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INFORMAL REPORT

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Nuclear Rocket Reference Data Summary

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of the University of California
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Prepared by

J. D. Balcomb

The Advanced Propulsion Comparison Study is being conducted by the AEC-NASA Space Nuclear Systems Office.

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NUCLEAR ROCKET REFERENCE DATA SUMMARY

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ABSTRACT

A brief description of the design and operating characteristics of a nuclear rocket engine is presented. The engine has a mass of ~ 2550 kg and is designed to operate at a specific impulse of 875 s for one hour at a thrust of 73 000 N or at a specific impulse of 860 s for two hours at a thrust of 71 700 N. The startup, shutdown, and cooldown performance characteristics are described. Operating characteristics special to a nuclear engine are summarized including radiation environment, nuclear criticality safety, prestart conditioning, and postrun deadbands. The technology status and proposed development schedule of the engine are discussed. The growth potential of the engine to a 975-s specific-impulse version incorporating carbide fuel elements is presented, and the potential of the reactor to double as a heat source for a long-term 10-kW electrical power supply is discussed.

I. INTRODUCTION

The data presented herein have been prepared in response to a requirement indicated by the Advanced Propulsion Comparison study* effort for a concise nuclear engine description and statement of its characteristics. Two types of engine are described: (1) the Alpha Engine, which is based on well-proven and conservative design concepts and which is proposed as a low-risk engine for initial flight operations, and (2) the Gamma Engine, which will more thoroughly exploit the performance potential of the nuclear engine and will become the work-horse design after the Alpha-Engine establishes basic operational characteristics and techniques.

II. NUCLEAR ENGINE DESCRIPTION

The Alpha design is undergoing preliminary definition studies at the Los Alamos Scientific Laboratory, and much more data are available for this design than for the Gamma Engine. The following description pertains to the Alpha design only; however, the operating characteristics for the Gamma Engine are similar, except as noted.

The principal function of the Alpha nuclear engine is to heat the hydrogen monopropellant to an average temperature of ~ 2700 K so as to achieve a maximum net specific impulse of ~ 875 s. The required heat energy is generated by fissions of uranium-235 in a small reactor core. An axial cross section of the engine is shown in Fig. 1. The reactor fuel is contained in hexagonal elements, as shown in Fig. 2, measuring roughly 1.9 cm (0.75 in.) across flats; these elements are made up of a composite mixture of graphite and a solid solution of UC-ZrC, and contain 19 flow passages each. Hydrogen is heated by passing through these holes, which are coated with a layer of ZrC to inhibit hydrogen corrosion. The reference design contains 564 of these elements in a core that has a diameter of 0.655 m (25.8 in.) and is 0.89 m (35 in.) long. The total core uranium loading is 60 kg (92.5% enriched uranium). Heating the 8.5 kg/s (18.75 lb/sec) of hydrogen flow to produce the nozzle-plenum condition at maximum specific impulse requires a total thermal power of ~ 367 MW and results in 72 975 N (16 406 lb) of thrust.

*The NASA-sponsored Advanced Propulsion Comparison Study is being conducted by the AEC-NASA Space Nuclear Systems Office.

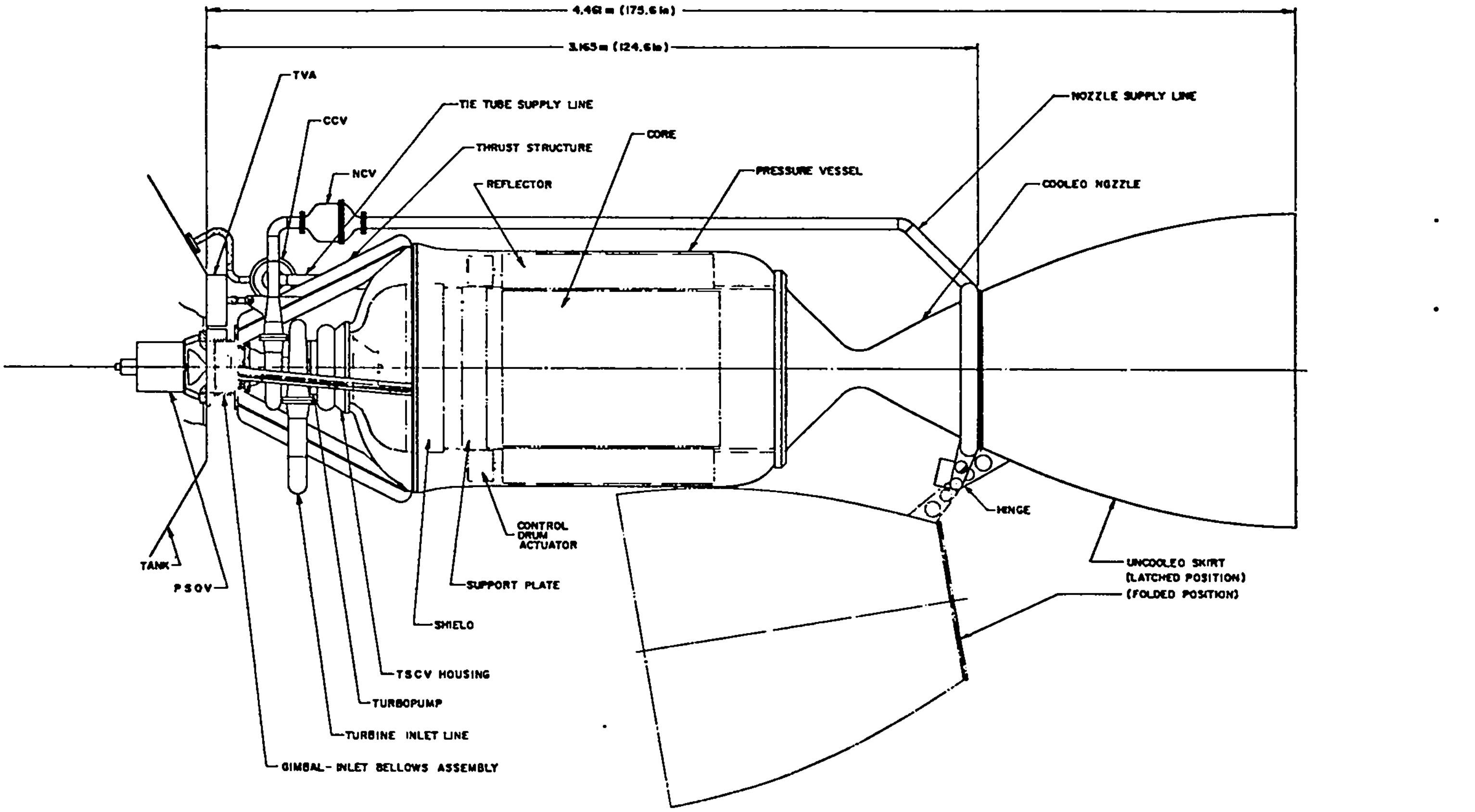

Fig. 1. Nuclear engine axial section.

