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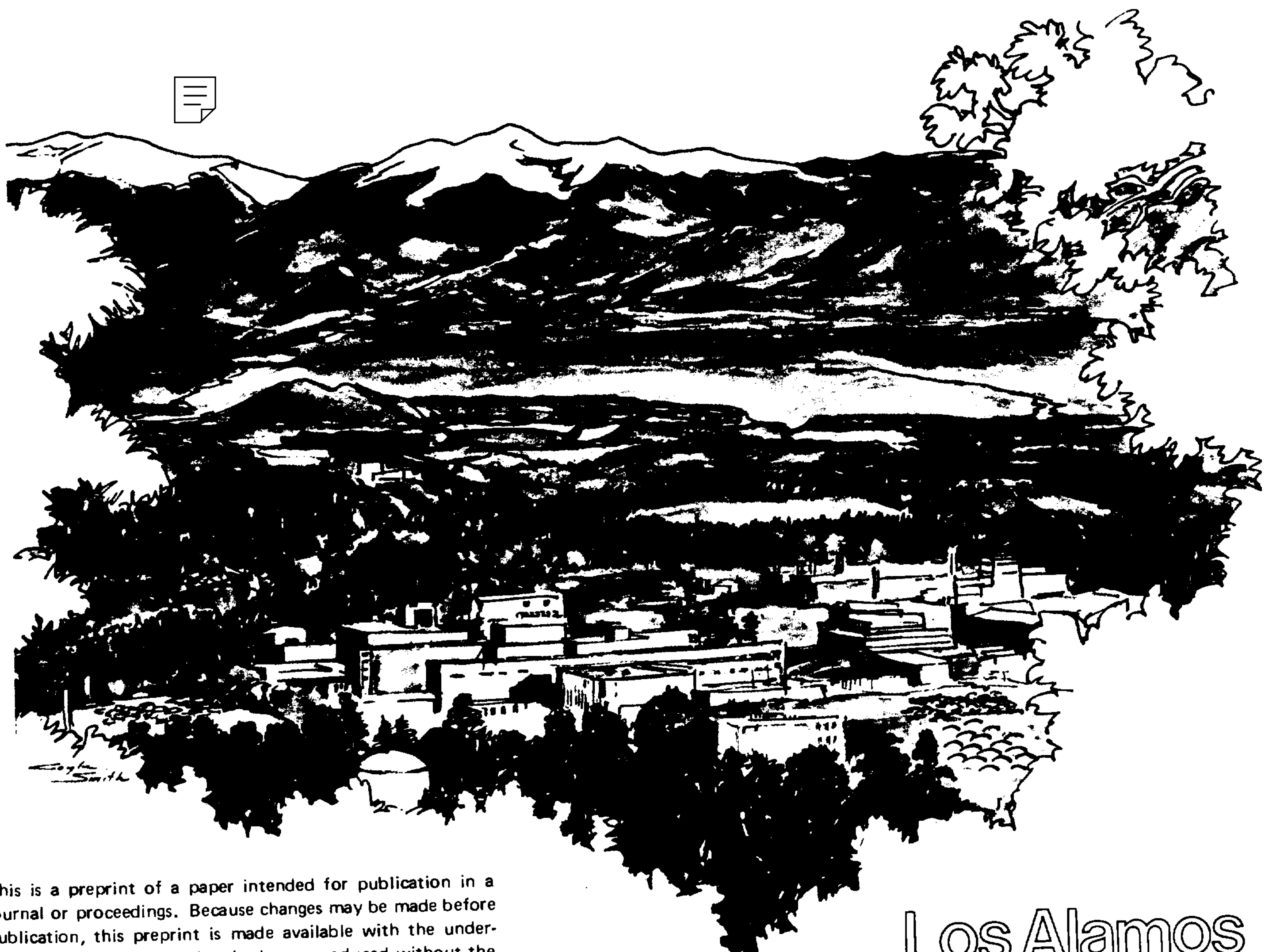

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ASSESSMENT OF THE ADVANTAGES AND FEASIBILITY OF A NUCLEAR ROCKET FOR A MANNED MARS MISSION

by

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ABSTRACT

The feasibility of rebuilding and testing a nuclear thermal rocket (NTR) for the Mars mission has been investigated. Calculations indicate that an NTR would substantially reduce the earth-orbit assembled mass compared to LO_2/LH_2 systems. The mass savings were 36% and 65% for the cases of total aerobraking and of total propulsive braking respectively. Consequently, the cost savings for a single mission of using an NTR, if aerobraking is feasible, are probably insufficient to warrant the NTR development. If multiple missions are planned or if propulsive braking is desired at Mars and/or at Earth, then the savings of up to $7 billion will easily pay for the NTR development.

Estimates of the cost of rebuilding a NTR were based on the previous NERVA program's budget plus additional costs to develop a flight ready engine. The total cost to build the engine would be between $4-5 Billion. The concept of developing a full-power test stand at Johnston Atoll in the Pacific appears very feasible. The added expense of building facilities on the island should be less than $1.4 billion.

