are at high power, this propellant is available to you for shielding. When you shut down, you no longer require all the shielding, so you can use that propellant up as a way of doing your cool down. This looks like a way to save shielding weight.

This particular configuration also fits into what our ground rule says is the launch envelope. We have 10 meters in diameter and 30 meters in length. You can completely assemble it on the ground, and you can launch it as a unit. If you have the ten-hour life capability, you could even take this stage and use it for a lunar mission as part of your check out, then bring it back. After a lunar mission, you are sure you have a stage that works and you can then mount all the stuff up for a Mars mission. It is a pretty versatile stage.

For our mission analysis we picked three cases: low, medium, and high performance (see Figure 15). The low performance is the 3,200 K, the medium performance is 3,600 K, and the high performance is 3,600 K--dual mode--where we operate at 15,000 pounds thrust for everything except Earth departure.

We ran at 15 psi pressure for our main thrust, and 3 psi for our low thrust. The specific impulse for low performance would be 1,190 seconds, if we were to find a way to get hydrogen to equilibrium. If it were 1,012, it would completely be frozen, with no recombination. We picked 1,050.

We are very conservative in what we assume (see Figure 16). If we can get to 3,600 K, these jump to 1,400. We picked 1,210. Again, this is very conservative.

If we look at our dual mode performance, we picked 1,350 seconds. This is a little more optimistic, but it is based upon the gain that was predicted by Bussard and Corliss in the old days. It looked like they have done a lot of thinking about it because as they got to the point where the hydrogen densities became too low, they showed a loss of performance. So we use that as our basis and projected the 1350.

If you look at the mass in orbit, we looked at two missions (Figure 16). The reference mission left the engine in a huge ecliptic orbit around Earth, where it was going to take a lot of energy to make it reusable. We took advantage of the specific impulse we had by circularizing. It is one of the ways that you can take advantage of the increase in capability. You cut your initial mass in orbit in half, if you are going to leave it in the highly ecliptic orbit. If you are going to circularize, you gain almost a factor of three in your performance advantage. It looks like if you are willing to put that much mass in orbit, you can do the mission in a hundred days out and get a substantial gain in time.

If you look at reliability potential of this concept, you see the elimination of troublesome components (see Figure 17). We have eliminated the turbo pumps, the control drums, the engine gimbal and the valves, and the number of reactor parts have been reduced.

We have a complete "two-engine-out" capability, with a seven engine configuration. The low pressure does a lot for you on thermal problems. You get improved core heat transfer. Because of the dissociation/recombination, you have much reduction in your nozzle heat flux. Aerojet even proposed that we not cool it at all. You have the potential to not cool your pressure vessel because the heat flux is down, but we didn't take advantage of that. We assumed you had to cool it.

We picked three major safety areas (Figures 18 & 19): If you look at explosive rupture, you have no pumps. You operate below the tank pressure, so you are pretty sure there is no way to get a high pressure. In other words, it can't go over the tank pressures.

For reactivity insertion, we have eliminated the mechanical drums. There is a whole gamut of potential accidents we got rid of.

On loss of flow, which is the other major safety issue, you can manifold this to get your emergency flow from any one of the tanks, so that if any engine goes out, you can keep the flow into them.

The development program (Figure 20) is a fuel development program. I really believe that any concept that can get high temperature fuels will be able to get a good specific impulse. In order to prove your fuel, you are going to have to have reactors. In other words, you can run all the electrical tests you want, but if you read the final report on NERVA, they were arguing how good the electrical tests were. You have to get into a reactor. If you only consider the U.S. reactors, I think the fastest one you can get into that comes close to doing what you want is to go into the ATR. We projected you could get into there by the middle of 1994.

The best way to test is what we call the "nuclear furnace." What it really amounts to is a driver core with a hole in the center where you can test all kind of fuel elements. It's very versatile, gets the power densities you want and provides a real configuration.

We feel that you must have your environmental impact statement before you start on the facility. Therefore you really have a problem in getting into a reactor in fast order. As a solution to the problem, we went ahead and showed both types of contexts (see Figure 20). Ultimately, you have to get into your engine testing.

We have some cost data (Figure 21). We have two big costs; lab fuel development and environmental impact statement. The design work on the engine is very small. Generally, we talk of a few million dollars to do an environmental impact statement. When you get into this environmental impact statement, you are going to have to do a study that says <u>where</u> you are going to test. You are also going to have to do a study that says <u>how</u> do you want to test. It is more than a typical environmental impact statement, so I put in $7 million to do the whole job.

In order to get these things available to you by the end of year four, you must spend most of your money on getting the facilities ready. By the end of year four you would have resolved the issues of temperature, fuel form, dissociation/recombination, and engine design. You would have made the decision of what performance you are going to get and how you package this thing and put it together.

I came up with $4 billion for the whole program. But I have a lot in there (Figure 22). I have defined all the tests in Figures 23-28.

I had 11 complete engine tests to get qualified. I built three flight engines. I tested for three years in the test reactor. In the nuclear furnace, I tested the whole time. In the cases when I completed my development program, I kept those facilities operating on my quality control. In other words, I continue to use the nuclear furnace to check out the what is being built at that point.

In order to get through this, I will just summarize the major technical issues (Figure 29).

First of all, you have to look at the nozzle pressure vessel design to optimize performance. You are talking hundreds of points of specific impulse, if you can find a way to to approach equilibrium recombination. It is really worth looking carefully at that because it is one of the biggest payoffs you are going to get.

The second point is you have got to be able to have a good flow/power match within the fuel element and core. There was a lot of money spent in NERVA getting that match. They were talking about running at 3,200 K core outlet gas temperature, with a material that melts at 3,600 K; there were 400 degrees (which is a lot of specific impulse) that went with the mismatch in order to put a real engine together. We have got to be that good, or better, to get any of the performance claims we have made, so you have to look into that detailed design.

It's going to cost more to test this on the ground. Because we are at low pressure, you have got to put some pumping systems in to run your exhaust clean up system.

