N92-11093

UPGRADED NERVA SYSTEMS: ENABLER NUCLEAR SYSTEM

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What is the "Enabler?" (see Figure 1). That's a term from people like myself who are incurable marketeers. We say the "Enabler." When Westinghouse talks about it, it's NERVA/ROVER, when Los Alamos talks about it, it's ROVER/NERVA.

The NERVA/ROVER "Enabler" technology enables things to be done. It enables you to go on a low risk, short-term program to meet the requirements of the Mars mission and maybe even some lunar missions.

To put things in perspective a little bit, Figure 2 shows a full-page ad back in early 1966 published in the New York Times, the Washington Post, the Los Angeles Times, the Wall Street Journal and the Pittsburgh Post Gazette. This was after we had tested the first nuclear engine at Jackass Flats, and the words say "Today Mars is closer." And I sure wish we were able to say we continued that effort and we are that much closer right now, but at least that's where we were at that time. Hopefully we can get to that kind of point again.

Our contention is that the NERVA technology, the Enabler, is a foundation for tomorrow's space missions (Figure 3).

The pictures we have here are fuel elements, the NRX/EST. Again, NRX/EST was the reactor that was tested and was the system that made Mars that much closer in February 1966, and it was real.

Figure 4 lists all the tests that were made during the program.

Figure 5 approaches the NERVA program from a little different perspective. It shows the overall program objectives and milestones, the progress made, and where we were when the program ended. The program started with a demo flight engine objective (which got changed partway through the program). It was changed to a technology program to demonstrate rated thrust for 20 minutes, and then 60 minutes, and then demonstrate operation of engines, restart, cool down, and mapping. Then, we were to develop an engineered flight system.

Westinghouse bid on the program back in early 1961. We were under contract in late 1961. The first test that we put together on an engine, (a complete engine as opposed to just reactors with nozzles or orifices at the aft end to give us a pressure drop), was the EST engine. That was in early 1966.

The reactor technology goals were met by 1968. The engine technology goals were met by 1969 when we tested the XE prime engine. The preliminary design report on the flight engine was completed and presented and approved, and then the program was terminated.

We had gone through all of these activities and had things left to do, such as the final reactor design, and the final engine design. What it turned out was just storage of technology data.

Although the program ended in that time period, we at Westinghouse continued working on the program as best we could. We kept the technology alive (at least we sure tried to), with a whole bunch of miscellaneous contracts, all of them small compared to the NERVA contract (see Figure 6). We tried to keep a cadre of people knowledgeable of the NERVA technology, using the NERVA technology, so that today the technology is available and ready to be used. It can provide a meaningful start to the revisit of a Mars mission.

We have talked about a $1.4 billion ROVER/NERVA program several times. I thought it might be interesting just to show how that was broken down (see Figure 7). The Los Alamos part, as best we can reconstruct the numbers was about $177 million. The Westinghouse Aerojet NERVA program was $660 million; technology, $328 million; operating costs at the test site, $90 million; and facilities at the test site, $153 million. So that's your $1.4 billion in "then year" dollars. I just added on what we have spent at Westinghouse, both other people's money, and our own money since then keeping the thing alive.

In Figure 8 we are talking about direct thermal propulsion. A couple of weeks ago at the NEP Workshop, we talked about a steady state electric power system using NERVA technology. Tomorrow, at the mission analysis panel, we will also talk about a dual power system where we can get direct thrust and electric power for whatever purpose you want, either propulsion or housekeeping. The same technology is available to be used in all of these kind of systems.

With the NDR engine, direct propulsion, we are trying to provide an optimum amount of energy to the turbo pump and the optimum temperature out of the reactor to get the optimum Isp. All these things are based on a 75,000 pound thrust engine because that was the requirement that had been established for this application.

We have looked at flow here in Figure 9. Figure 10 is a color picture of the NERVA nuclear subsystem, but I don't want to spend the time going through it. We have all seen this, and the model (NERVA model at the workshop) alludes to the kind of design we're talking about anyway.

Figure 11 shows the arrangement of fuel within the reactor. We are talking of fuel elements that are extruded composite matrix elements containing fuel within the structure. There are 19 coolant holes within each of the fuel elements, coated both on the external and internal surfaces with zirconium carbide to provide resistance to hot hydrogen attack.

These are then assembled around central elements which are support tubes, the tie tubes. The tie tubes have associated with them some zirconium hydride moderator to thermalize the neutron spectrum in the reactor and reduce the amount of uranium that's needed for criticality. We show here the materials and how the whole thing is put together. The tie tubes are reentry type tubes where the coolant flows down and then back up and out. That was shown on the schematic. This is an approach to show you how these things look.

For our reference case, we are talking about composite fuel, as shown in Figure 12. The vintage 1972 NERVA was a beaded fuel within a graphite substrate. We are talking about UC-zirconium dispersion within a graphite substrate, and this is what has been termed the "composite" fuel.

The shaded NDR column in all cases is what we have set as the reference case for the Enabler reactor system. Column one on the left describes the reactor that was run as XE prime. I put that in here because that had the technology readiness level of 6 by everybody's assessment. Composite fuel was developed late in the ROVER/NERVA program, but never fully tested to technology level equivalent to the fuel in the XE prime.

The NERVA '72 update incorporates today's requirements and could include some general improvements, like improved beads, and is the next step in a NERVA-type system. The composite is the Enabler target for now. From there, we can go to a different fuel material, a binary carbide, and get a temperature of 3100 K as chamber temperature and increase the Isp to 1020. Perhaps we can even go to ternary carbides, although the technology level on the ternary carbides is pretty low. But if we can get there, we can further increase our chamber temperature to 3300 K and get an Isp perhaps of about 1080 seconds.

So, there is room for improvement in the technology. We are not pushing things excessively. We are working on a system that had a reasonable amount of demonstration and testing in respect to fuel during the NERVA program. Composite fuel was run in the nuclear furnace, and it was run in electrical tests, and so we had a reasonable database.

What is the technology level? (Refer to Figure 13) Again, for argument sake, I assigned a 6 to everything on XE prime because that is conventional wisdom. Things kind of back off as you start adding new requirements and changes, but the things that are most significant are really in the fuel area, where we are now talking about composite fuel probably at a technology level today of somewhere in the order of 4 to 5. There has been testing done on it, but not enough to give you the good, comfortable feeling that you know all about the fuel.