The concept of using a Nuclear-Thermal Rocket (NTR) for a manned mission *to* mars has been considered for over 30 years.[1,2] The obvious advantage of producing about 2 times the Isp of chemical rockets allows 1) a lower total mass to be assembled for a given payload mass, 2) the possibility of much faster, high-energy transfer orbit to be used, or 3) more relaxed launch windows to be used. One other distinct advantage of the NTR is that the development and use of NTR engines will bring the possibility of future missions to more distant planets into the realm of possibility.

The major tasks of this study are to

a) compare the use of an NTR system to a chemical ($L0_2/LH_2$) system for the proposed 1999 launch scenario;

b) assess the economic feasibility of redeveloping the NERVA class NTR;

c) determining the possibilities of testing the NTR; and

d) assessing the concept of using the NTR as an electrial power source during the mission.

Nuclear Rocket Principles

The fundamental principle of an NTR is that a nuclear reactor operating at high power levels can heat and expel injected coolant at very high temperatures.[3] Thus, the reactor simply is an energy source which replaces the chemical energy released in $L0_2/LH_2$ reaction engines for example.

A schematic diagram[4] of a “standard” NTR is shown in Fig. 1. The reactor core is composed of highly enriched uranium-carbide fuel in a graphite matrix. Control drums composed of berated cages around beryllium cylinders, to either absorb or reflect neutrons, surround the cylindrical core. Liquid hydrogen is injected into the core, heated to temperatures as high as 4500°R, and ejected out through the nozzle. A small amount of liquid hydrogen is also heated and diverted to run the LH_2 turbopumps. The pumps are located at the top of the engine and are protected from the intense radiation fields of the reactor by a ZrH shield.

The intense neutron and gamma-ray radiation fields produced by the operating reactor are clearly the main difficulty in using a NTR on a manned mission. The ejected propellant poses a relatively minor radiation hazard since the LH_2 does not become radioactive and the fuel element particulate which abrades into the LH_2 from the core will rapidly disperse in the interplanetary environment.

Shielding the crew from the reactor during the "propulsive burn" can be accomplished by the combination of a tungsten and LiH shield. Further, reduction in the neutron dose to the crew can be accomplished by incorporating a few meters of LH_2 in a tank between the crew and engine. This tank for example might contain the 15% contingency LH_2 and would be the last tank to be used.

After the full power burn of the engine, the radiation from the reactor will be only gamma-rays and within a few days the intensity will have dropped by over three orders of magnitude. The thickness of tungsten required to shield the reactor in transit will be substantially less than for propulsive maneuvers. Thus, the tungsten shield may be designed to "unfold" around the reactor for post burn shielding which will provide a 211 or greater shield around the reactor and allow docking or EVA activity. Another possibility is to use mercury as the gamma-ray shield. Change of configuration is then accomplished by pumping the Hg into preformed reservoirs as shown in Fig. 2.

After the full power "burn" of the engine, delayed neutrons in the subcritical reactor core continue to produce fission heating. This delayed heat output causes a penalty in propellant mass since LH_2 must be fed to the reactor for a few days at a reduced flow rate. If the ejected hydrogen is not used to provide thrust, an extra mass of propellant must be carried. The amountof extra LH_2 which must be carried along to cool the core is around 24% of the mass of LH_2 used during the burn of the engine.[5]

Another approach is to utilize the delayed heat to produce low Isp thrust. Since the Isp of the NTR scales as the square root of the propellant temperature, the cooldown flow can be used to provide thrust with an Isp of around 400 s. This application reduces the average Isp of the engine by between 6-10%, and will necessitate carrying extra fuel. **For most missions with ΔV requirements** of a few km/s, the extra LH_2 required will be less than the 24% penalty previously described.

<u>NTR vs. Chemical</u>

A comparison between NTR and chemical propulsion systems is shown in Table I. In the comparison, an Isp of 450 s and 825 s was used for the chemical and NTR respectively. The NTR value was chosen as a reasonable compromise

TABLE I

NTR TO CHEMICAL PROPULSION

	Aerobraking (Mars and Earth)		Propulsive Braking		Hybrid , (Earth Aerobrake)
	hem	N	Chem	NTR	N
EOI					
Payload (K lbs)	112.69	112.69	112.69	112.69	112.69
Engine/Aeroshell	19.83	19.83	.78	26.00	19.83
Tankage			16.88	13.34	
Propellant			198.92	102.31	
	132.52	132.52	329.26	254.34	132.52
TEI					
Engine	1.96	26.00	1.96		26.00
Tankage	20.37	6.29	26.50	10.09	6.29
Propellant	77.18	41.95	183.13	67.30	41.95
	232.03	206.76	540.85	331.73	206.76
MOI					
MEM	128.20	128.20	128.20	128.20	128.20
Tankage/Aeroshell	63.40	58.95	26.50	34.33	25.00
Propellant	423.63		694.71	228.87	166.68
	423.63	393.92	1390.26	723.13	526.64
TMI					
Probes	24.48	24.48	24.48	24.48	24.48
Engine	16.02	26.00	16.02	52.00	26.00
Tankage	75.02	62.79	130.66	112.97	81.54
Propellant	1035.33	418.58	3105.70	753.16	543.59
	1574.	926.	4667.	1666.	1202.

between cooldown losses which would lower the effective Isp and studies in the NERVA program which concluded that a flight ready version of the NRX reactor, which would include a topping or bleed cycle to power the turbines, would have an Isp of about 900 s.