You must decide what fuel form you are going to use to operate at these maximum temperatures.

We have assumed that you don't need pumps. We have come to some preliminary pressure drop calculations that looks as though you can do it. But within this core you have got to have a lot of little cooling channels that keep everything cool. In order to get your flow to distribute through these cooling channels, you have to have pressure drop. We haven't done all the detailed design work to see if you can really keep everything cooled properly. We also need to investigate the viability of the feedback power control.

To summarize this (see Figure 30), we have not identified any problems that require technical breakthroughs. There are many engineering problems that could reduce the performance. Typically these things go against you. But we have been on the very conservative side as far as the dissociation/recombination issue goes.

Everything ought to be a plus in that area if we can find a way to design it. So we have plus pluses and minuses. We think the performance, reliability and safety makes a promising candidate for early development and we think you ought to start on it next year.

LPNTR Has Inherent Advantages In Critical NTR Requirement

Performance	1SP 1050-1350, up to 6/1 T/W
Reliability	Potential to eliminate troublesome components
Safety	Reduced susceptability to safety critical failures
Versatility	Two engine out capability Multimode operation for maximum performance

Currently at NASA level 2

0-7790

Concept verification required

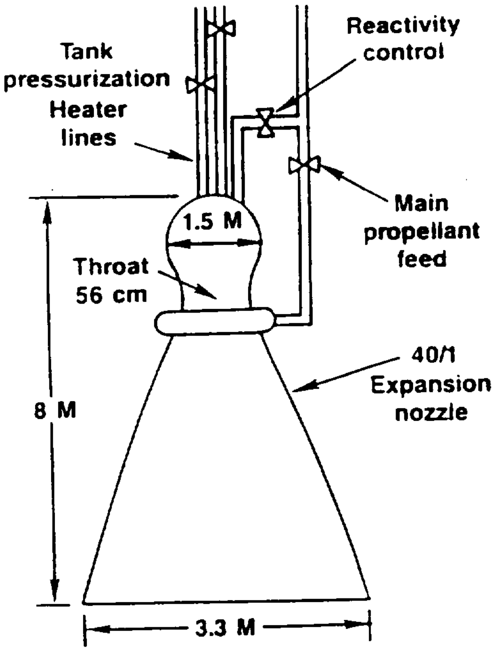
Figure 1

Preliminary Considerations Reactor Trade Studies

• Safety	Eliminate inherently unsafe design features
• Performance	
High temp	— Favorable neutronics for highest temp fuels
Minimum temp losses	— Good power/flow matching no leakage
Low pressure	— Optimum nozzle/reactor engine configuration
• Operational utiiity	
Weight	— >6/1 T/W
Reliability	— Simplicity, minimum of troublesome components
Other	— Look for obvious problem areas

0-7407

Figure 2



Reference LPNTR

- Concept designed to maximize flow at low pressure & high temp

Features

Radial outflow core
Particle or plate fuel
Operates on tank pressure
Reactivity power control

Performance

Thrust 11,000#
Weight 1840#
T/W ~ 6/1
Isp ~ 1050-1210 @ full thrust
~1350 @ low thrust