If we go to a binary carbide, you have to back off a little bit more on technology level as assessed today. If we go to the ternary carbide, it's kind of like a semi-dream, not a full dream, because we know something about it but not enough to really assess what its capability is. The other things are generally all 5's and 6's.

We are adapting the SP-100 approach for putting additional control rods within the reactor core to meet some of the new safety requirements on multiple capability for shut down, positive shut down, and positive protection against launch accidents, immersion, and things of this sort. Therefore, we backed off on the technology level a little bit because there is more work to be done on that to be able to assess the adequacy of that design and the applicability to a propulsion system.

The key design parameters for all the systems are listed on Figure 14. For the composite NDR column, thrust is 75,000 pounds (not 75 pounds), engine availability at 2006, reactor power 1600 megawatts, and you can read the rest of the numbers. The engine thrust-to-weight without a shield is 4. And that's where we pegged it because that's where the baseline requirements said. I will present some curves to show where it can go if you change some parameters.

Adding in a nonoptimized shield, far from being optimum, the thrust to weight drops down to 2.3. We are talking about a specific impulse of 925 seconds. This is a thousand pound chamber pressure, 500 to 1 expansion ratio nozzle, and so forth.

Stan Borowski talked about core power density having an effect on thrust-to-weight ratio. Figure 15 shows that if we increase core power density we can go from a 4 to perhaps a 6 and a half. This results from shrinking the reactor as you get more and more power per fuel element. Of course there is some additional risk as you do that, but it's within the realm of possibility. For the purpose of this workshop we did not try to push the reactor, we tried to be reasonably conservative in the approach we used.

We also took a look at what the thrust-to-weight ratio would be as we changed the thrust level of the engine and reactor. On Figure 16 you can see that going from about 25 pounds of thrust up to 250,000 pounds of thrust, this is the kind of range you get for thrust-to-weight ratio. Again, these are representative numbers.

The reactor is not growing on a linear basis with increased power. Recall we are thermalizing the reactor quite a bit, so it's a basically thermal machine. You are just putting in some more flow area for the higher power requirements, but it's not growing linearly.

One is always concerned as to what kind of life you can get out of these reactors. Of course, that's a function of the kind of fuel you have and the temperatures of the fuel. The lower the temperature, the more life you will get out of it, the higher temperature obviously the shorter life. The curves on Figure 17 are really bands and not single lines. They ought to be thought of in terms of bands to give an indication of what you can do in fuel life as a function of temperature.

The lower curve represents the vintage NERVA type of design. The middle line represents the composite design, recognizing we are going to operate at about 2700 K nozzle chamber temperature, which says we ought to be able to get, without any strain at all, two hours of operation based on the data that was assembled during the NERVA program. More data ought to be assembled to see where the true limits are.

With carbide fuel, where we were hoping to operate at about 3100 K chamber temperature, we ought to get several hours worth of operation. Again, more data is required to pinpoint what the limits are and what the capabilities ultimately ought to be.

What are some of the key technical issues? (Refer to Figure 18) Fuel has to be one of them. We need more data on fuel. There was limited testing in the nuclear furnace. We have to do more testing. We have to demonstrate once more the effectiveness of the zirc-carbide coating, the so-called "super-coat" that in electrical test did last ten hours through some 64 cycles of temperature swings. We have to do it again, show that we can do it, and demonstrate the lifetime.

Safety. Somebody earlier today said safety has to be the byword, and that surely has to be addressed in anything we do. It is a key issue, not only a technical issue but it's a programmatic issue and an emotional issue and a public perception issue. Therefore, we call safety inherent, engineered-in. Public perception, and all of these things, have to be addressed, some from a technical viewpoint.

The issue of intact reentry, permanent shutdown and fuel integrity are some of the technical issues. The public perception issue is one that has to be addressed in a different fashion and doesn't get addressed really in a research and development program or demonstration program.

Critical tests and activities are listed in Figures 19-22. We have gone through what we think might be a first-year type of program in Figure 19. One of the key issues in the first year is to initiate design of the ground test facility. Whatever this ground test facility is going to be, it is on the critical path. And the sooner we can get started on that, the sooner we are ready for anything that comes along later on.

We have also looked at near term activities, including fuel elements tests and showing that we can meet the fuel reactor safety issues. (See Figure 20).

Far term tests include nuclear subsystem tests of all sorts (See Figure 21). And then further into the far term, there are engine tests to be done where you put the whole system together and run it through its mapping and performance characterization (Figure 22).

We then get to something that is very controversial, and that's how long does it take to do this? (Refer to Figure 23). Any number that I put up (any number that anybody puts up) for the schedule is obviously not the right answer, because we don't know what the right answer is. We don't know what the parameters of the problem are or the funding availability. So what we have done is said, okay, if we had to get to technology readiness level 6 and we were not constrained by funding but constrained by the time that it takes to do things --where a critical piece of the whole thing is the test facility -- how long would it take to get to technology level 6? And we think we can be there in eight years.

Will it take eight years? Undoubtedly it will take longer because the money is it not going to flow this way. What will it cost? Well, this one I guarantee is the wrong number (see Figure 24). But it is a number, and again it's based on saying, we are going to be success-oriented. We are going to do things quick, we are not going to stretch the program out. If you want to round that off to around $1 billion, I am willing to go from $755 million to $1 billion and say it's the same number.

But it's an order of magnitude for a program that is an eight-year program and not a program that, as I fear will happen with the way government funding tends to go, be a lot longer program as costs obviously go up when programs stretch out.

There are two sets of facilities that one needs (see Figure 25). One is the major facility for full-scale, ground testing of the engine. The other facility that is needed is for fuel testing, and here there are several options available to us: the ATR (Advanced Test Reactor at INEL), and also some Soviet test reactors where they are very anxious to test fuel, U.S. space reactors within their currently available and operating reactor systems. It's an option that might be considered. Figure 26 is a different version of the same sketch that Stan showed. I won't go into that.