The tankage mass for the NTR was determined as being 0.15 of the propellant mass. This factor derived from the LH_2 tankage used in the chemical system study.

The dry-weight masses of the ship were also taken from the chemical study and totaled to 128,208 lb for the MEM, 112,690 lb for the mission modules, and 24,480 lb of probes.

The flight scenario is that the entire ship is launched from earth orbit, the probes are jettisoned before Mars Orbital insertion (MOI), the MEM is detached and remains in Mars orbit, and the remaining ship including all waste products are returned to Earth. Both an aerobraking maneuver (ABM) at Earth and Mars and a propulsive braking maneuver (PBM) are considered. The mass of the aeroshell was assumed to be 0.176 of the mass required to brake. The AV'S of the flight plan were 4.4289 (TMI), 2.7569 (MOI), 1.6238 (TEI), and 3.7246 (EOI) km/s. All propellant masses include an extra 15% for contingency and boiloff following the example of a previous Mars study. No mass penalties were made for post-burn cooldown of the NTR since the average Isp which was used included the penalty.

The propulsive NTR scenario assumes that 3 engines of 75,000 lb thrust are used in earth-orbit departure. After MOI, 2 engines are detached and are left in Mars orbit and a single engine is used on the return trip. The aerobraking-NTR scenario is similar except that only 2 engines are used for earth departure. The number of engines was chosen to produce thrust-to-weight ratios of near 0.20 in Earth orbit. This value was chosen following the results of a study which optimized thrust to weight ratios for maximum payload fraction for orbital launch. The mass of the engines includes an 11,000 lb shield for each engine which will allow approximately a 10 Rem dose to the crew from the engine burns.

The final calculation shown in the last column of Table I is for a combination of propulsive braking at Mars, where the ship is bulky and difficult to cover in an aeroshell, and of aerobraking at Earth where the mission modules should be easy to cover in a shell. Before EOI, the NTR is assumed to detach and boost itself into an appropriate helio-centric orbit, possibly the stable Legrange point, L_2, lying between the Earth and the Sun.

The masses in Table I show that the NTR has a significant advantage over chemical propulsion. The ratios of NTR mass to chemical mass for the entire ship in earth orbit are 0.64 and 0.35 for the aerobraking and propulsive braking scenarios respectively. The hybrid scenario mass is 26% of the mass for the chemical PBM scenario. The number of shuttle launches to put the difference of the respective masses into orbit for assembly are 8 and 46 for the ABM and PBM respectively, assuming 65000 lb per launch. At $0.15 billion per launch this equates to $1.2 billion and $6.8 billion in savings due just to launch the mass to orbit. Further savings will be incurred from reduced handling of the mass both on Earth and in orbit.

NERVA Program

In 1960, the Space Nuclear Propulsion Office (SNPO) was established by joint AEC/NASA agreement. The Nuclear Engine for Rocket Vehicle Application or NERVA program began in 1961 with selection of an industrial-contractor (I-C) team of Aerojet General Corporation and the Astronuclear Laboratory of the Westinghouse Electric Corporation (see Fig. 3). The I-C team was to "pursue the development of nuclear-rocket-engine technology with reactor designs based on the KIWI concepts" of the Los Alamos National Laboratory. The KIWI reactor was the product of project ROVER which began at Los ALamos National Laboratory in 1955.

The Nerva Program existed for 11 years and succeeded in developing and testing the NRX reactor ***series*** and the Phoebus reactor series as shown in Fig. 4. The NRX reactor operated between 1100 to 1500 MW and produced 75000 lb of thrust while the Phoebus reactor operated at 4500 MW and developed 250,000 lb of thrust. Characteristics of both engines are shown in Table 11. Both engines were tested at the Nuclear Rocket Development Station (NRDS) in Nevada with the NRX series being much more thoroughly developed. The NRX-EST and NRX-XE tests actually incorporated the non-nuclear system components such as LH_2 turbo pumps, valves, and regenerative LH_2 cooled nozzles in the tests at NRDS. By the end of the program in 1971, a fully integrated engine had been tested under simulated

TABLE II

ENGINE CHARACTERISTICS

	NRX	Phoebus
Power (MW)	1500	4500
$\dot{m}$ (lb/s)	92	285
Thrust (lb)	75,000	250,000
Tested Isp (s)	825	820
Mass (lb)	15,000	40,000

altitude conditions and efforts were shifting to define and develop a flight ready engine.