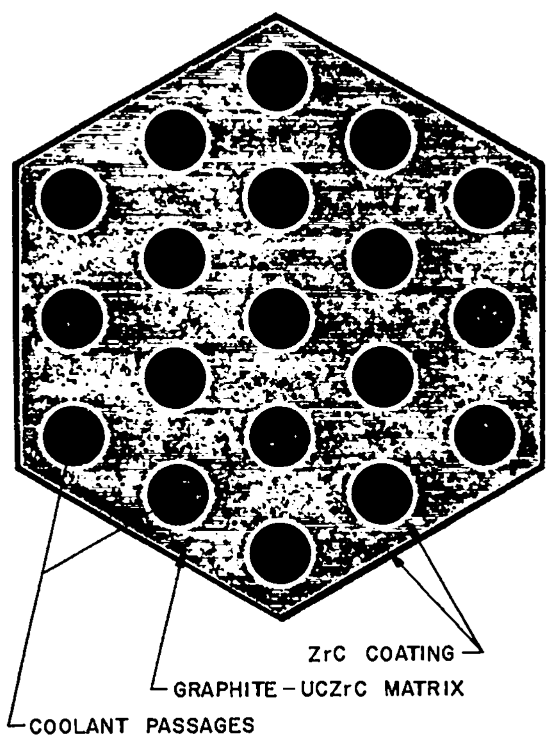

Fig. 2. Fuel element cross section.

Nuclear criticality in this nuclear reactor is achieved by the following three means:

(1) One out of every three positions in the hexagonal core array is occupied by an element that combines the functions of neutron moderator and core support (Fig. 3). These elements are of the same size as the fuel elements, but contain a zirconium-hydride moderator, a low-density ZrC insulator, and a metal tie tube which supports the entire core against the pressure-drop load of the flowing hydrogen. A cross section of a support element is shown in Fig. 4. These 241 elements are cooled regeneratively by passing 47.5% of the total hydrogen flow through the tie tubes; the flow then turns to cool the moderator and is subsequently used to drive the main turbine before it is returned to the core inlet.

(2) The core peripheral space, between the irregular outline defined by the hexagonal fuel pattern and the circular outline desired for the reflector, is filled primarily with beryllium slats, which are protected from the high core temperatures by low-density ZrC insulators. These slats are regeneratively

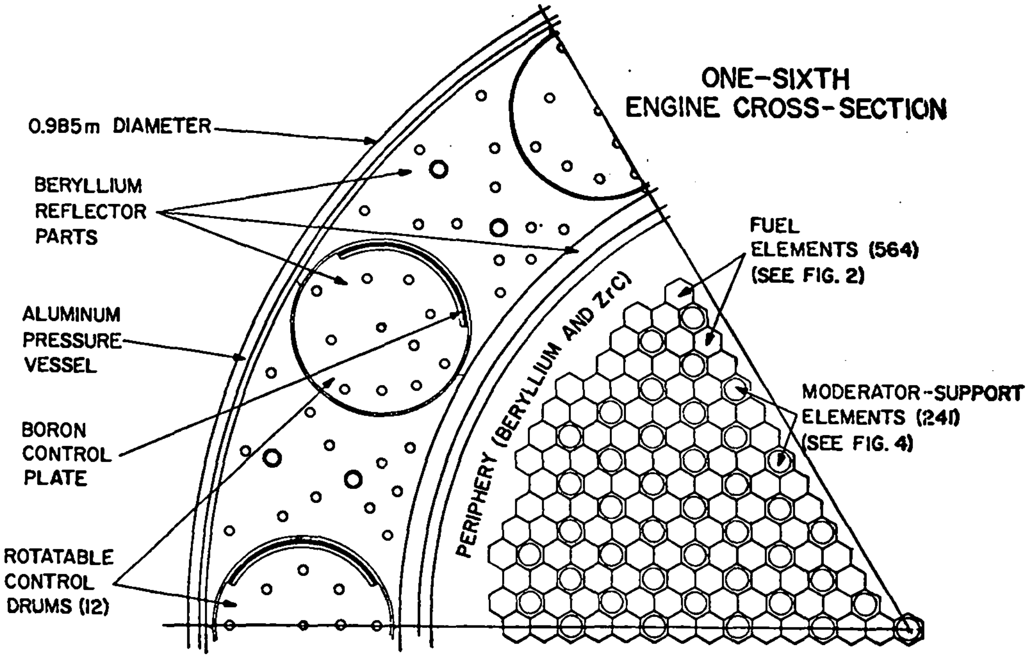

Fig. 3. One-sixth engine cross section.

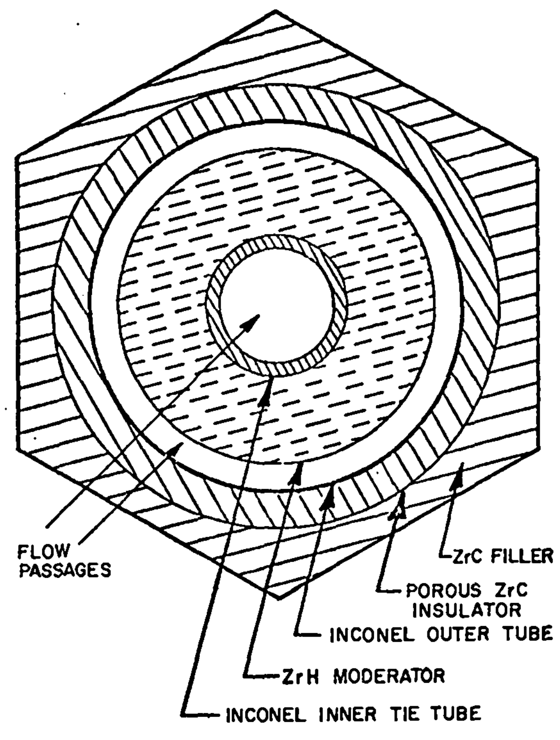

Fig. 4. Moderator/support element cross section.

cooled by 7.5% of the total hydrogen flow, in parallel with the tie tubes. These slats are, neutronically speaking, part of the reflector.