And again, as the unrepentant marketeer, I have my final vugraph. Figure 27 lists all the goodies that come with this kind of system: it's technology-based, demonstrated under demanding ground test conditions. We went through a whole series of ground tests in the 1960's and early 1970's, and it worked; a wide range of thrust capabilities; no need for technical breakthroughs (we are talking about evolutionary changes, evolutionary changes to get to the composite fuel, evolutionary changes to get us beyond that); there is a technology synergism between the direct thermal thrust and other uses in space of the same kind of technology.

We think we have identified solutions to all the safety concerns, the technical safety concerns. The public perception concerns I back off on. There are modest development needs. Modest is in the view of the beholder. Your idea of modest may be different than my idea of modest. And as I said at the beginning, it's an Enabler for near term, low risk, low cost power systems. At least that's our position.

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Gerry Farbman
Enabler

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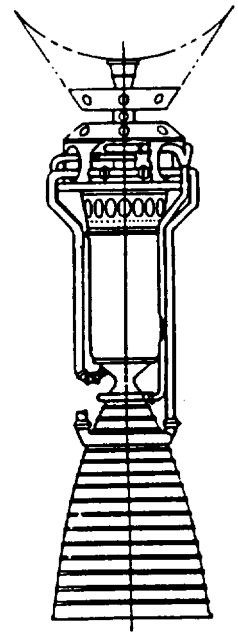
The Enabler
(Based On Proven NERVA Technology)



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July 10 – 12, 1990

Figure 1

As Appeared In:

- *New York Times*
- *Washington Post*
- *Los Angeles Times*
- *Wall Street Journal*
- *Pittsburgh Post Gazette*