The budget for the NERVA program and the total costs of the entire rocket development effort are shown in Fig. 5. Clearly a major portion of the effort was the development of the reactor/engine with the next largest category being materials and non-nuclear component development. In the event that this nation would decide to build a nuclear engine for a Mars mission, much of the costs of the NERVA program would not be duplicated by the new effort. The KIWI, much of the Technology, and some of the NERVA categories would be removed. The magnitude of effort to build the engine will depend if only a redesign of the NRX or Phoebus engines is requested from existing data bases or if a redevelopment and improvement is desired. Reestablishing the capabilities existant at the termination of the NERVA program can probably be accomplished for under $2.5 billion (1985 $) as shown in Table III.

TABLE 111

ESTIMATED COSTS TO REBUILD A NERVA ENGINE

Engine Design and construction		1218	M$	(80% of NERVA)
Technology		377	"	(50% of previous)
NRDS:	Capital	460	"	
	Operating	210	"	
		2265	"	

The capital investment of NRDS is estimated by subtracting the value of the major facilities currently at NRDS which could be refitted and adding the cost of improvements estimated in a 1972 Los Alamos study.

In addition to the costs of rebuilding the engine, significant costs will be incurred to make the engine flight ready. Determining this expense is more difficult since only estimated requirements exist from the previous program. Furthermore, many of the costs previously estimated will already be incorporated in the new rebuilding effort. A reasonable estimate according to researchers who were involved in the previous program is $2-3 billion. Thus, a reasonable estimate for the cost of rebuilding a flight-ready nuclear-thermal rocket is between $4-5 billion.

Testing Feasibility

The estimates of the costs of a new NERVA type program are somewhat dependent on the ability to test the new engines when built. The NRDS at Nevada still retains some major facilities such as the EMAD building (for post test reactor analysis), the tank[9] farm for pressurized gases, and several large (up to 500,000 gal of LH_2) dewars. The possibility of refurbishing some of these facilities, the accessibility of the Nevada Test Site (NTS), and the existance of experienced operations and security personnel currently at the site make the testing of the engines at NTS appear quite feasible.

The major obstacle to testing at NTS will be the reduced levels of radioactive debris which are allowed to transport into the public domain. The levels are more stringent than those present during the NERVA program. The current exposure limits of 150 m Rem to civilian personnel may restrict the tests of the NTR to low power levels and mass flows in the reactor.

While low power tests may be sufficient for early tests and rebuilding, eventually a full power test will be necessary for flight readiness. A simple solution to this problem may be to utilize one of the Pacific Ocean Islands owned by the United States--namely Johnston Island **(JI).** Johnston Island is part of a large atoll lying about 700 miles southwest of Hawaii at 15°N latitude. The island currently supports an active military base, an airstrip and an active shipping port as seen in Fig. 6. **The advantages of using JI** for NTR testing are:

1. that several hundred acres of slightly submerged coral atoll can be dredged to make test stands or can be used to anchor test platforms;

2. constant easterly trade winds 10 months out of the year;

3. ecological desert of ocean surrounds the area due to the stagnation of the return of the Japanese current;

4. exposure limits for badged, base personnel are 500 m Rem;

5. several hundred miles exist to the nearest human settlement and a 100 mile warning radius can be extended into international waters.

6. a 100 channel telephone cable exists to the Hawaiian islands.

The Defense Nuclear Agency and U.S. Army currently have activities on the island so that personnel with security experience already exist on the island.

Clearly, construction of facilities will be more expensive at JI, primarily due to transportation costs. The general rule of thumb, however, is that facilities cost a factor of 3 more. Applying this factor to the capital costs in Table III, results in only a $1.4 billion increase if the entire NRDS facility were reproduced on JI. Since only the full power test stands may be needed, the use of JI may not entail a major cost increase at all!

The other option instead of testing at JI is to execute zero power tests at NTS, the still "cold" NTR could then be launched on the shuttle, docked with previously filled LH_2 tanks in orbit, and full power tested. Once completed, the NTR could launch itself into close heliocentric orbit for disposal. The increased difficulty, however, of post-burn analysis of engine components may preclude orbital testing.

Possible Development

Several improvements to the NRX engines are possible if time and budget allow for some development. Studies performed at the end of the NERVA program indicated that an Isp of 900 s was achievable and that the use of UC-ZrC fuels might allow an operating Isp of 975 s which would substantially reduce the required mass of the Mars ship in earth orbit. Even without a change in the nuclear fuel structure, improvements in the engine Isp may be possible by reducing the operating lifetime requirement from 10 h down to 3-5 h, thus allowing the reactor to run at higher temperatures. Furthermore, several new materials with improved qualities such as Mo-Re alloy and high strength ceramics have been developed in recent years and may significantly improve device performance.

An attractive concept which was developed in the early 1970s[10] was to operate the NTR in a lower power mode after the impulse burn to produce electrical power for the ship. Calculations at that time indicated that a closed loop rankine cycle using an organic working fluid could provide electricity for an additional specific mass of about 70 kg/KW(e). More recent developments indicate that a specific mass between 10-40 kg/ KW(e) is possible.