(3) The core is surrounded by a 0.142-m (5.6-in.)-thick annulus of beryllium metal, which is very effective as a neutron moderator and reflector. Nuclear criticality control is achieved by 12 circular solid drums of beryllium, which are covered over a 120-deg sector of their periphery with a boron-containing "poison" plate. Gang rotation of the drums changes the position of the boron plates, thus controlling the number of neutrons in the reflector which can return to the core without capture. The total control span is roughly 9.0¢ of reactivity. These drums and their drive mechanisms are the only moving parts housed within the reactor pressure vessel.

The reactor nozzle is a conventional, regeneratively cooled, U-tube design. The nozzle and the reflector are cooled in series by 45% of the hydrogen-coolant flow. This flow enters the nozzle at a torus located at the 25:1 area-ratio point, passes through thin-walled inconel tubes toward the core, and discharges into the reflector aft-end plenum. After passing through the reflector, this flow is mixed with the turbine discharge flow, and the combined flow then cools the shield, the core-support plate, and the core in series. The flow path is shown in Fig. 5.

The aft end of the nozzle, from the 25:1 area-ratio point to a 100:1 area ratio, is a lightweight uncooled graphite-fiber structure. This nozzle

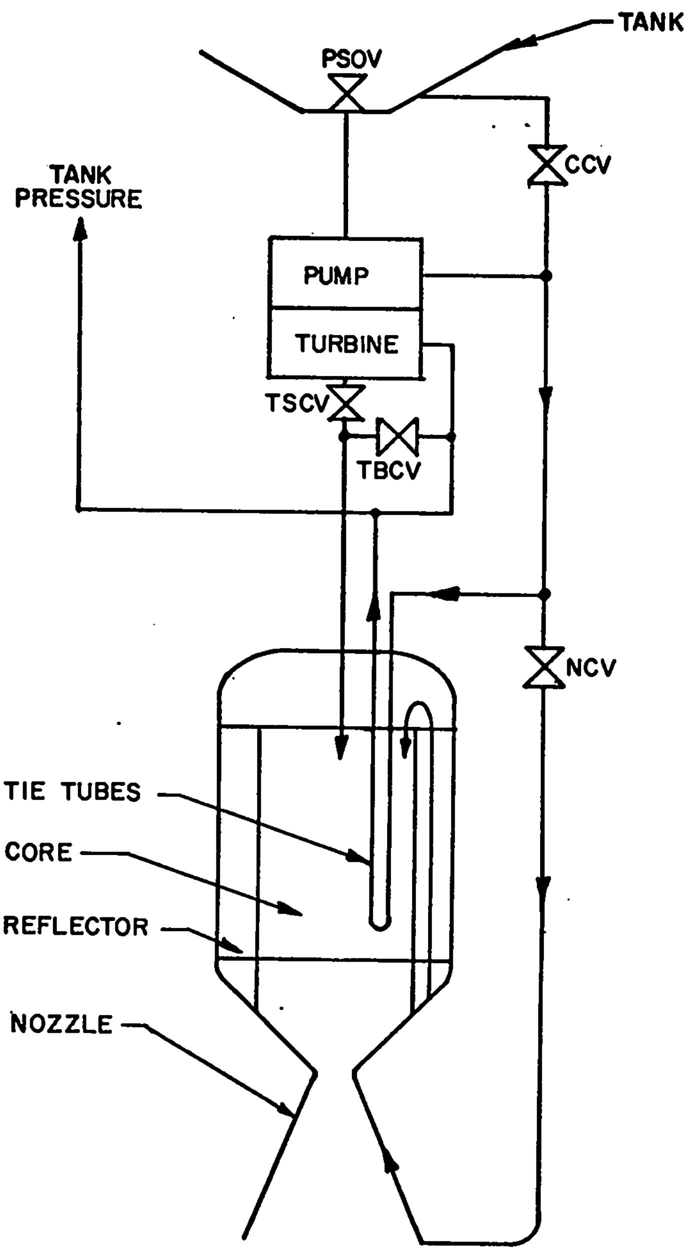

Fig. 5. Nuclear engine flow diagram.

skirt can be unlatched and turned back on hinges to be positioned alongside the cooled nozzle portion so as to reduce overall engine length for stowage inside the cargo bay of the space shuttle vehicle.

Hydrogen pressure is supplied by a turbopump with a nominal discharge pressure of 603 N/cm^2 (875 psia) corresponding to a nozzle chamber pressure of 310 N/cm^2 (450 psia).

The overall length of the engine is 3.165 m (124.62 in.) with the nozzle skirt folded back, and the mass is about 2550 kg (5623 lb). An engine mass statement is given in Table I.

TABLE I

NUCLEAR ENGINE MASS STATEMENT

	kg	lb
Reactor core and hardware	868.2	1914
Reflector and hardware	568.8	1254
Shield	239.5	528
Pressure vessel	150.1	331
Turbopump	40.8	90
Nozzle and skirt assembly	224.5	495
Propellant lines	15.4	34
Thrust structure and gimbal	27.7	61
Valves and actuators	206.8	456
Instrumentation and electronics	158.8	350
	2500.6	5513
Contingency	50	110
TOTAL	2550	5623

The engine is mounted as closely as possible to the hydrogen tank. Thrust-vector control is achieved by gimballing the entire engine. Chamber pressure (and thus thrust) is controlled by adjusting the turbine bypass valve, whereas chamber temperature (and thus specific impulse) is controlled by adjusting the reflector control-drum rotational position.

III. ENGINE PERFORMANCE

A. FULL POWER PERFORMANCE

The Alpha Engine design is based on operation at either of two full-power conditions as described below:

	State Point Condition	
	A	B
Duration, h	2	1
Operating cycles over duration	20	3
Specific impulse, s	860	875
Thrust, N (lb)	71 724 (16 125)	72 975 (16 406)

The 875-s design point is based on a maximum calculated fuel material temperature of 2880 K. The corresponding average fuel-element exit-gas temperature is 2730 K. The fuel-element weight loss by

TABLE II

STATE POINT DESCRIPTION

Operating Point	A	B
Reactor power, MW	354	366
Nozzle flow fraction, %	44.88	44.94
Turbine bypass flow fraction, %	10.70	11.81
Turbopump speed, rpm	46951	46738
Turbopump shaft work, MW	0.92	0.93
Pump efficiency, %	65.00	65.00
Turbine efficiency, %	80.00	80.00
Nozzle valve area, cm^2	2.63	2.63
Turbine control valve area, cm^2	2.70	3.02