Figure 2

NERVA Technology – The Foundation for Tommorrow's Space Missions

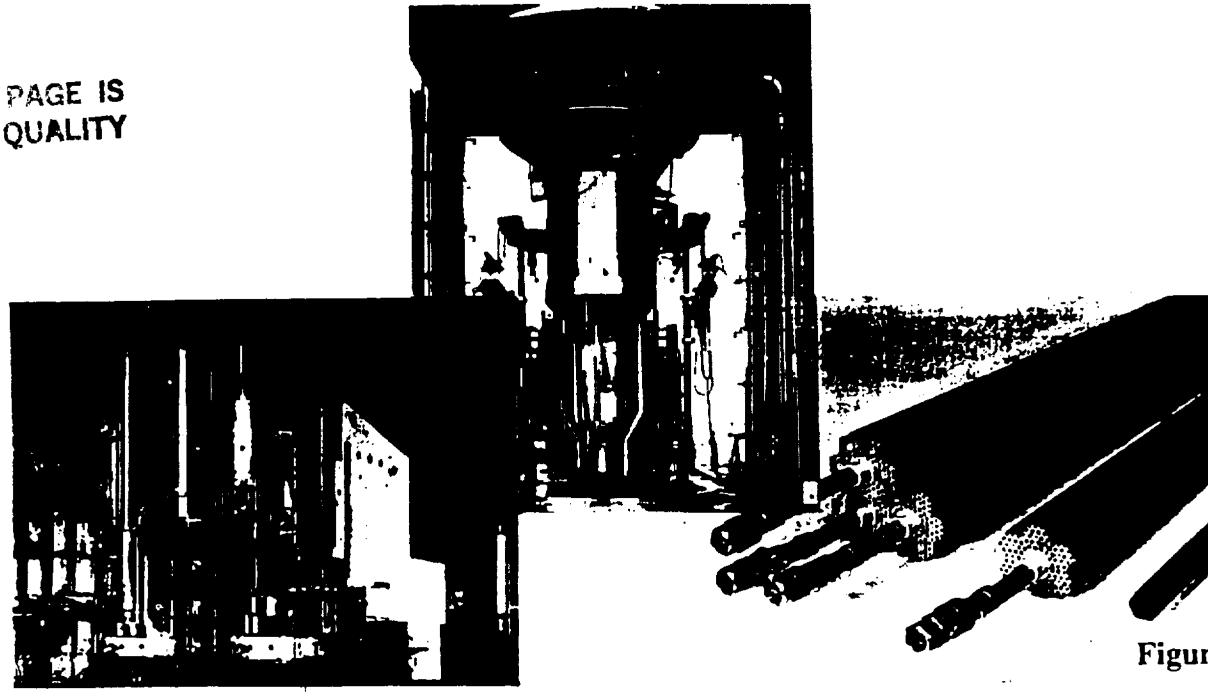


Figure 3

NERVA/Rover Reactor System Test Sequence

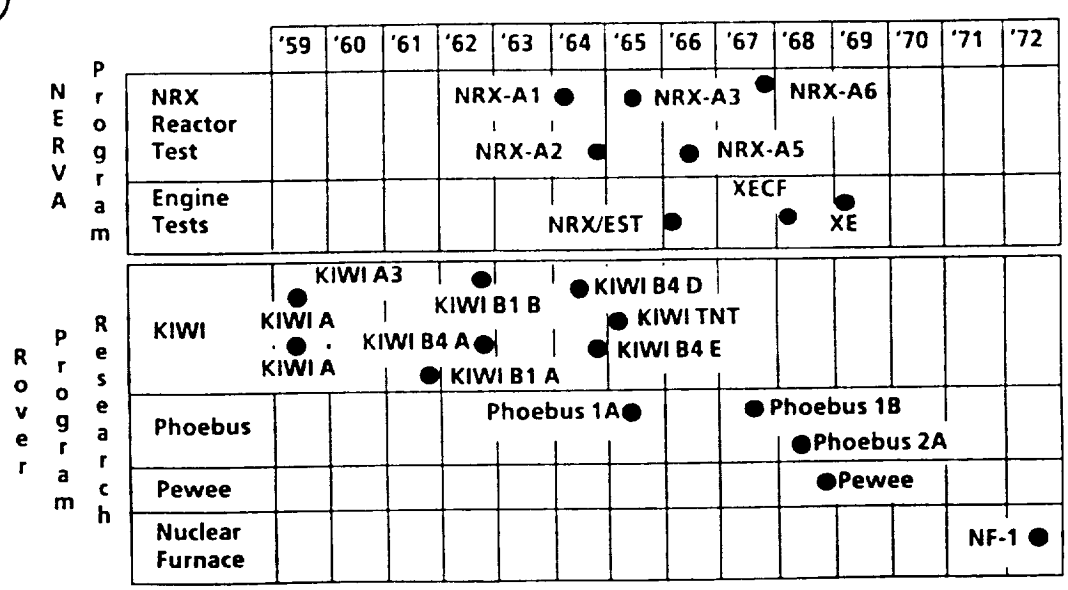


Figure 4

NERVA Engine Development Program

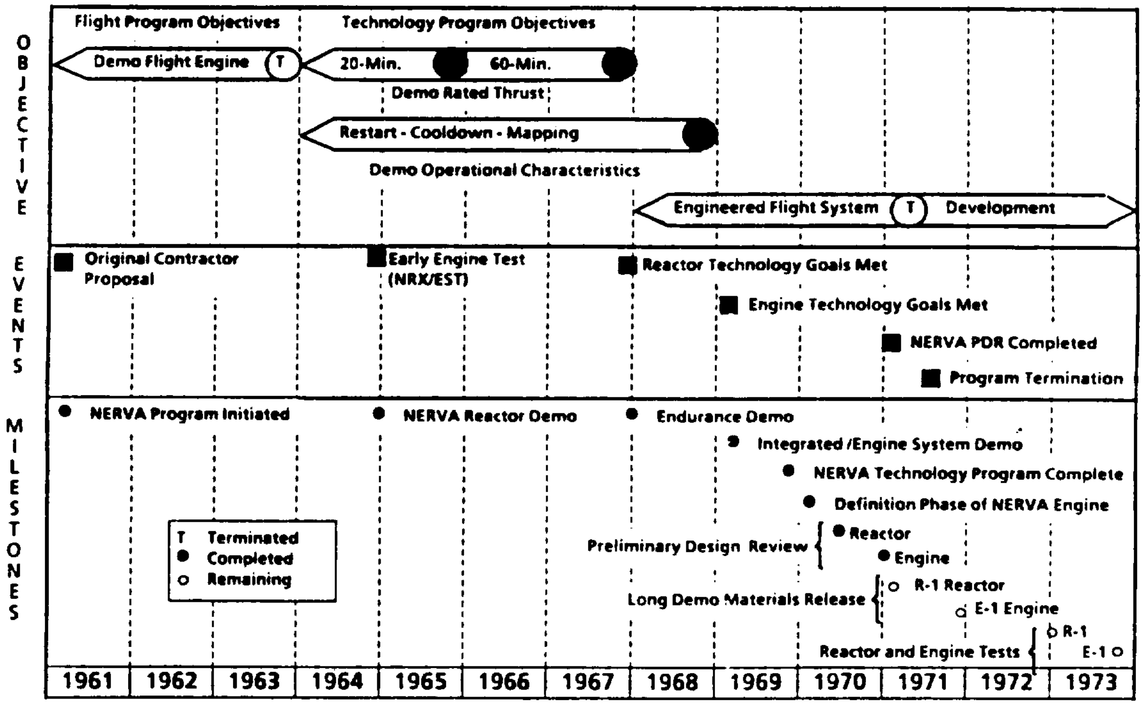


Figure 5

Nuclear Thermal Reactor Capability Based On Many Related Westinghouse Technology Programs

Program	Customer	Time Period
NERVA	NASA/DOE	1961–72
Nuclear Rocket Shielding Methods	NASA/LeRC	1969–70
Afterheat Distribution	NASA/LeRC	1970–71
Reactor Study for Nuclear Powered Aircraft	USAF	1970–72
In-Space Maintenance Concepts	NASA/MSFC	1971–72
Terrestrial Applications of NERVA Technology (Marine, transportable, etc.)	IR&D	1972–82
Nuclear Waste Disposal in Space	NASA/LeRC	1972–73
The Very High Temperature Reactor for Process Heat	DOE	1974–76
Closed Cycle Brayton Gas–Cooled System Feasibility Study	ONR	1976–79
Nuclear Bi–Brayton System for Aircraft Propulsion	USAF	1978
Space Reactor Evaluation	DOE	1983
Space Applications of NERVA Technology	IR&D	1983–Present
Integrated Spacecraft Total Energy System Analysis	AFWAL/TRW	1983–85