The development of the SP-1OO program and the associated technology has provided another avenue for dual mode NTRs. After the high power burn of the NTR, high temperature heat pipes may be inserted into the core. The heat conducted out of the core would then be used to operate thermoelectric converters to provide a fluctuating power level as required. The electrical power produced could even be of sufficient magnitude to power an electric propulsion system. Such a dual mode propulsion system employing a single set of reactors may provide the ideal symbiosis between impulse and continuous thrust systems and allow the shortest, feasible transit time to Mars of any near term propulsion systems.

Summary

An operating nuclear thermal rocket engine has been thoroughly tested during the NERVA program which ended in 1971. Estimates made at the end of the program concluded that the ground tested Isp of the engine of 825 s would equate to about 900 s in a flight-qualified engine. If NTR's were used for a Manned Mars Mission, the required mass in LEO would be reduced by almost a factor of 3. For the all propulsive braking scenario, this translates into about 1.6 million pounds instead of about 4.5 million pounds for the NTR and chemical systems respectively. The launch costs which would be saved would be greater than $5 billion. Preliminary cost estimates to rebuild the NRX engine tested in the NERVA program are between $3-5 billion. These estimates include the expense of building a full power test stand at Johnston Island in the Pacific Ocean. If an all propulsive-braking mission is planned or if multiple Mars missions are planned, the cost of rebuilding a nuclear rocket appears to be justified.

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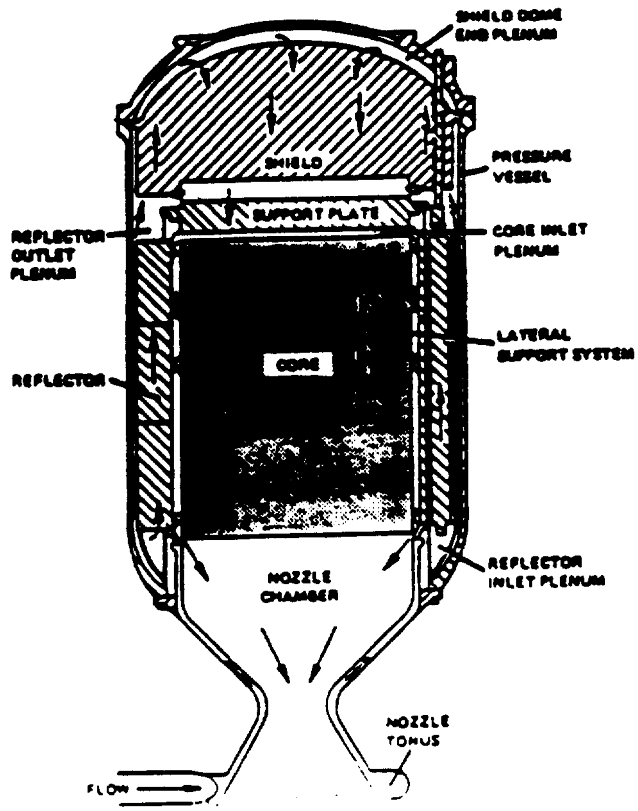


Fig. 1 . Solid core nuclear rocket diagram.

