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Particle Bed Reactor Propulsion Vehicle Performance And Characteristics As An Orbital Transfer Rocket*

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ABSTRACT

The particle bed reactor designed for 100 to 300 MW power output using hydrogen as a coolant is capable of specific impulses up to 1000 seconds as a nuclear rocket. A single space shuttle compatible vehicle can perform extensive missions from Leo to 3 times GEO and return with multi-ton payloads. The use of hydrogen to directly cool particulate reactor fuel results in a compact, lightweight rocket vehicle, whose duration of usefulness is dependent only upon hydrogen resupply availability. The LEO to GEO mission has a payload capability of 15.4 metric tons with 3.4 meters of shuttle bay. To increase the volume limitation of the shuttle bay, the use of ammonia in the initial boost phase from LEO is used to give greater payload volume with a small decrease in payload mass, 8.7 meters and 12.7 m-tons. The reactor fuel elements consist of HTGR-type fuel particles 700 microns in diameter held between coaxial porous metal or ceramic frits forming annular elements through which coolant gas flows radially. Nineteen of these elements are arranged in a reactor core matrix with a canned ^{7}LiH moderator between them, forming a thermal reactor. The nominal core size is 40-cm diameter by 60-cm length, with a 5-cm liquid H_2 reflector. The incoming hydrogen gas flows through holes in the moderator cooling the moderator before entering the thin inlet plenum around each fuel element. The gas flows radially inward through the frits and packed particle bed exiting along the central channel of each element. The neutronic studies

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INTRODUCTION

The gas-cooled particle bed reactor can be used for direct heating of the propulsion gas for an orbital transfer rocket. When hydrogen is used to cool the nuclear reactor, the specific impulse approaches 1000 seconds, which is more than twice that of chemical rockets. Reactor power levels of 100 to 300 megawatts are possible from a small particle bed reactor, which provide thrusts high enough to perform true Hohmann orbit transfers.

REACTOR DESIGN

The reactor design that produces the high gas temperatures of up to 3500 K is of the particle bed fuel technology design. A typical fuel is made up of particles 700 microns in diameter each with a 300 micron kernel of zirconium carbide, which contains several percent of uranium carbide. The uranium carbide is in solid solution in the zirconium carbide and has a melting point of about 3600 K. The 300 micron kernel is coated with alternating layers of porous carbon to contain the fission products, a pyrocarbon barrier, silicon carbide, and zirconium carbide for hydrogen resistance. The superior heat transfer of the small particles, which allows the high power densities of 10 kW/cm^3 is readily evident from their large surface area (86 cm^2 per cm^3), and the heat transfer coefficient of the high velocity gas, which flows over them. The film temperature difference is about 100°C. The fuel has been tested at Brookhaven National Laboratory in beds at high power densities. The fuel has also been tested as HTGR fuel at Oak Ridge National Laboratory, General Atomic Company, and Los Alamos Scientific Laboratory, ref. 1, 2, and 3.

The particle bed is held between concentric porous cylindrical frits. The coolant gas flow is radially inward to the central channel, exiting axially to the rocket nozzle, see Fig. 1 and 2. The fuel is held in nineteen fuel elements arranged in a triangular pattern within the zirconium hydride or lithium-7 hydride moderator (Fig. 3). The reflector around the core has been varied from a stainless steel vessel, to beryllium metal, to zirconium hydride to cold hydrogen gas depending upon the reactor weight desired and reactivity control method. The core size is optimized at a 40 cm diameter and 60 cm length with the overall reactor size at a 56 cm diameter and a 100 cm length with a minimum weight of 300 Kg (see Fig. 4). The design parameters for the base case reactor is shown in Table 1 (Fig. 5).

The Mark-2 reactor using reflector reactivity control is shown in Fig. 6. The cold hydrogen gas at 1500 psi is fed to the outside region of the reactor where radiation heating warms the hydrogen from 30 K to about 100 K. The hydrogen then passes upward through the fuel elements to be heated to 2750 K before reaching the rocket nozzle. The reactivity of the reactor is controlled by the temperature of the hydrogen in the reflector. As shown in Figure 7, the critical multiplication constant for a 4.0 Kg uranium-235 loading requires that the average hydrogen temperature be about 50 K. A 4.5 Kg uranium-235 loading is critical when the average hydrogen temperature is 110 K, while a 5.0 Kg uranium-235 loading cannot be controlled with a 5 cm H_2 reflector. Table 2 (Fig. 8) lists the characteristics of the Mark-2 reflectivity control reactor.

MISSION STUDY

For the study, the orbital transfer vehicle (OTV) begins operation at an altitude of 150 nautical miles above the earth in low earth orbit (LEO) and reaches geosynchronous orbit (GEO) at 19,365 n-miles within 5.28 hours. The volume and lift capability of the space shuttle are used as limitations on the various missions. The bay cross-section available is four meters in diameter with a length of 17.7 meters (see Fig. 9). The shuttle lift capability of 29,500 kilograms is used to carry the OTV and its payload to LEO in a single mission.

Five basic missions were calculated; 1. LEO to GEO, 2. LEO to Polar orbit, 3. LEO to GEO and drop package, go to three times GEO altitude, back to GEO with payload, 4. LEO to 3x GEO, back to GEO with payload, 5. LEO to GEO, drop package, reverse direction with payload. The studies for the five missions assumed the necessary fuel volumes as well as the equipment that fit within the shuttle bay volume. One of the limitations is that the bay is volume limited when using hydrogen as a propellant rather than weight limited. To allow more volume for payload, the more dense coolant ammonia was substituted for hydrogen in the initial boost phase from LEO orbit, and hydrogen used for all subsequent propellant thrusts. An additional option to the missions was the ability to jettison the empty ammonia tank. The ammonia is carried in a toroidal tank surrounding the reactor and rocket nozzle and is released rearward (see Fig. 10).