	Flow Rate, kg/s		Pressure, N/cm^2		Temperature, K	
Operating Point	A	B	A	B	A	B
Pump inlet	8.51	8.51	12	12	17	17
Pump exit	8.51	8.51	595	603	19	19
Tie tube manifold inlet	4.06	4.05	565	572	20	20
Tie tube first pass exit	4.06	4.05	531	538	55	56
Tie tube exit	4.06	4.05	496	502	410	428
Slat manifold inlet	0.63	0.64	565	572	20	20
Slat first pass exit	0.63	0.64	518	524	164	167
Slat exit	0.63	0.64	496	502	421	431
Turbine inlet	4.19	4.13	480	486	411	428
Turbine exit mixed	4.69	4.69	407	413	399	415
Turbine bypass inlet	0.50	0.55	480	486	411	428
Nozzle inlet	3.82	3.83	456	463	21	21
Nozzle exit	3.82	3.83	415	421	233	240
Reflector exit	3.82	3.83	415	421	285	294
Shield inlet	8.51	8.51	400	406	347	361
Core inlet	8.51	8.51	390	396	356	370
Fuel element exit	8.33	8.33	306	310	2668	2728
Core bypass exit	0.18	0.18	306	310	356	370
Chamber	8.51	8.51	306	310	2634	2695

diffusion of carbon through the coatings is assumed to be, based on calculations, 12.3 g/element/h under these conditions. To provide for a two-hour duration, the fuel-element exit-gas temperature would be reduced by 60 K. This would result in a lower fuel-element mass loss rate (~ 9.2 g/element/h) and would provide a wider margin between the operating temperature and the limit.

State-point tabulations for these two operating conditions are listed in Table II. Recent calculations indicate that the actual specific-impulse predictions for these state points exceed the target values by about 6 s.

B. STARTUP, SHUTDOWN, AND COOLDOWN PERFORMANCE

Due to thermal-stress limits of the fuel elements and of other carbide reactor core components, the startup and shutdown transients are limited to roughly 83 K/s. Recent engine mapping and transient calculations were made with the engine computer model to estimate startup and shutdown transients for minimum propellant use within material temperature constraints. Indications are that the specific-impulse degradation during startup and shutdown may be decreased by a factor of two over early rough estimates that were based on linear thrust and linear temperature ramps. The run profiles are given in Fig. 6. Approximate values of the flow-rate and thrust integrals for these intervals are:

	Hydrogen Mass, kg	Impulse, N·s
Engine conditioning (30 s)	15.0	0.81 F_o*
Startup (26.4 s)	83.9	8.75 F_o
First 30 s of shutdown	95.5	9.75 F_o

*F_o = full-power thrust in newtons.

The specific impulse (averaged over engine conditioning, startup, full power, and the first

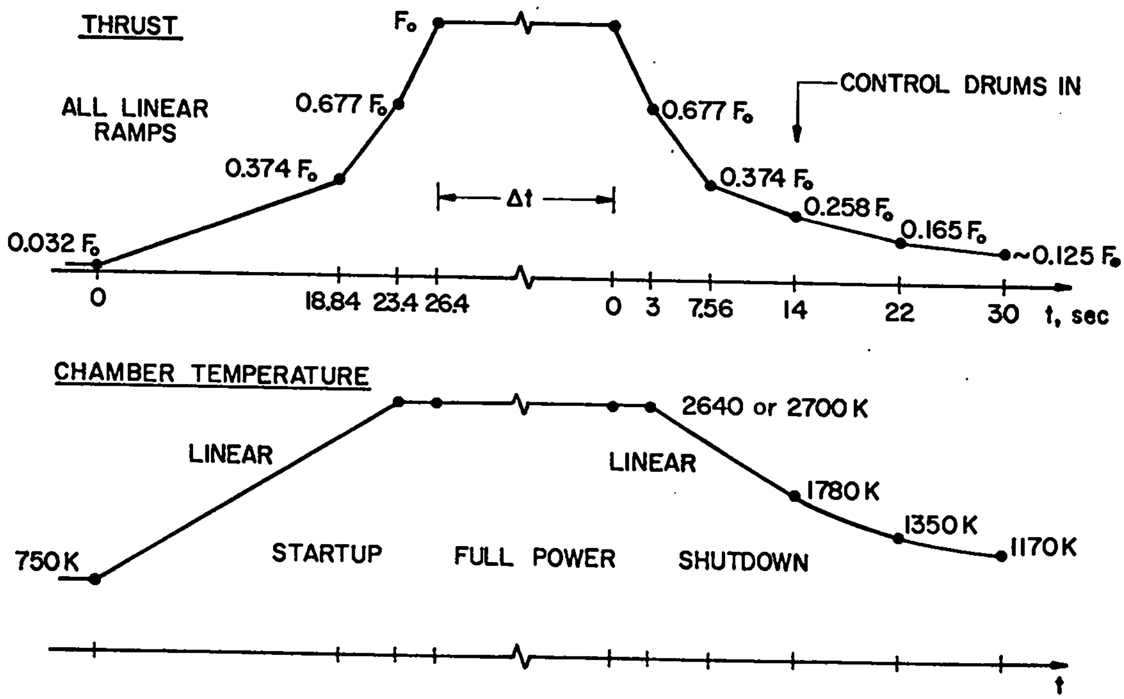

Fig. 6. Run profile.

30 s of shutdown only) is:

$$\frac{I_{sp}, \text{ av}}{I_{sp}, \text{ full power}} = \frac{\Delta t + 19.3}{\Delta t + 22.8}$$

where Δt is the full-power duration in seconds.

The shutdown of a reactor must be followed by a cooldown period to remove the residual heat generated in the reactor core as a result of the radioactive decay of fission products formed during the full-power run. This heat is generated in three types of decay: (1) fission chains triggered by delayed-neutron precursor decay, (2) beta decay, and (3) gamma decay. The fission heat drops off quickly and is virtually zero within about ten minutes, but the beta and gamma decay tail off more slowly and require some reactor cooling for a period of a day or longer, depending on run duration. The heat release rate is predictable and depends strongly on run duration, Δt.

An equation fit for the thrust profile through the final portion of shutdown and cooldown has been developed as follows:

Interval	Thrust/Full Power Thrust (F/F_o)
$30 < t < 2\Delta t$	$0.1781\ (t/20)^b$
$2\Delta t < t < t_c$	$0.05755(\Delta t + 20)t^{-1.25}$

where t = time measured after the beginning of shutdown, s

t_c = time of cooldown cutoff, s

$$b = \frac{\ln[0.3231\ (\Delta t+20)] - 1.25\ \ln(2\Delta t)}{\ln(\Delta t/10)} .$$

The power at which cooldown can be discontinued, t_c, has not been determined. A reasonable estimate can be based on the radiated energy from the pressure vessel to space at a temperature of 390 K. This power is roughly 7 kW. On this basis a rough estimate of t_c, in seconds, is:

$$t_c = 322\ (\Delta t + 20)^{0.8} .$$

During cooldown the specific impulse must be decreased gradually as the thrust decreases, to maintain material temperatures below operating limits. An equation for the specific impulse along the selected engine operating line is:

$$I_{sp} = 385\sqrt{1 + 7.6\ F/F_o},\ s;\ F/F_o < 0.374$$

where F/F_o = thrust/full-power thrust. This relationship indicates that, as the cooldown progresses, the specific impulse decreases asymptotically to 385 s, corresponding to an engine chamber temperature of 600 K. The upper limit for this terminal temperature has not been determined. It may be possible, as the analysis progresses, to increase this temperature and to improve cooldown performance.