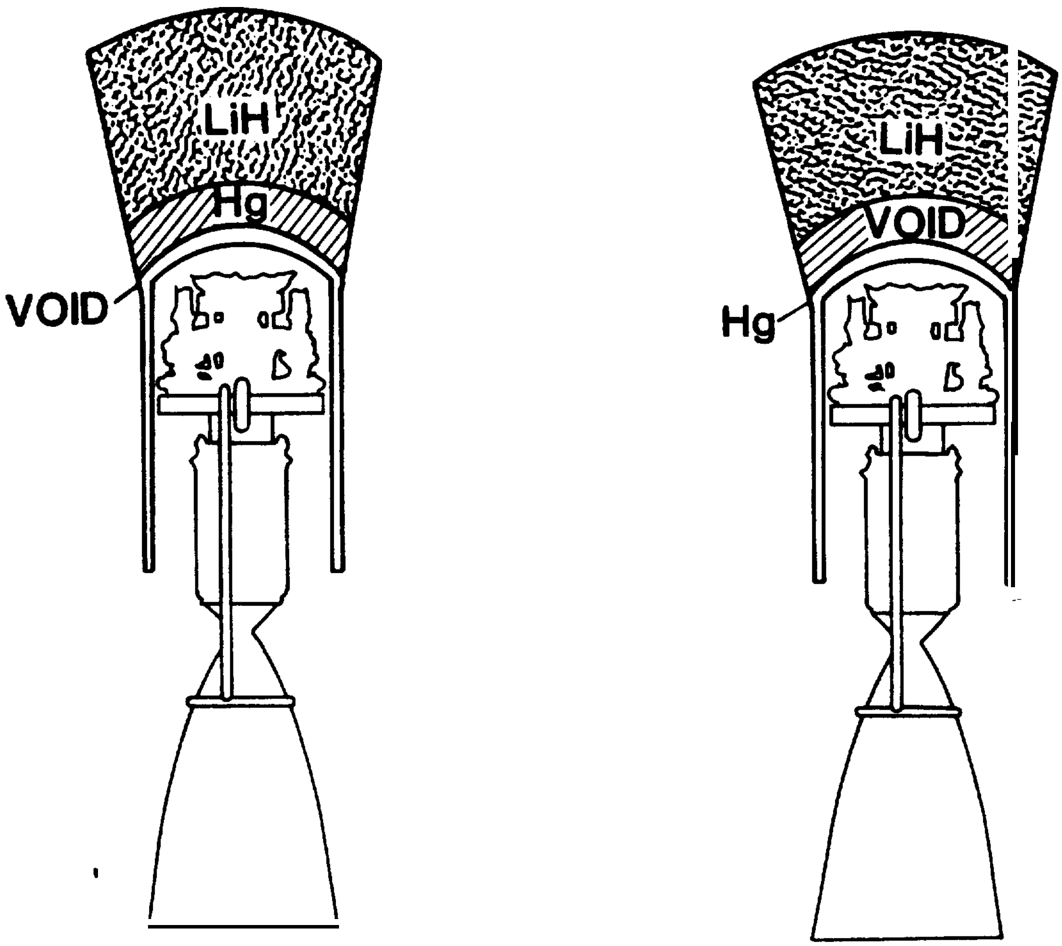


Fig. 2. Possible configuration of a moveable shield using mercury. The figure is to scale except for the plenum around the engine which was expanded for clarity.

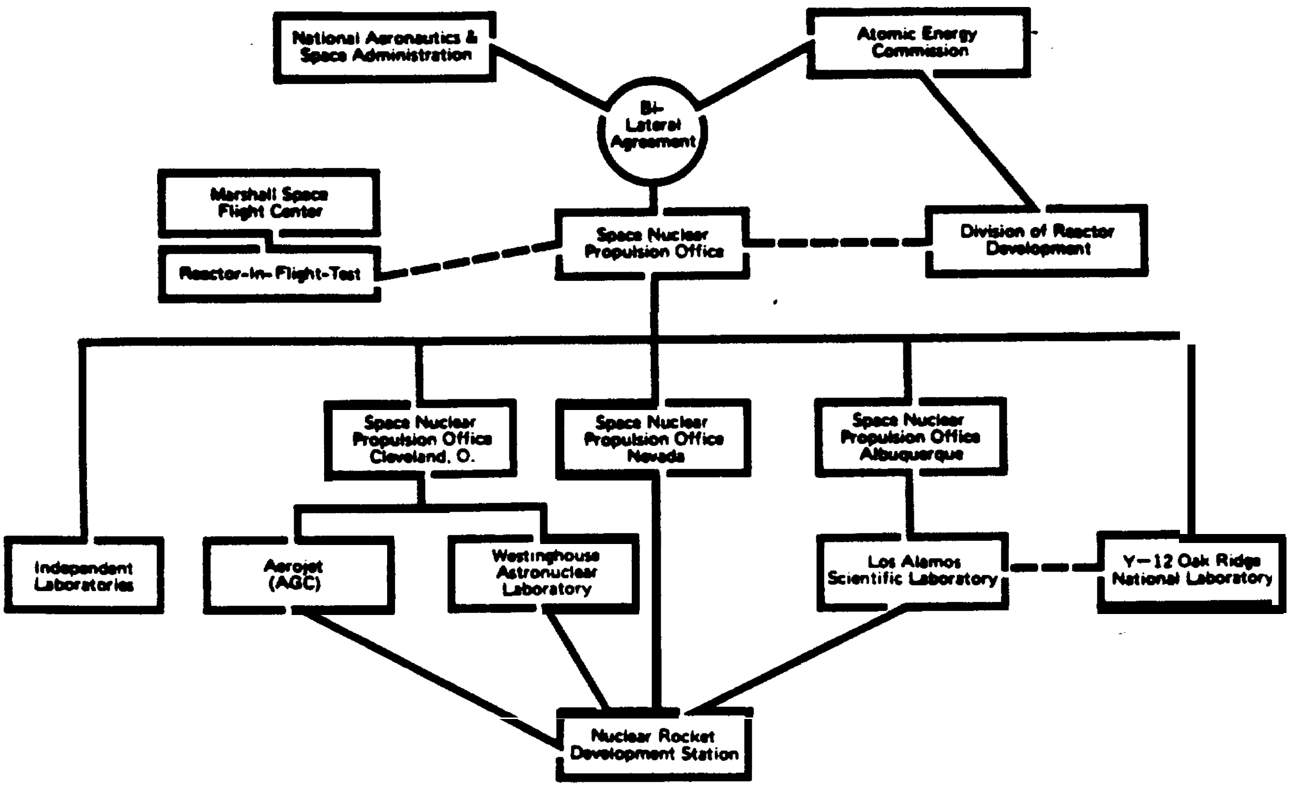


Fig. 3. Organization chart for the NERVA program.