Gas Cooled Reactors for Advanced Terrestrial Applications	IR&D	1985
SDI Architecture Study	SDIO/SAIC	1985–86
NDR/MHD (Linear Channel) Study	INEL	1986
NDR/Brayton MMWe Space Power System	DOE	1986–87
Space Power Architecture Study	AFSTC/TRW	1986–87
NDR Nuclear Space Propulsion	AFAL/INEL	1986–88
NDR/MHD (Disk Generator) MMWe Study	DOE	1987–88
MSNPS	DOE	1988–Present
Manned Lunar/Mars Mission Propulsion System Studies	SAIC/NASA-LeRC	1989–Present

Figure 6

2379-21

Rover/NERVA Technology Represents A Significant Investment

	Total
• Rover/NERVA program (1955–1972)	$1,400 million
– KIWI – $177 M (LANL)	
– NERVA – $662 M (W/Aerojet)	
– Technology – 328 M (technology)	
– NRDS – 90 M (operating)	
– Facilities – 153 M (capital/test facilities)	
• W Post–NERVA technology programs (1972–present)	$15 million

Figure 7

NERVA Technology Has Synergistic Applications

Steady-State Power

- 10's of MWe for electric propulsion

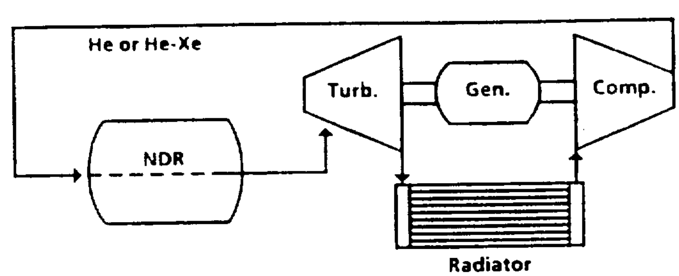
Direct thermal propulsion

- 15,000 to 250,000 pounds of thrust

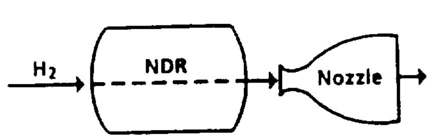
Dual Power Systems

- High direct thrust (e.g., 75,000 pounds) plus low electric propulsion (e.g., 1MWe)