These functions can be integrated to generate the total cooldown impulse obtained and the total cooldown coolant mass required as a function of run duration. The results are given in Figs. 7 and 8, respectively. These results are slightly higher than previous estimates, and the effect approximately compensates for the improved startup and shutdown performance.

The usefulness of the cooldown impulse to the mission depends greatly on where the thrust occurs and this is dependent on the specific mission being analysed. A practice which has been developed for estimating payloads is to define a cooldown effectiveness factor, f_{cd}, as follows:

$$f_{cd} = \frac{\text{reduction of required full-power impulse attributable to the cooldown}}{\text{cooldown impulse}} .$$

Appropriate values of f_{cd} can be determined for each burn by an orbital integration using the actual run profiles. Values determined in this manner can then be used for parametric analysis of similar missions. Typical values of f_{cd} vary from 0.6 to nearly unity.

If a fraction of the cooldown impulse, f_{cd}, is effectively utilized then an average specific impulse for the startup, full-power, shutdown, and cooldown sequences can be determined. This function is given in Fig. 9 for various values of f_{cd}.

IV. STAGE CHARACTERISTICS

A parallel effort to the nuclear-engine study at LASL is a design study of the associated vehicle, or stage, performed for NASA's Marshall Space Flight Center by the McDonnell Douglas Astronautics Co. (MDAC) under contract NAS8-27951. This Nuclear Stage Definition study is a comprehensive, continuing effort that has been redirected from similar studies performed for the NERVA engine.

For completeness of this report, Fig. 10 is included to indicate the characteristics of a typical nuclear stage as described in the MDAC study. It is a reusable stage consisting of a command and control module (CCM) docked to the forward end of an insulated and meteoroid-protected tank. Thrust-vector control is achieved by gimballing the engine. The stage is designed for hydrogen-propellant resupply in orbit, and is sized to fit within the payload bay of the Space Shuttle Orbiter leaving a 2.43-m (8 ft)-space allowance for payload. This stage can be used either alone or in conjunction with one or more propellant modules to increase the available propellant if needed for a particular mission. The maximum propellant module size that could be placed into orbit by the Space Shuttle Orbiter is 18.29 m (60 ft) although smaller units could also be considered. Typical mass estimates for these vehicles are:

	Initial Loaded Mass, kg (lb)	Usable Propellant, kg (lb)
Nuclear stage (including engine)	17 783 (39 205)	12 814 (28 250)
60-ft propellant module	23 181 (51 105)	21 265 (46 880)

V. SPECIAL OPERATIONAL CHARACTERISTICS

A. RADIATION ENVIRONMENT

1. Prerun Environment

Prior to the first burn phase, the reactor contains no fission products and is innocuous as a radiation source.

2. Payload Radiation Environment During Run

By power-plant standards, the engine reactor has a very high power density and is only lightly shielded. Thus it represents a large radiation source to its environment. Because the payload is forward of a large tank of hydrogen, the payload is very effectively shadow-shielded by the tank, its remaining hydrogen and all the engine components being forward of the core. Because the engine is operated in space, there is no scattering of the side-leakage radiation by the environment into the payload region. The 240-kg shield provided in the design is included primarily to reduce engine component heating rates by roughly a factor of ten. It also reduces propellant tank heating by roughly a factor of two and payload doses by a factor of nine. The dose rate at the payload increases by a factor of 50 as the hydrogen propellant is drained from the propulsion module tank. The total dose is obtained by integrating the rapidly changing dose rate over the entire profile, with 99% of the total being accumulated over the last half of the full-

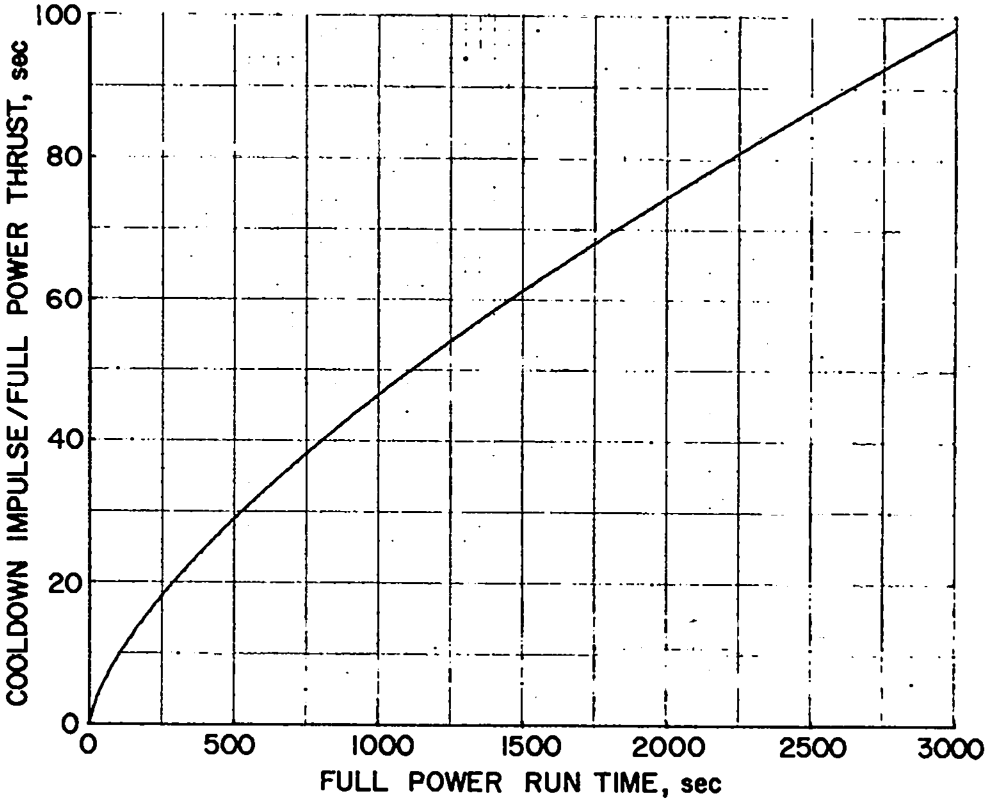

Fig. 7. Cooldown impulse.