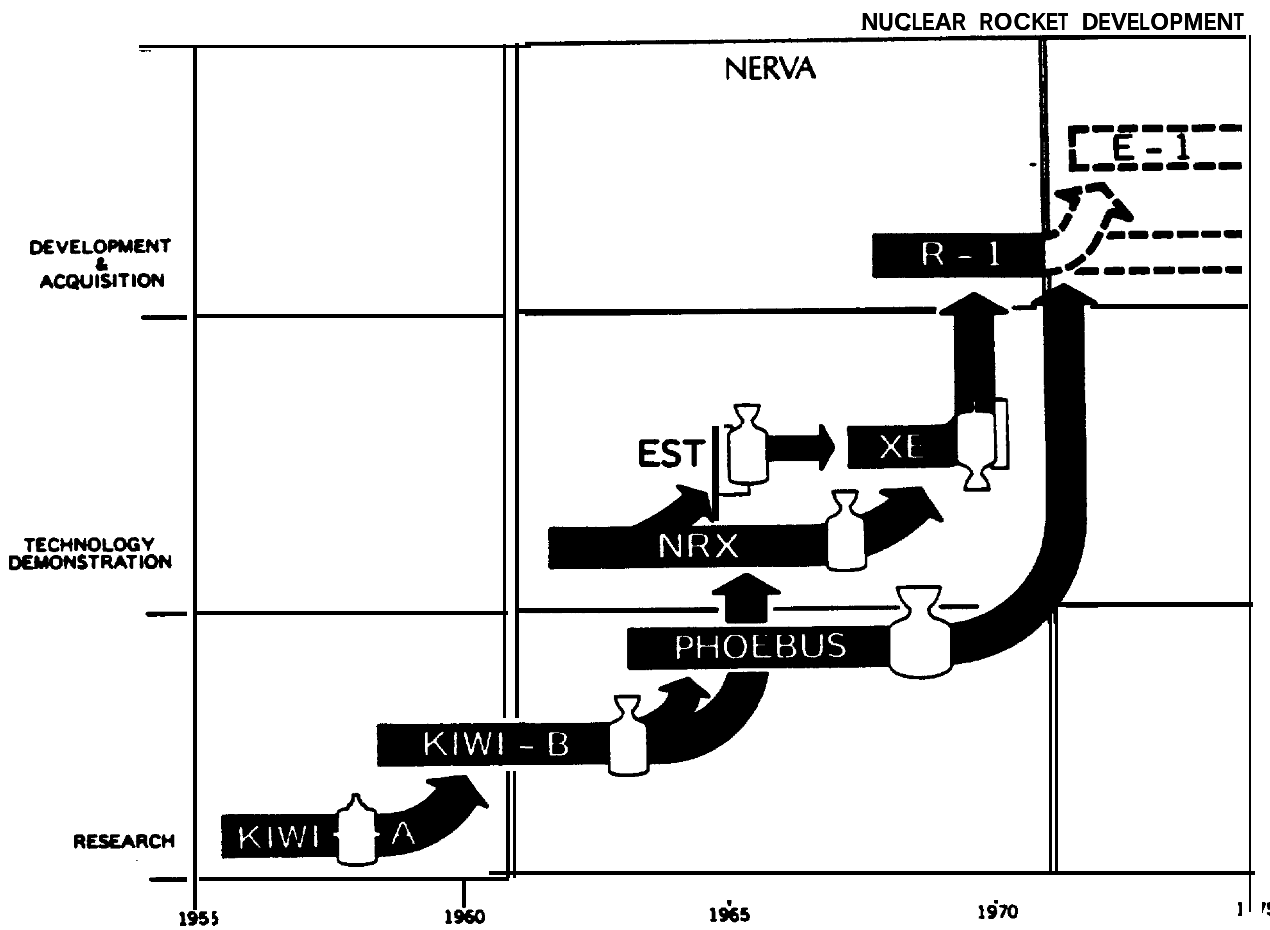


Fig. 4. Nuclear rocket development time line.

NERVA BUDGET (MS)