Steady-State Power



Direct Thermal Propulsion



Dual Power System

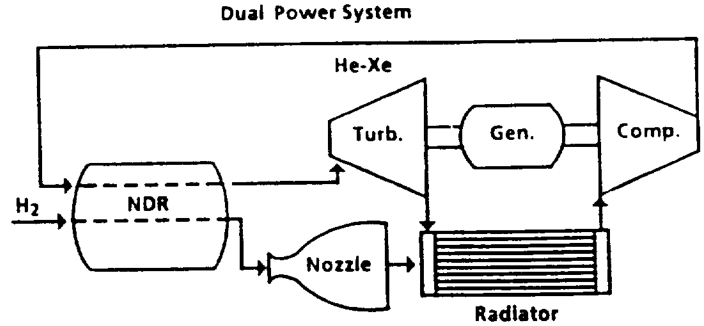


Figure 8

Flow Schematic of the NDR Engine

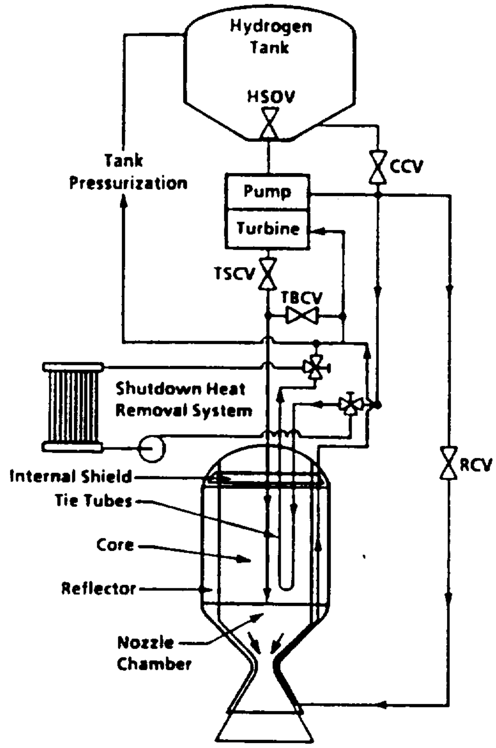


Figure 9

The NERVA Nuclear Subsystem

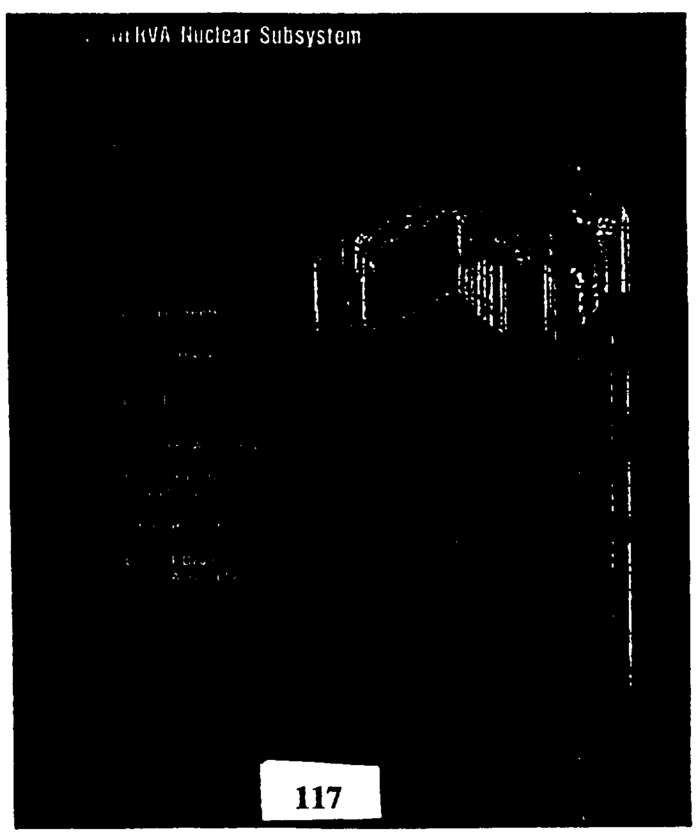


Figure 10

Proven NERVA/Rover Reactors

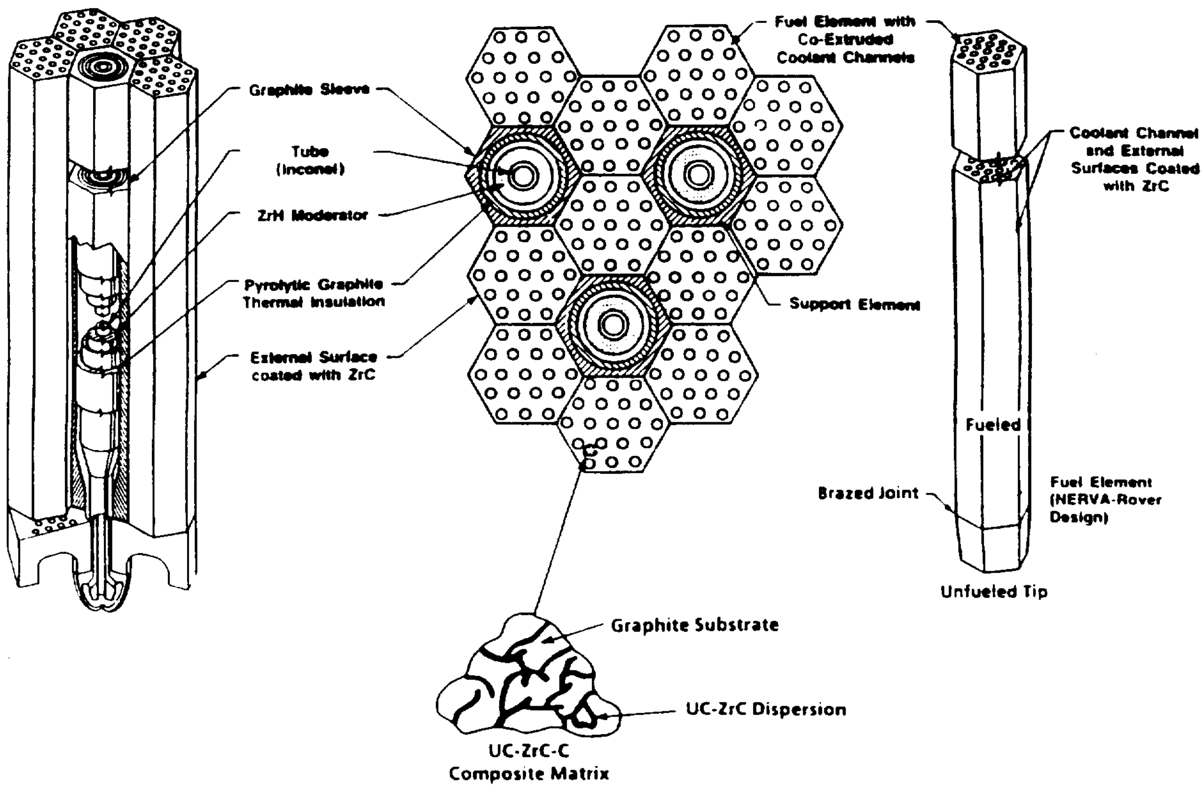


Figure 11

TECHNOLOGY EVOLUTION

	NRX XE'	NERVA 72 UPDATE	COMPOSITE	BINARY CARBIDE	TERNARY CARBIDE
• Fuel	Duplex Bead	Duplex Bead/ZrC Coated	UC-ZrC-C	ZrC-UC	UC-ZrC-NbC
• Moderator	Graphite	$Zr\ H_x/C$	$Zr\ H_x/C$	$Zr\ H_x/C$	$Zr\ H_x/C$
• Reactivity Control	Drums Plus Poision Wires	Drums Plus Safety Rods	Drums Plus Safety Rods	Drums Plus Safety Rods	Drums Plus Safety Rods
• Axial Support	Tie Rod	Tie Tubes	Tie Tubes	Tie Tubes	Tie Tubes
• Control Drives	Pneumatic	Electric	Electric	Electric	Electric
• Reactor Vessel	Aluminum	High Strength Steel	High Strength Steel	High Strength Steel	High Strength Steel
• Chamber Temp (K)	2270	2500	2700	3100	3300
• Pressure (psia)	450	1000	1000	1000	1000
• Nozzle Exp. Ratio	100:1	500:1	500:1	500:1	500:1
• Isp (sec)	710	890	925	1020	1080

NDR

Figure 12

STATUS OF TECHNOLOGY LEVEL

Nuclear Subsystem:	NRX XE'	NERVA 72 UPDATE	COMPOSITE	BINARY CARBIDE	TERNARY CARBIDE
• Fuel	6	4-5	4-5	3-4	2
• Moderator	6	5	5	5	5
• Fuel Element	6	5	5	3-4	2
• Axial Supports	6	5	5	5	5
• Lateral Supports	6	6	6	6	6
• Core Periphery	6	6	5	5	5
• Reflector	6	5-6	5-6	5-6	5-6
• Control Drums/ Drives	6	5-6	5-6	5-6	6
• Internal Dome Shield	6	6	6	6	6
• Core Support Plate	6	5-6	5-6	5-6	5-6
• Safety Rods	-	4	4	4	4

NDR

Figure 13

Key Design Parameters

	NRX XE'	NERVA 72 UPDATE	COMPOSITE	BINARY CARBIDE	TERNARY CARBIDE
• Thrust (lb)	55	75	75	75	75
• Engine Availability (yr)	-	-	2006	-	-
• Reactor Power (MWt)	1120	1520	1613	1787	1877
• Engine Thrust/ Weight (w/o Shield)	3.9	4.2	4.0	3.7	
• Engine Thrust/ Weight (w/Shield) (lbf/lbm)	-	2.4	2.3	2.2	-
• Specific Impulse (s)	710	890	925	1020	1080
• Mass (kg)					
Reactor	3159	5476	5853	6579	-
Non-nuclear	3225	2559	2559	2624	-
Internal Shield	1316	1524	1517	1517	-
External Shield	-	4537	4674	4967	-