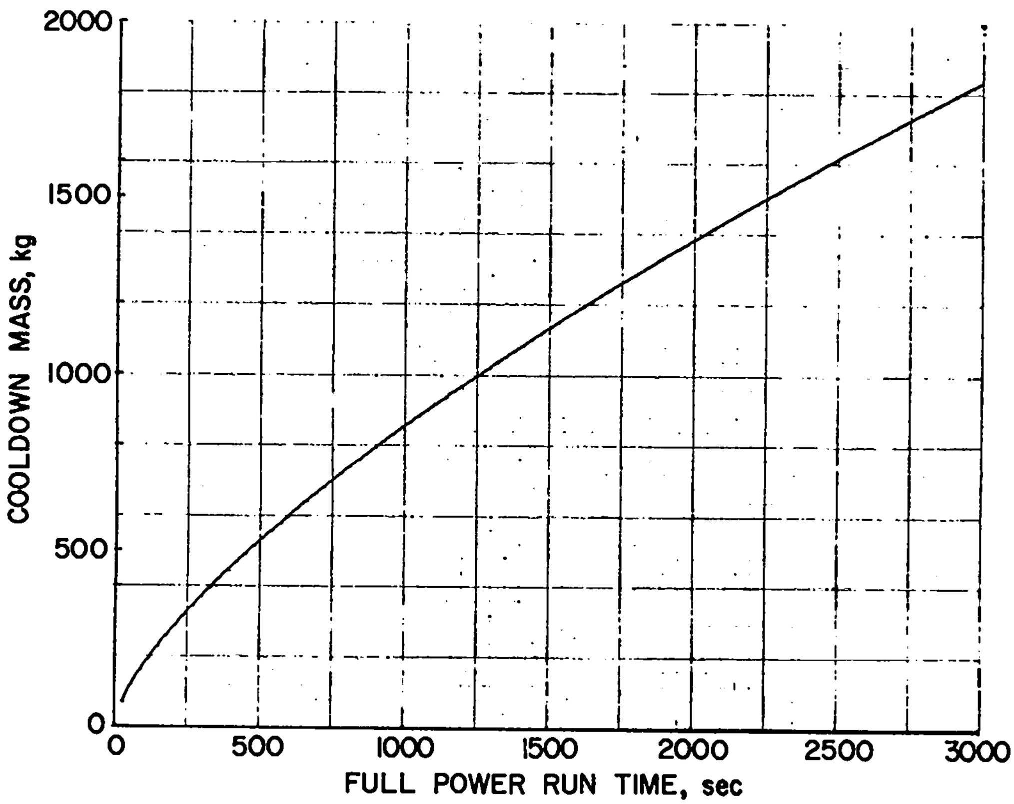

Fig. 8. Cooldown mass.

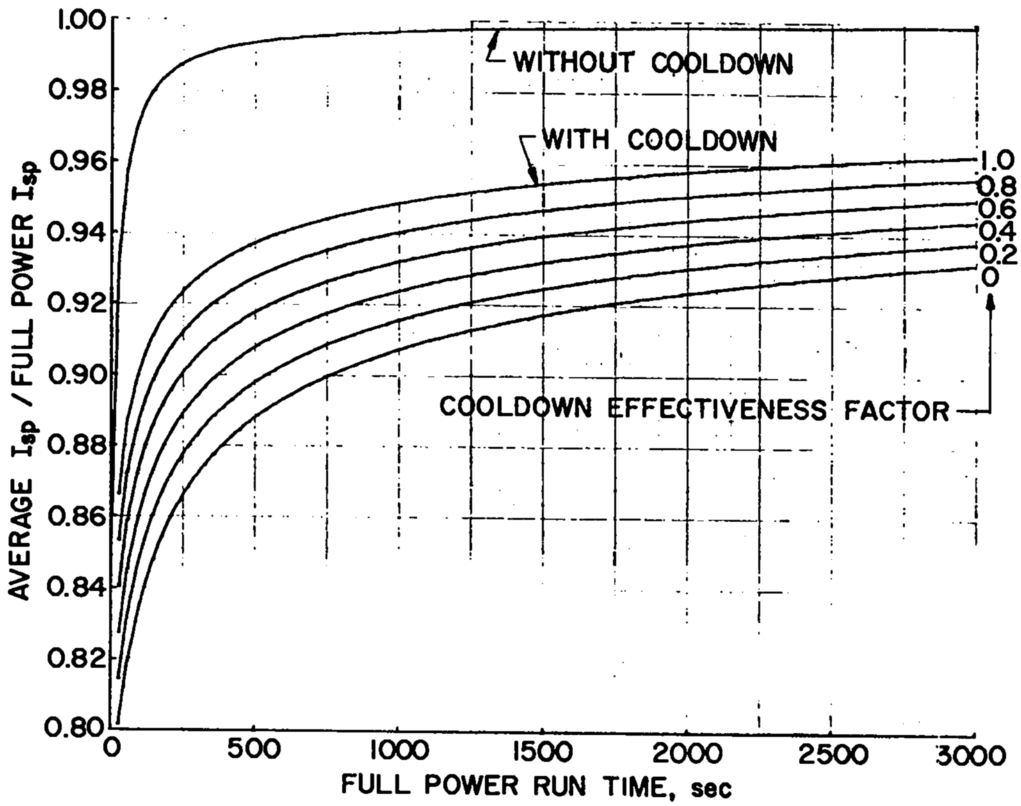

Fig. 9. Average specific impulse.