0 7785

Figure 3

Preliminary LPNTR

Internal Configuration and Flow

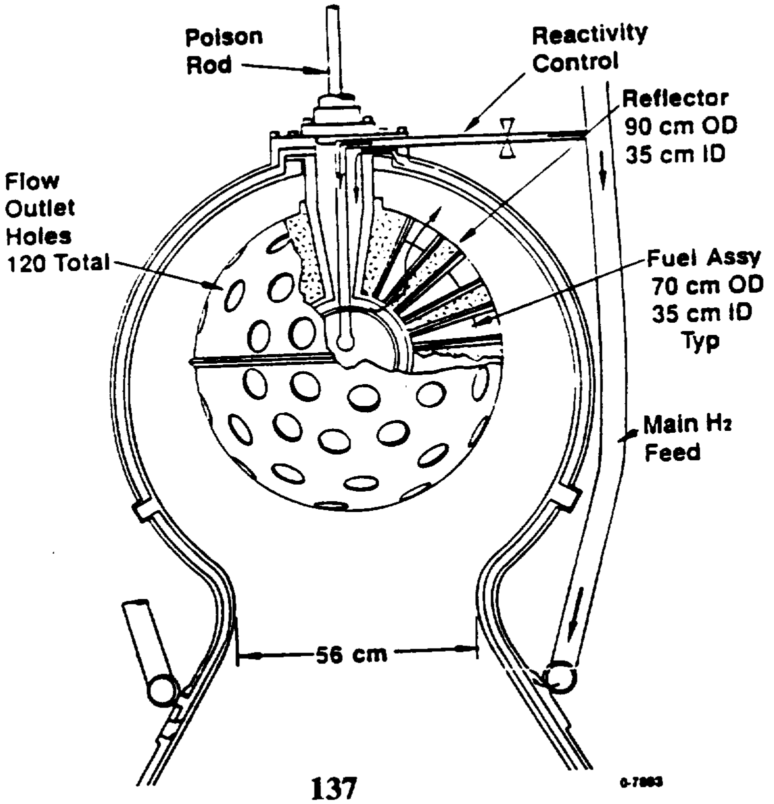


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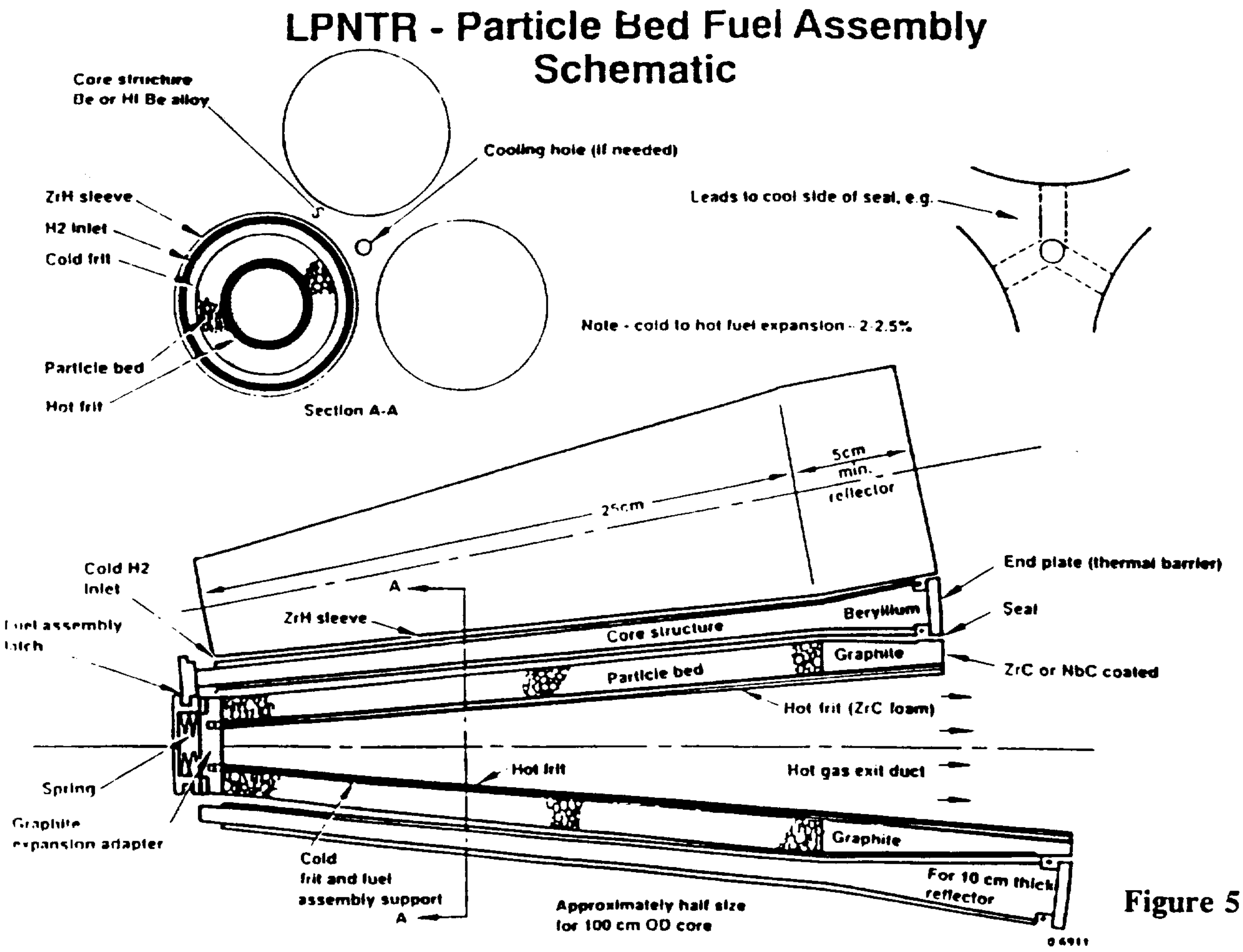
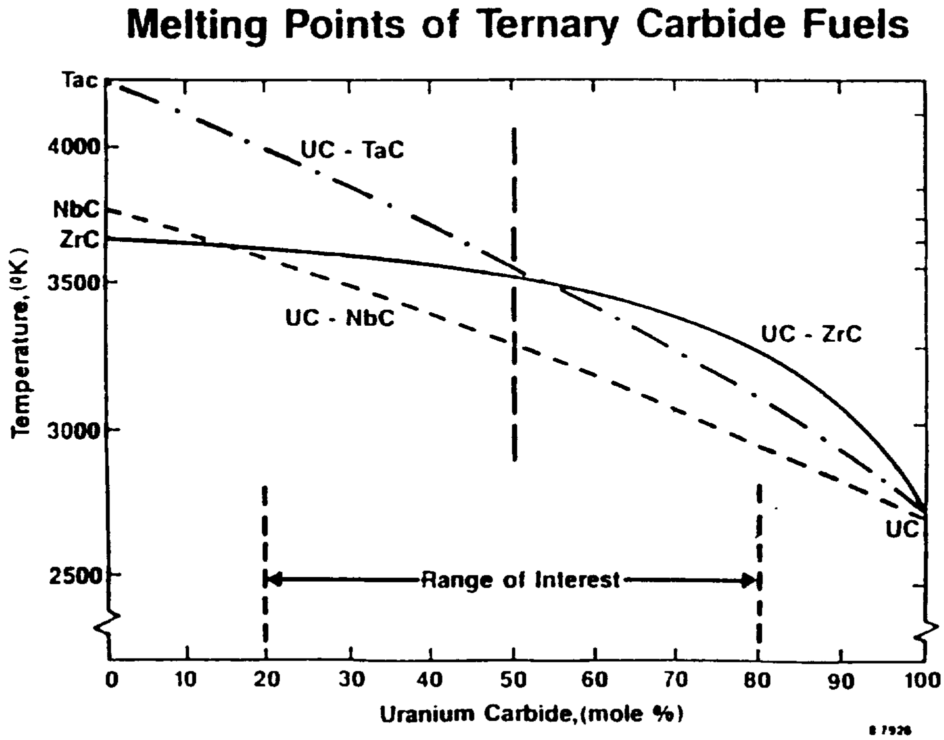
Figure 4