NDR

Figure 14

Thrust To Weight Ratio Dependant On Core Power Density

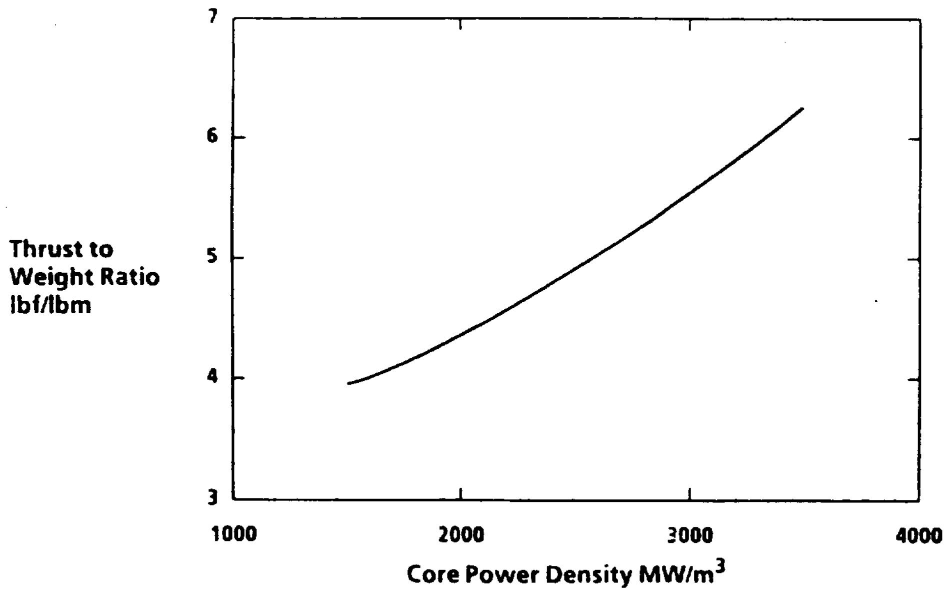


Figure 15

Growth Capability Of The NDR Engine

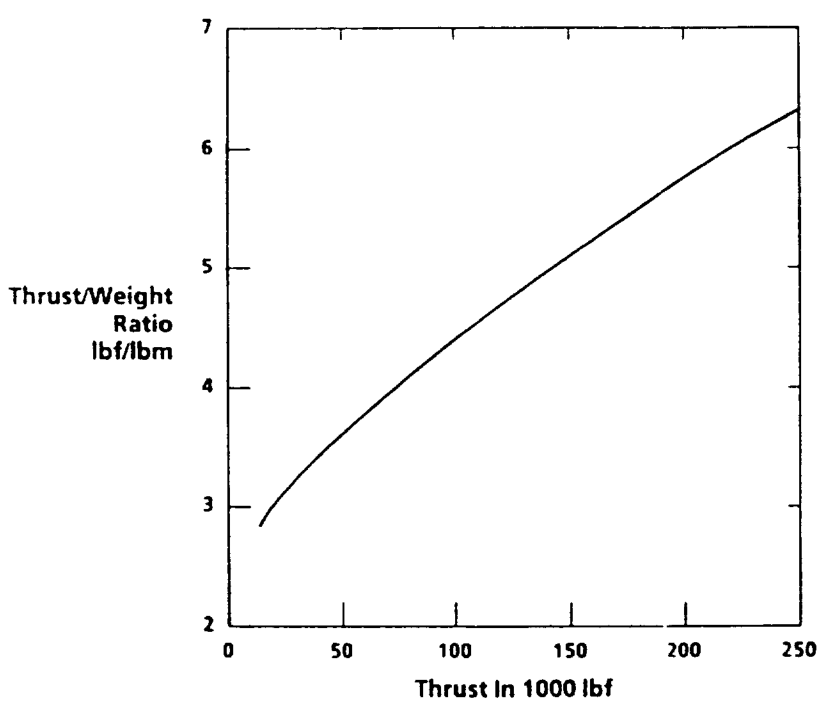


Figure 16

Effect Of Nozzle Chamber Temperature And Fuel Form

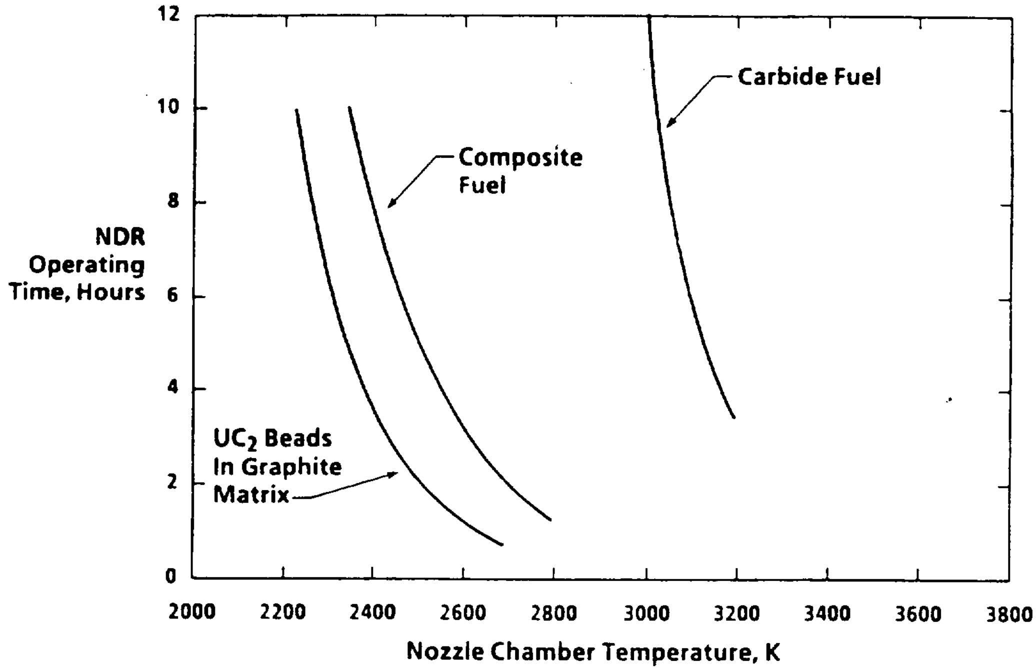


Figure 17

Key Technical Issues

- UC-ZrC-C composite fuel
  - Limited testing in nuclear furnace near end of Rover/NERVA program
  - Demonstrate effectiveness of ZrC coating ("Super Coat")
  - Demonstrate lifetime
- Safety: Inherent, engineered and public perception
  - Intact reentry
  - Permanent shutdown - applicable experience with comparable system operations (SP-100)
  - Fuel integrity

Figure 18

Critical Tests/Activities

- First year
  - Retrieve NERVA data
  - Review for required and/or desirable updates of drawings, specifications and procedures
  - Identify required analytical models and update or revise for current computer use
  - Initiate design of ground test facility

Figure 19

Critical Tests/Activities

- Near term (Phase I)
  - Fuel element test: demonstrate the capability of the composite fuel elements to meet current performance requirements
    - Demonstrate effectiveness of ZrC coating
    - Demonstrate fuel integrity/lifetime
  - Demonstration of complete fabrication of fuel element
    - Extrude fuel elements
    - Tests to assure quality of extrusion
    - Conduct in-pile tests
  - Reactor safety issues:
    - Subcriticality issues under full core immersion and core compaction
    - Approach to ensure intact reentry depends on design and materials for reactor vessel and internals
    - Demonstrate reactor shutdown and final shutdown capability in critical tests (drums and safety rods)

Figure 20

Critical Tests/Activities

- Far term (Phase II)
  - Nuclear subsystem tests
    - Control train tests
    - Test system controls and prototypic flight system control tests
    - Shielding tests
    - Feature tests - support structures, etc.
    - Safety tests
    - Etc.