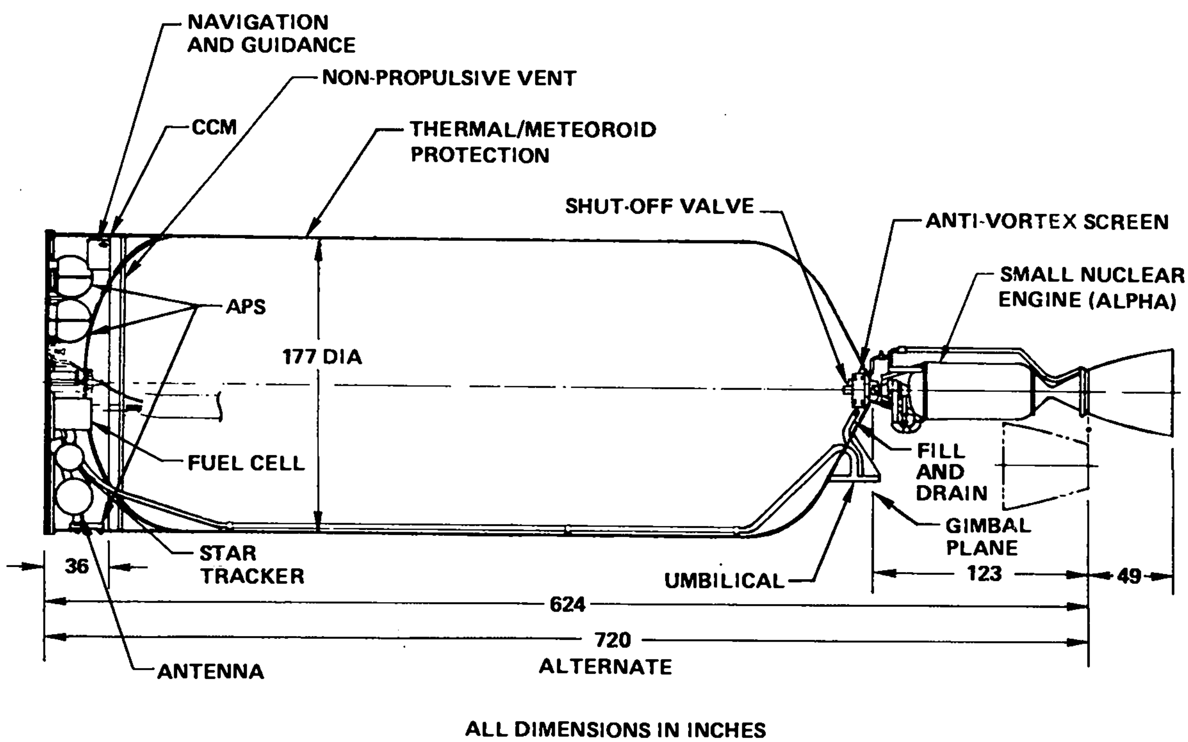

Fig. 10. McDonnell Douglas reusable nuclear stage concept.

power run and its cooldown. Estimated payload doses are:

	Neutron (Energy > 1 MeV)	Gamma
Maximum dose rate	10^7 n/cm^2·s	24 rad/s
Total dose	10^6 to 10^9 n/cm^2	1.3×10^4 rad

3. Post-Run Radiation Environment

The radiation field around the reactor decays rapidly during cooldown, and after about 0.5 h becomes basically a gamma field which diminishes roughly according to the following relationship:

$$\text{dose rate, rad/h} = 5 \times 10^7 \frac{\Delta t \; t^{-1.25}}{R^2},$$

where Δt = run time, s

t = time from end of run, s ($t > 2000$ s)

R = distance from reactor core, m ($R > 10$ m).

This relationship will apply at locations along a line-of-sight of the reactor. Both in the tank and forward of it the field is depressed due to the shadowing effects of the shield and other structure. The dose in the payload region is roughly 1/33 of the value predicted by the above relationship, provided the tank is empty.

B. NUCLEAR CRITICALITY SAFETY

Prior to launch, each engine will have been operated only briefly and at a negligible power level to determine the exact critical control-drum position for that particular core. After this operation, poison wires will be installed in the reactor core to provide an absolute safety precaution against a neutronic startup which would result from an inadvertent outward rotation of the control drums or from water flooding the reactor core. The poison wires will remain in the reactor through the prelaunch, launch, and subsequent man-tended operations in space. They will be removed remotely prior to the first startup. Once removed they cannot be replaced.

C. LOW POWER MODE

The engine can be used in a low power mode in which a low flow of hydrogen is heated to 700-1000 K. The turbopump is not used so that the hydrogen is either pressure-fed or fed from a small electrical pump in the cooldown line. Possible uses of this mode are:

- Tank prepressurization
- Orbit trimming
- Preburn maneuvers
- Midcourse corrections
- Propellant settling.

D. PRESTART CONDITIONING

Although no details are available, it is certain that at least the following two types of operation will be required prior to the 30-s bootstrap startup to full power.

1. Neutronic Startup

Neutronic startup is accomplished by a programmed positioning of the control drums to bring the reactor to critical, bring both power and core temperature up to the prestart level, and execute the transition to temperature control. This operation will require a maximum of roughly ten minutes.

2. Thermal Conditioning of the Turbopump

Trickle flow through the turbopump for a period of a few minutes will be required for thermal conditioning. This or other trickle flow can also be used to perform propellant settling in the tank.

E. POSTRUN DEADBANDS DUE TO XENON POISONING

After a lengthy full-power run, there will be intervals during which the engine cannot be restarted, due to the buildup of the radioactive isotope Xenon-135, which is a neutronic poison. These exclusion intervals will start three to eight hours after a full-power run and will last from a few hours to a day or slightly more. The duration will increase as the run duration increases. These intervals are not yet precisely known.*

*These deadbands apparently will not interfere with a normal one-module geosynchronous mission. They may affect the selection of intermediate orbits for perigee propulsion on escape missions.

VI. TECHNOLOGY STATUS - ALPHA ENGINE

A. INTRODUCTION

The design objective of the Alpha Engine has been to derive the greatest benefit from the technology developed over the 17 years of the nuclear propulsion program and thus to minimize development risks. The resulting engine combines the best and most straightforward application of the successful developments of LASL Rover and NERVA programs. In general, the design does not require any major technology advancements to achieve the desired goals.

B. TECHNOLOGY BASE

1. Fuel Elements

Although graphite fuel elements have been used during most of the program, composite fuel has been the predominant development effort at LASL since 1967. Composite fuel elements have been tested successfully in one reactor test (Nuclear Furnace-1) and in many hundreds of electrically heated runs over a wide range of conditions bracketing the design-point conditions. These highly reliable fuel elements are superior to the graphite elements originally developed. Neither the basic cross-sectional size nor their shape have been changed for this engine design, and all the manufacturing and test equipment is set up and operating at LASL. The shorter elements of the Alpha Engine (compared to Nuclear Furnace elements) are expected to present only routine development problems.

2. Reactor Neutronics

The core design, particularly the crucial use of zirconium-hydride center elements for neutron moderation, has been successfully tested in a very similar size and configuration in the Pewee-1 reactor.

3. Regenerative Core Support Cooling

The tie-tube design principle has been tested successfully in the Phoebus 1B and Phoebus 2A reactors.

4. Core Insulators

Low-density ZrC insulators will be used in the core instead of the traditional pyrolytic-graphite insulators. The change is being made because it is believed that ZrC is more reliable and inherently capable of longer life. The development of low-density insulators is progressing well, and such insulators will be incorporated throughout Nuclear Furnace-2 now being fabricated.