LPNTR - Particle Bed Fuel Assembly Schematic

Figure 5



Melting Points of Ternary Carbide Fuels

Figure 6

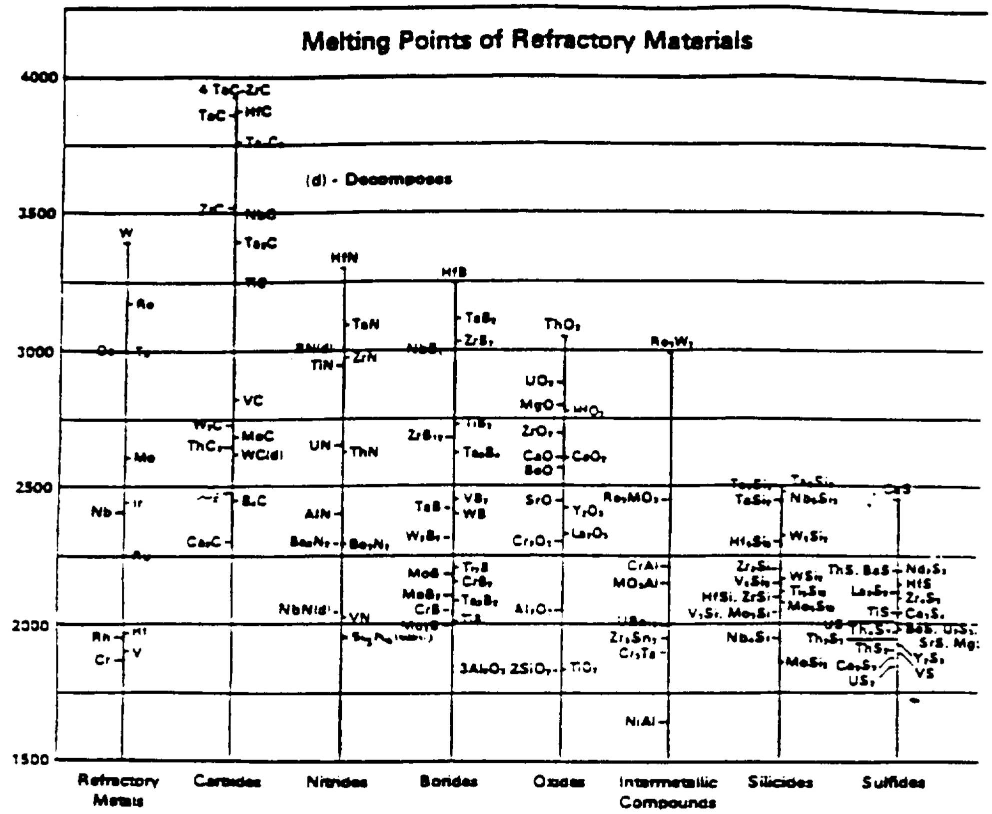


Figure 7

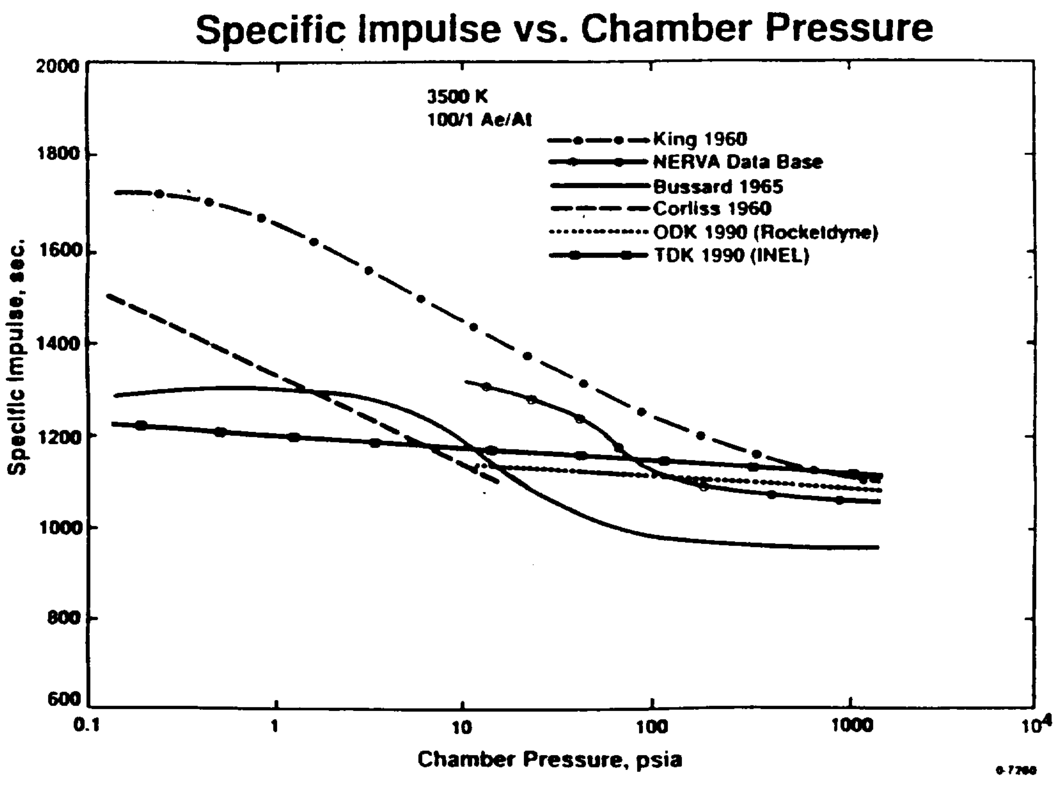


Figure 8

Preliminary LPNTR Neutronic Study Results

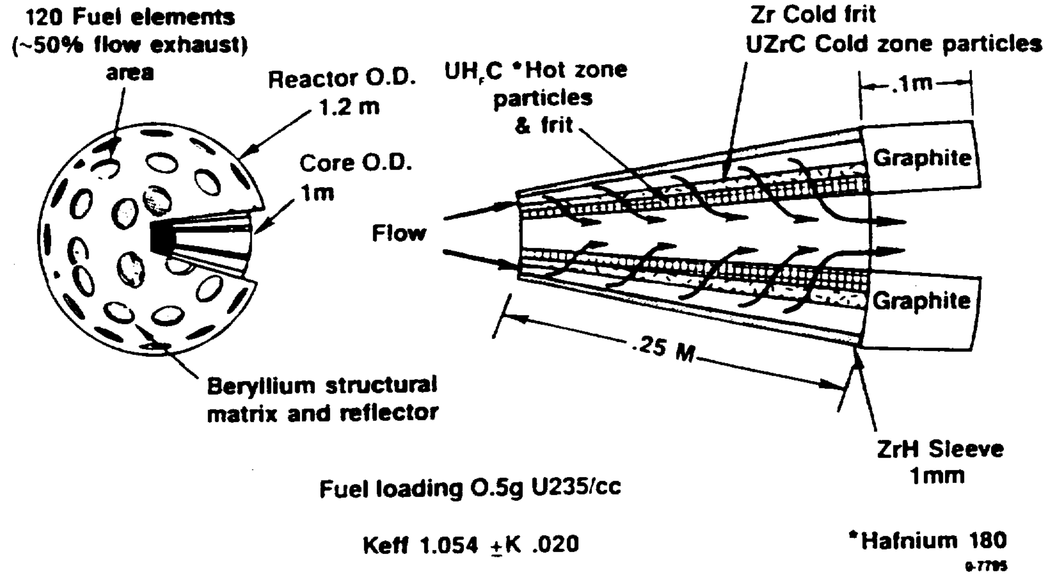


Figure 9

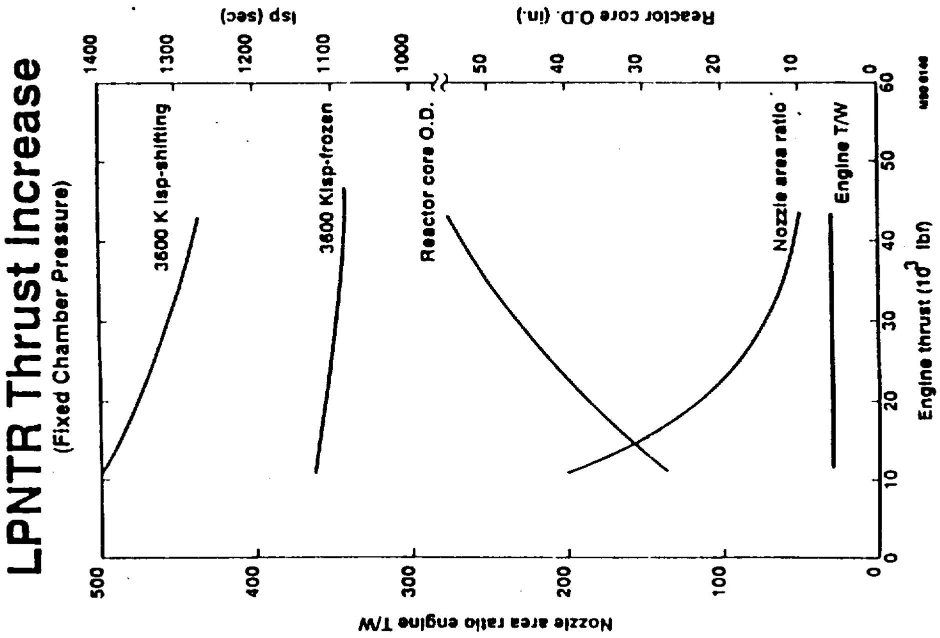


Figure 10