Figure 21

Critical Tests/Activities

- Far term (Phase III)
  - Engine tests
    - Demonstrate operating envelopes
    - Perform cold flow experiments
    - Demonstrate startups/shutdowns/cooldowns/ emergency responses
    - Verify endurance/cyclic performance capability/ component interactions
    - Verify post test component conditions

Figure 22

Schedule For Ground Test Of Nuclear Thermal Rocket

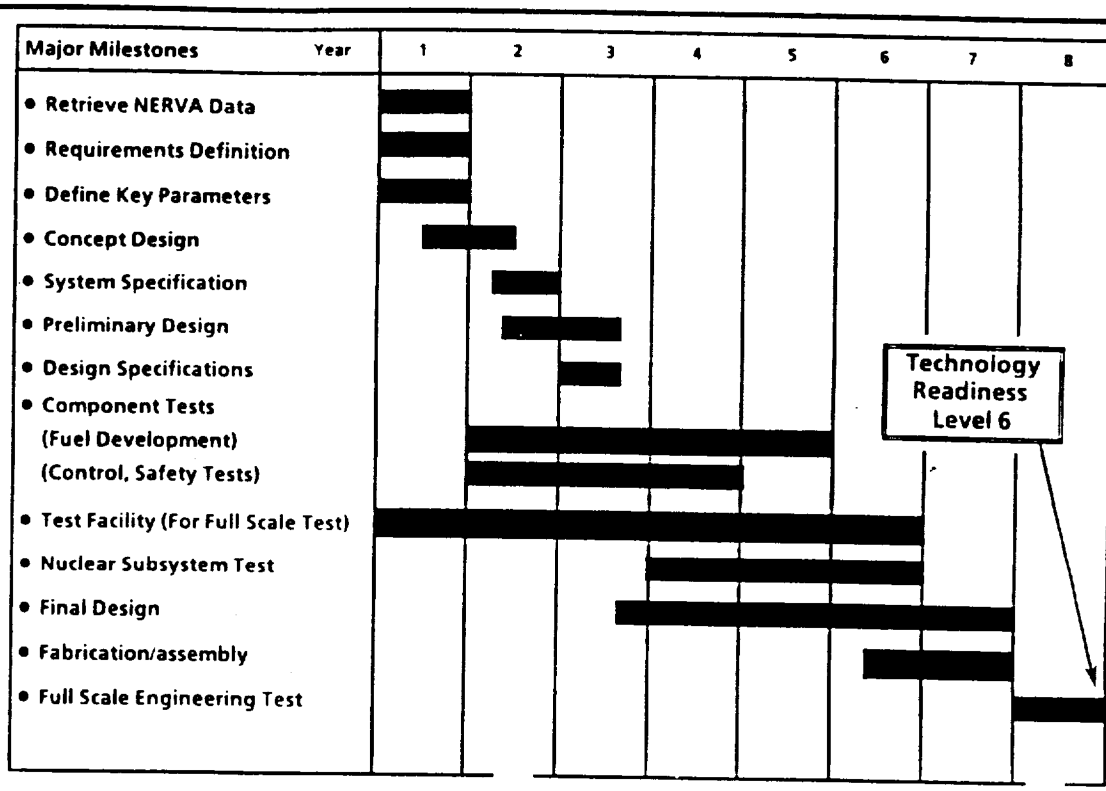


Figure 23

Development Costs For NTP/NDR

	($ M)
Reactor development and design	350
Engine development and design	150
Procure and assembly for full scale test	100
Facility preparation	125
Test costs	30
Total	755

Figure 24

Facility Requirements

- Options for integrated tests:
  - Exhaust hydrogen to a cleanup/scrubber system
  - Exhaust hydrogen into an underground tunnel
  - Test in space
- Can use existing containment facilities with modification for the hydrogen cleanup system

Figure 25

Nuclear Test Facility Option – Hydrogen Cleanup System Concept

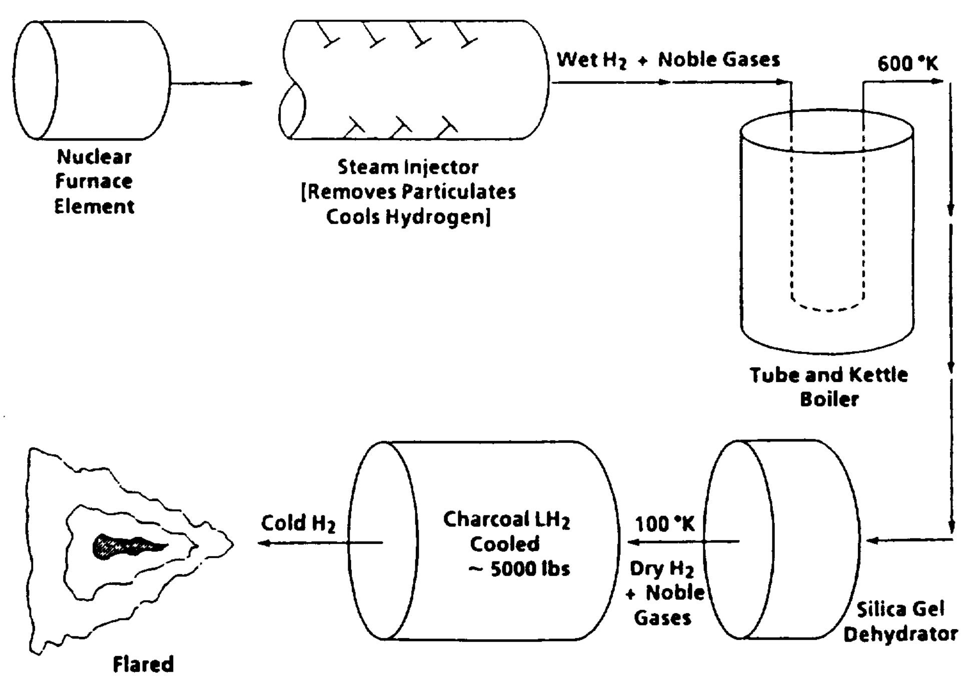


Figure source: LANL

Figure 26

Rover/NERVA Technology Provides Closed Cycle Power Systems With:

- A technology base demonstrated under demanding ground test conditions
- A wide range of thrust capabilities
- No need for technical "breakthroughs"
- Technology synergism between electric and direct thermal thrust propulsion systems for overall program economies
- Identified solutions to safety concerns
- Modest development needs
- An ENABLER for near-term, low-risk, low-cost power systems for nuclear thermal rocket applications

Figure 27