5. Beryllium Reflector and Rotary Drum Control

These principles have been tested in all but three of the 19 reactors in the nuclear rocket program.

6. Turbopump

The turbopump design appears to be straightforward although two areas may require development. These are the pumping of slush hydrogen (SH_2) and the further development of radiation-resistant bearing retainers in the event that the conventional Armalon retainers prove to be marginal. Based on the limited experience with SH_2, no large problems are anticipated. Existing radiation-damage data for Armalon indicate that these retainers should be adequate for the intended application, but confirmation is required.

7. Nozzle

A standard U-tube regeneratively cooled nozzle using conventional materials appears to be adequate, although confirmation of low-cycle thermal-fatigue resistance will be required. Development of the uncooled skirt is believed to be straightforward, but will be confirmed by scale-model testing.

8. Actuators

Development of the actuators is based on existing technology but will require radiation-hardening, particularly in the area of lubrication of gears.

9. Other Components

A sound technology base also exists for all other components including structures, valves, and instrumentation.

10. Test Facilities

Existing test facilities at the Nuclear Rocket Development Station on the Nevada Test Site will be used for ground-testing. The main new addition required is a "scrubber" effluent cleanup system, which has been tested successfully in 1/7th size during the Nuclear Furnace-1 test.

VII. GROWTH POTENTIAL

A. INTRODUCTION

Three primary improvements can be designed into future nuclear engines:

- A fuel-element change will allow a higher gas temperature and provide a higher specific impulse.
- A dual-mode system, if incorporated, will use the reactor to generate electric power for long periods of time when propulsion is not needed.
- The heat energy in the reactor will be used for such purposes as attitude-control thrust and payload heating.

The design features listed above are logical second-generation improvements to the state-of-the-art Alpha Engine.

B. SPECIFIC IMPULSE (GROWTH TO GAMMA ENGINE)

1. General

As discussed, the Alpha Engine is designed to use fuel elements and nozzles of existing technology. Increases in specific impulse can be anticipated by increasing the temperature level at the nozzle exit although many unknowns, technologically, will be involved in the design. A specific impulse of 975 s may be achievable in a core containing carbide fuel elements. This carbide-core engine is referred to as the Gamma Engine.

2. Fuel Elements

It is known that corrosion loss rates can be greatly reduced and temperature limits extended through the use of pure carbide, i.e., UC·ZrC, fuel elements. This material has been studied experimentally at IASL since 1969, and some preliminary work has been done on the design of a reactor core based on such fuel. By using carbide fuel elements the temperature limit of the exit gas can be extended from the present 2730 K to roughly 3150 K. This material is more brittle and cracks more easily under thermal stress than composites, and the core design must take this into account. Also, the carbide fuel is denser than composite fuel, which will increase the engine mass by roughly 260 kg. The carbide fuel technology program will continue at IASL in parallel with the Alpha Engine work.

3. Other Components

In striving for higher temperatures, components other than fuel elements may also be changed. The low-melting-point aluminum pressure vessel would be changed, and the nozzle may change from one incorporating a thin-walled cooling jacket to an uncooled structure. The latter change may or may not be advisable depending on engine and mission lifetime requirements, all of which will be affected by Alpha Engine flight experience and by the developing United States space program.

C. DUAL-MODE ELECTRIC GENERATING SYSTEM

A nuclear propulsion system possesses the singular advantage of using the reactor as a thermal-energy source for a long-life electrical generating system (dual-mode system). With the nuclear rocket engine as a thermal-energy source, power levels of 10 to 25 kWe for durations of two to five years can be achieved for more ambitious missions than are possible with the Pioneer or Mariner probes, at a mass expense less than that of currently envisioned space-power systems, such as SNAP-8 and the Brayton cycle. Some applications requiring these power levels are data transmission at high bit rates and side-looking radar mapping.

An additional advantage for dual-mode operation arises for outer-planet missions where the nuclear stage is used for orbit injection; namely, by operating the power system during reactor cooldown, the additional mass of the power system can be compensated by savings in cooldown propellant. Also, the electric-generating system can be operated during the transit for payload conditioning, vehicle attitude control, communications, and data transmission for scientific experiments such as mapping of the asteroid belt.

The power-conversion system is based on the Rankine-cycle using thiophene (C_4H_4S) as the working fluid. Thermal energy is removed from the reactor by circulating hydrogen through the core-support structure (tie tubes) and through the boiler of the power-conversion system (primary loop). The waste heat is rejected via a radiator encircling the propulsion module by circulating hydrogen through the radiator and through the condenser of the power-conversion system. For a typical 10-kWe electric generating system, the total additional mass (including the radiator and engine modifications) would be roughly 600 to 700 kg.

Only minor modifications to the Alpha Engine would be required to accommodate the primary loop. Such modifications include the substitution of a higher-temperature material (e.g., titanium) for aluminum engine parts that are in contact with the primary-loop hydrogen and the addition of valves (to isolate the primary loop during the propulsion mode and to isolate the tie-tube circuit during the electric-generation mode). Other modifications may provide cooling of engine parts, e.g., of the control-drum actuators during the electric-generation mode.

D. OTHER HEAT ENERGY USES

Other uses, in addition to the dual-mode use of reactor energy, will be made of this ready source. For example, it may provide redundancy in attitude control, which is important for overall mission reliability. Hydrogen heated within the reactor would be an excellent working fluid for an attitude-control system (ACS) because it is a simple monopropellant with a good I_{sp}.

Warm hydrogen could also keep certain payload components at a desired temperature, which would be especially important if manned missions were reactivated.

VIII. DEVELOPMENT SCHEDULE

A. ALPHA ENGINE

The proposed Alpha Engine development schedule includes a reactor test in 1976, seven engine ground tests, and a prototype flight test in 1979. An extensive component test program would provide suitable qualified components as required in the engine program. This schedule would permit delivery of the first mission-qualified flight engine in 1982.

B. GAMMA ENGINE

Gamma-Engine component development, especially of fuel elements, would proceed gradually throughout the Alpha development period. By 1980, Alpha flight data would be available to guide the Gamma Engine design studies. Dual-mode and ACS hydrogen supply would be added to the program. Because Alpha development experience would be available, engine development could begin in 1980, leading to a flight-qualified Gamma Engine as early as 1984.

NOTE

This report is an unclassified summary of work reported in LA-5044-MS consisting of Volume I, Engine Description (Confidential); Volume II, Supporting Studies (Confidential); and Volume III, Preliminary Program Plan (unclassified).

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