Estimated Augmentation Factor for Dissociation-Recombination Effects in Convective Heat Transfer to Hydrogen (Bussard 1965)

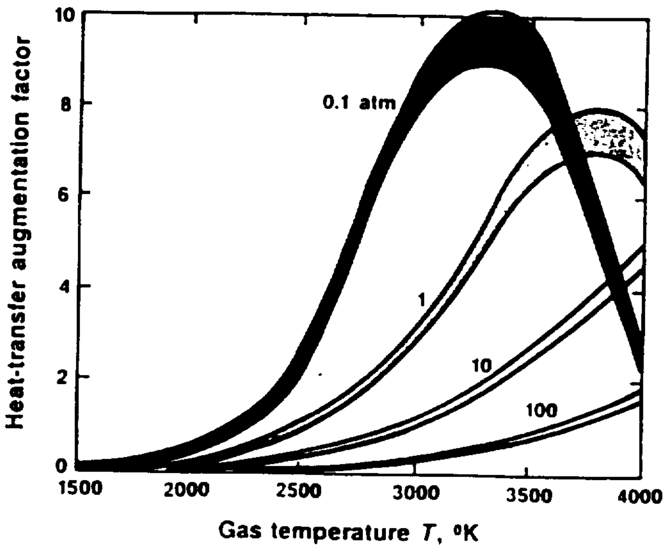


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Figure 11

11,000 lbf Thrust LPNTR with Expansion/Deflection Nozzle

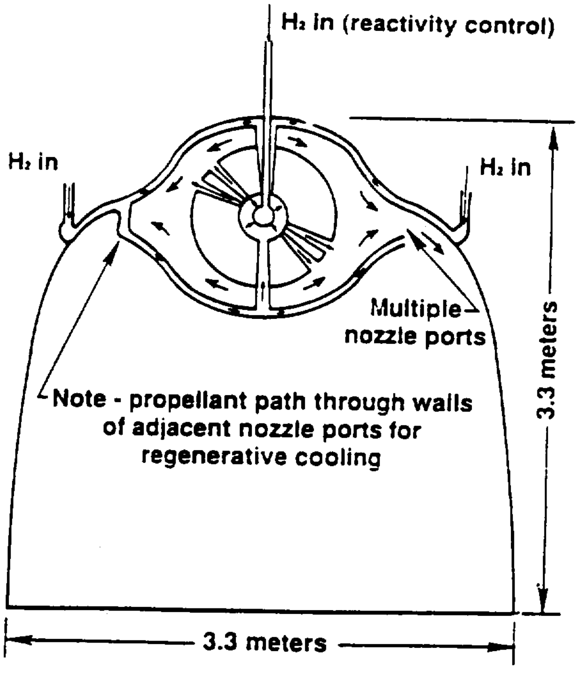

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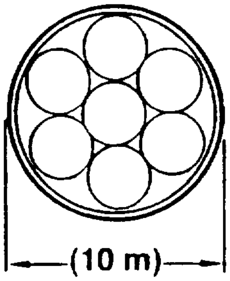
Figure 12