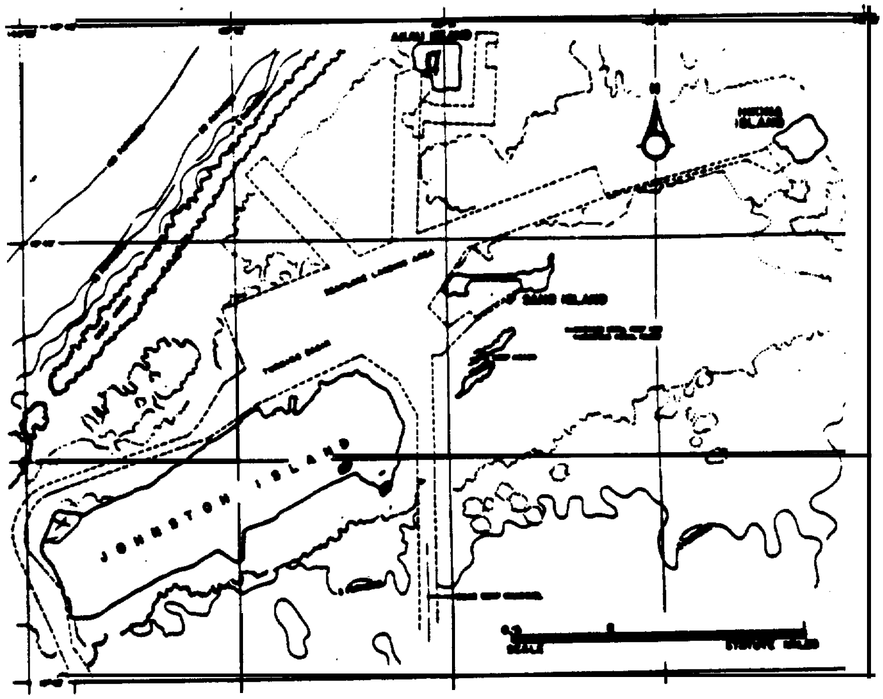
1962	63	64	65	66	67	68	69	70	71	72
20	58	84	80	70	72	65	53	53	50	25

TOTAL = 662

PROGRAM TOTALS (M$)

KIWI	177	Los Alamos
NERVA	662	Westing House (342/Aerojet)
Techology	328	Materials Development
NRDS	90	Operating
	153	Capital/Test Facilities
TOTAL	1410	AEC (866)/NASA (566)
Proposed NRDS Ugrades	112	1972 Estimate
	1522	
	(3501 in 1985 $)	

Fig. 5. NERVA program budget.



VICINITY MAP – JOHNSTON ATOLL

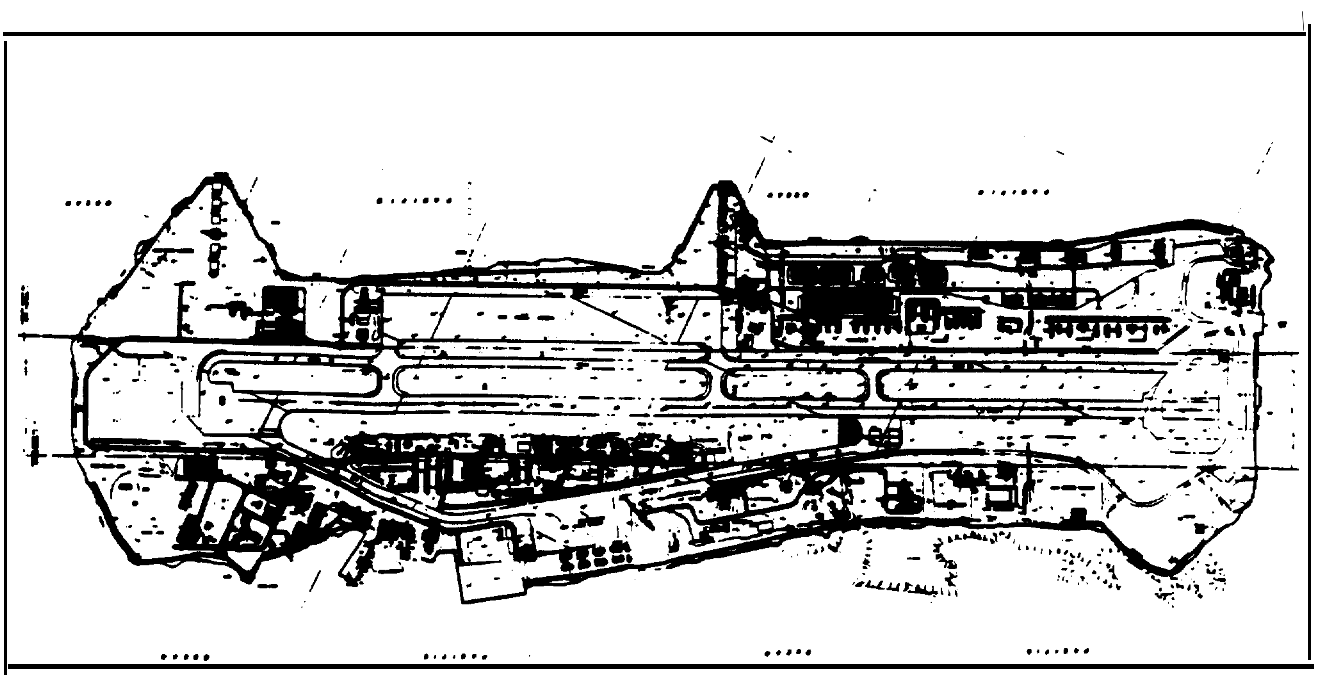


Fig. 6. Schematic views of the Johnston Atoll and Johnston Island.