Multiple LPNTR Engine Concept



Assumptions

- Control thrust alignment with engine thrust
- Abort mission with any failures during perigee pulse
- Partial thrust for any two engine failures after Mars injection

Advantages

- No gimbles
- Ground assembly
- Small engines easier to develop and ground test
- Smaller clusters for Lunar and Planetary missions

Figure 13

LPNTR
Tank & Engine Configuration for Mission Analysis

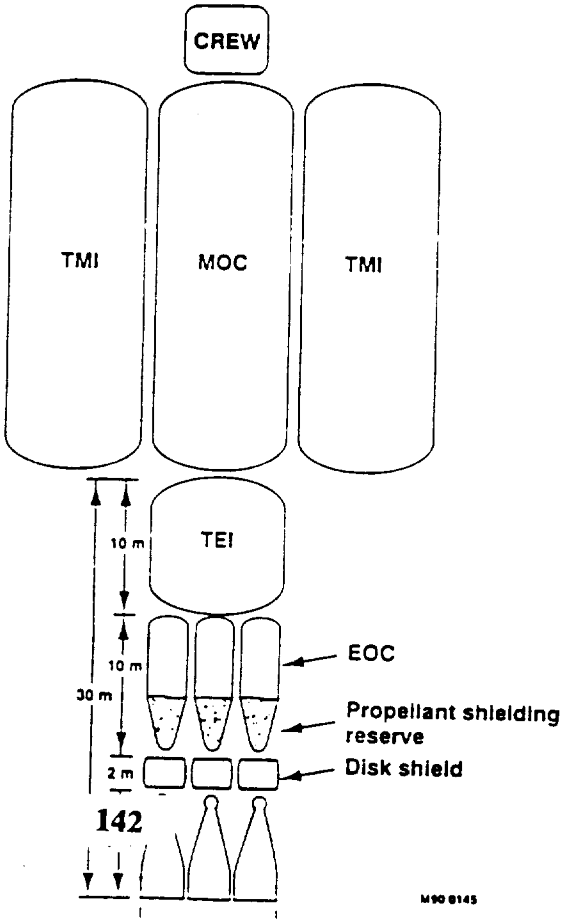


Figure 14

LPNTR Thrust Increase

(fixed engine size)

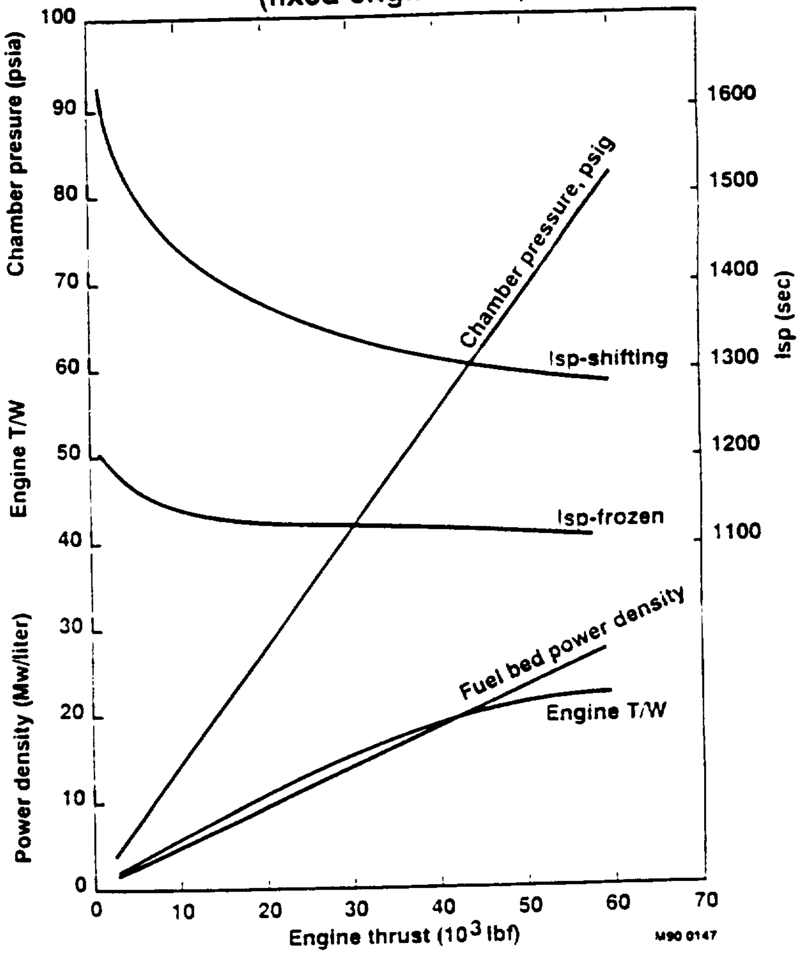


Figure 15

IMEO Advantate LPNTR

Engine	Isp	T/W		Mission	
		Engine	Engine plus shield	Ref / IMEO	500 Km Earth orbit / IMEO
Ref (NERVA)	850	4	2.6	884	1400
Advanced NERVA	925	6	3.3	713	1037
LPNTR 3200 K	1050	6	2.2	603	814
LPNTR 3600 K	1210	6	2.2	485	611
LPNTR 3600 K Dual mode	1210 1350	6 1.25	2.2 0.44	440	534

Figure 16

LPNTR Reliability Potential

• Potential to reduce or eliminate troublesome components	Turbo pump — eliminated Control drums — eliminated Engine gimbal — eliminated Valves — reduced Reactor parts — reduced
• Small engine size gives 2 engine out capability	Any two failures of 7 engine configuration
• Low pressure reduces thermal problems	Improved core heat transfer — dissociation/recombination Lower nozzle heat flux

0-7784

Figure 17

LPNTR Reduces Susceptability to Safety Critical Failures

Explosive rupture — No pumps - operates below tank pressure

Reactivity insertion — Mechanical drums eliminated

Loss of flow — Engines can be manifolded to get emergency flow from all tanks

0-7787

Figure 18

Safety Considerations

NERVA XE Safety Analysis Report: three major accidents

Control drum failure	50 pages
Liquid hydrogen insertion	14 pages
Loss of propellant flow	7 pages

∴ Elimination of control drum should eliminate many safety problems

0-7409

Figure 19

LPNTR Development Program

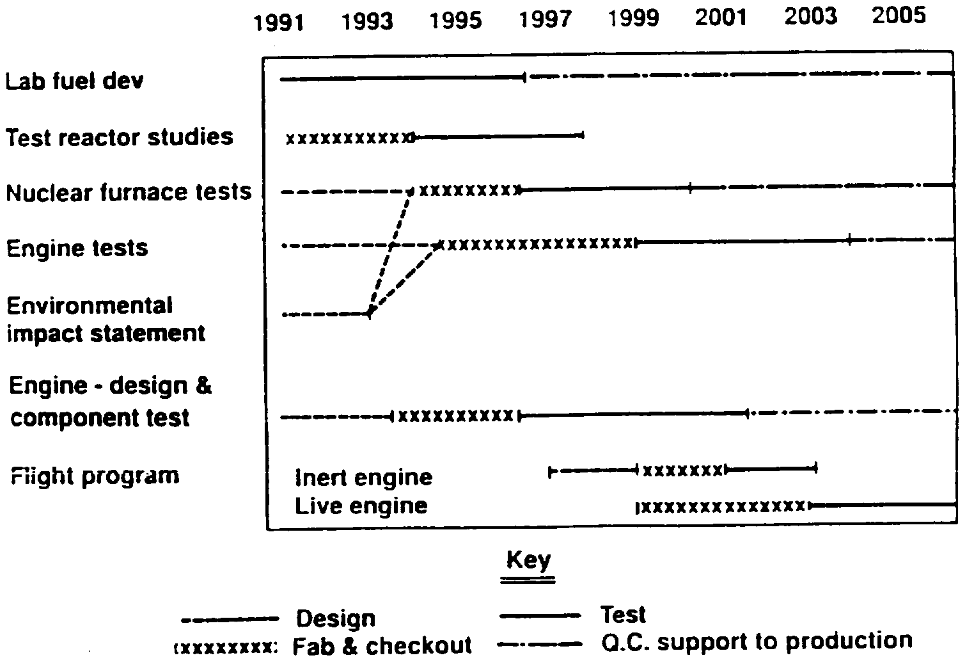


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Figure 20

LPNTR Program Initiation Costs

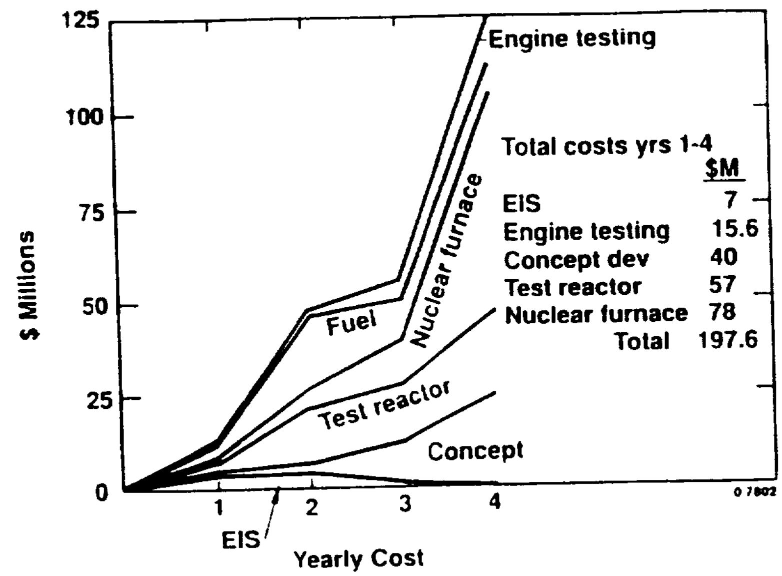

Figure 21

Total Program Cost 1991 - 2006

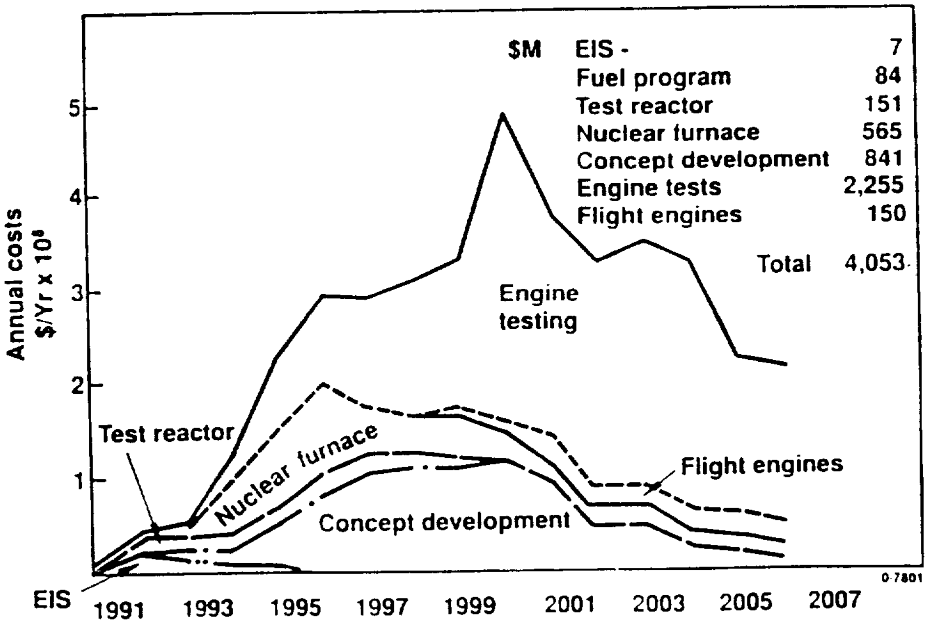

Figure 22

LPNTR Development
Two Qualified Flight Engines delivered to Launch Site

All $ in Millions

Item	Cost	Output
EIS	$ 7m	Test site selected Program Environmental Approval obtained
Fuel Program	$ 84m	Developed fuel, electrical test facility 10 years of quality control check on fuel production.
Test Reactor	$ 151m	Hydrogen test loop: 3.5 years development testing of sub scale fuel assemblies; D&D of loop
Nuclear Furnace	$ 565m	- 60MW driver reactor; hydrogen test loop, prototype exhaust scrubber; four years full scale fuel assembly development testing; Six years of quality control testing of fuel assemblies.
Concept Development	$ 841m	Program Management, developed concept, qualification of non-nuclear components.
Engine Testing	$2,255	Three reactor development tests. Four engine development tests. Three engine qualification tests. Two quality control engine tests for flight support.
Flight Engines	$ 150m	Inert engine. Two qualified production engines.

Figure 23

Total Program Costs
$ Millions

	EIS	Design & Fuel Dev.	Component Qualification	Test Reactor	Nuclear Furnace	Engine Testing	Flight Engines	Total Annual Cos
1991	3	4	1	2	1	.3		11.3
1992	3	16	3	17	6	.3		45.3
1993	1	10	12	16	12	5		56
1994		9	24.	22	59	10		124.0
1995		8	50.2	22	83	65		228.2
1996		7	79.5	22	110	75		293.5
1997		3	103.0	22	54	105		287.0
1998		3	109.5	17	40	140		309.0
1999		3	109.0	11	40	170	10	343.5
2000		3	116		40	320	10	489
2001		3	91		20	264	30	408
2002		3	44		20	260.4	20	347.4
2003		3	44		20	260	20	347
2004		3	22.5		20	260	20	325.5
2005		3	18.5		20	160	20	221.5
2006		3	14.0		20	160	20	217.0
	7	84	841.2	151	565	2255	150	$4053.2

Approximately $4B

Figure 24

Engine Facility

	Facility Construction Cost	Operations Cost	Experiment Costs	
1991	.3			.3
1992	.3			.3
1993	5			5
1994	10			10
1995	60	5		65
1996	80	10	15	75
1997	70	20	15	105
1998	70	40	30	140
1999	50	60	50	170
2000	60	60	200	320
2001	4	60	200	264
2002	.4	60	200	260.4
2003		60	200	260
2004		60	200	260
2005		60	100	160
2006		60	100	160
	400	550	1,300	$2,255

Figure 25

Nuclear Furnace

	Reactor Design & Fab	Facility Design & Fab	Operations	Experiment Lab and Analysis	Total
1991	1				1
1992	5	1			6
1993	10	2			12
1994	50	3	3	3	59
1995	60	9	7	7	83
1996	60	10	20	20	110
1997	14		20	20	54
1998			20	20	40
1999			20	20	40
2000			20	20	40
2001-2006			10/Yr = 60	10/Yr = 60	20/Yr = 120
	200	25	170	170	565m

Figure 26

Program Management Engine Design
Non-Nuclear Component Qualification

	Project Management	Mission Analysis	Flight Safety	Stage Interface	Engine System	Nuclear Subsystem	Total
1991	.2				.5	.3	1.0
1992	.7	.1	.1	.1	1.3	0.7	3.0
1993	1.7	.1	.1	.1	5	5	12.0
1994	3.7	.1	.1	.1	10	10	24.0
1995	8	1.0	1.0	.2	20	20	50.2
1996	15	2.0	2.0	.5	30	30	79.5
1997	17	2.0	2.0	2.0	40	40	103.0
1998	18	1.0	2.0	8	40	40	109.0
1999	18	0.5	2.0	9	40	40	109
2000	19		7.0	10	40	40	116
2001	14		8.0	9	30	30	91
2002	7		9.0	8	10	10	44
2003	7		10.0	7	10	10	44
2004	2.5		8.0		6	6	22.5
2005	2.5		6.0		5	5	18.5
2006	2		4.0		4	4	14.0
	136.3	6.8	61.3	54	291.8	291	841.2

Figure 27

Fuel Development Funding

	Labor & Mat'ls	Test Facility	Facility Operations	Emp. Cost	D&D	Total
1991	4					4
1992	4	10	2			16
1993	8		2			10
1994	7		2			9
1995	6		2			8
1996	5		2			7
	34	10	10			54
1997-2006	2/Y = 20m		1 1/2- 10m			3/Yr = 30m

Total: = 84m

Test Reactor Funding

1991	2				2
1992	10		7		17
1993	4	5	7		16
1994		10	12		22
1995		10	12		22
1996		10	12		22
1997		10	12		22
1998		5	12		17
1999			6	5	11
	16	50	80	5	151

= $150

Assume $150m

Figure 28

LPNTR Major Technical Issues

1) Nozzle pressure vessel design to optimize performance
2) Flow/power match within fuel element and core
3) Cost of ground test facilities
4) Fuel form/maximum operating temperatures
5) Total pressure drop
6) Viability feedback power control

0-7793

Figure 29

LPNTR Technical Summary

- No problems identified which require technical breakthroughs
- Many engineering problems exist which could reduce performance
- Improved performance could be obtained with revised thrust chamber/nozzle configurations
- Performance, reliability, and safety makes LPNTR a promising candidate for early development
- Technology verification should initiate in FY91

0-7796

Figure 30