The volume available for the payload is reported as the bay length in meters because the shuttle bay cross-section is constant at a 4-meter diameter (allowing side clearance). The payload weight is the difference between the shuttle lift capability (65,000 lbs.) and the weight of the propellants, reactor, rocket chamber-nozzle, tanks, and structures required reported in metric tons (2,200 lbs).

RESULTS

The number one mission, LEO to GEO, using all hydrogen propellant has the highest payload of any mission -15.4 metric tons (34,000 lbs) and an available bay length of 3.37 meters (11.0 ft). This is compared in Fig. 11 to the Centaur G' rocket that has a payload of 6.0 metric tons and payload length of 9.15 meters. The other missions of increasing complexity are also shown with decreasing payloads and lengths. The payload length becomes negative for the fourth and fifth missions, which are not possible with hydrogen.

The use of ammonia as the initial coolant-propellant in the reactor reduces the payload as shown in Fig. 12 by 17% for the first mission; however, the payload length increases to 8.68 meters (see Fig. 5). All five missions now become possible and are compared in Table 2 (Fig. 13). The payload length is a minimum of 4.5 meters on the most complex missions, and this may be sufficiently large. Payload weights and sizes will require that the propellant quantities of NH_3 and H_2 be proportioned to fit the particular case. The jettisoning of the empty ammonia tank is an important saving of vehicle weight in the multiple thrust missions.

In addition to the five basic missions, two missions were added that returned the OTV to the so-called high LEO. Hi LEO is a 250 n-mile high orbit with a long orbit decay time (hundreds of years) and is considered a nuclear safe orbit with sufficient fission-product decay time for the very low fission-product inventory. This orbit will allow the possibility of refilling propellant tanks or the discharge of reactor fuel prior to returning the OTV to earth.

The first of the two is the single LEO to GEO mission with return to Hi LEO. Using all hydrogen propellant, the payload is high (7.5 m-tons) but with no room in the shuttle bay for payload. This configuration could be used for satellite retrieval from orbit. When ammonia is used prior to the hydrogen payload, room becomes available at the cost of 1 to 2 m-tons of payload weight (see Fig. 14). A mid-LEO jettison of the ammonia tank allows a 5.5 m-ton payload with 2.2 meters of shuttle bay room. An after-LEO jettison of the ammonia tank gives a 4 m-ton payload, but a large 6.5 meter shuttle bay length.

The second mission of the two is LEO to GEO with the deployment of a 2 to 3 m-ton payload, continue on to three times GEO altitude with the rest of the payload, whose weight varies with reactor gas temperature and mode of tank jettisoning, either mid or after-LEO "burn" (see Fig. 15). A mid-LEO tank jettison provides very little room for payload (0.2 to 0.4 meter), while after-LEO provides 4.5 to 5.0 meters. After-LEO reduces the balance of payload to about one m-ton with two tons deployed using reactor temperatures of 3250 and 3500 K. The return from 3 GEO to GEO allows the pickup of the original deployed payload including exchange of on-board payload and return to Hi LEO. There is an area in Fig. 15 that indicates conditions that exceed the shuttle capability, and is an area that becomes smaller as the reactor temperature rises. The return to Hi LEO allows the discharge of payload for shuttle pickup, and possible reuse of the OTV.

SUMMARY AND CONCLUSIONS

This analysis indicates that a nuclear powered OTV greatly increases payloads for GEO and extra-GEO missions by two to three compared to a chemical hydrogen-oxygen rocket. The nuclear OTV enables new extra-GEO missions to be performed, including parking in ultra-high orbits and returning to GEO with a spare satellite, also the transfer to retrograde GEO orbits upon command. When shuttle compatible conditions are imposed, reasonable payload volumes become available with the use of ammonia propellant for the initial thrust and hydrogen propellant for the balance of the thrusts, at only a 15% reduction in payload. The reactor used is small and lightweight, of the HTGR particle bed technology with a critical loading of about four kilograms of uranium-235. The total reactor weight of 300 Kg can produce 200 megawatts of power at a gas temperature of 2750 K (4490°F). The short operating time, of about an hour, produces negligible radiation damage, fuel burnup, an fission product buildup. The reactor can be disposed of, after use, into a non-returning orbit.

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REFERENCES

Hollabough, C.M., Wahman, L.A., Reisurg, R.D., White, R.W., and Wagner, P. "Chemical Vapor Deposition of ZrC Mode by Reactions of $ZrCl_4$ with CH_4 and With C_3H_4," in J. of Am. Nuc. Soc., Vol. 35, No. 2, (1977). Los Alamos Scientific Laboratory, Los Alamos, NM.

Kaae, J.L., Sterling, S.A., Yang, L. "Improvements in the Performance of Nuclear Fuel Particle Offered by Silicon Alloyed Carbon Coatings," in J. of Am. Nuc. Soc., Vol. 35, No. 2, (1977). General Atomic Co., San Diego, CA.

Morgan, M.T., Malinaukas, A.P. "Cesium Release and Transport in Biso-Coated Fuel Particle," in J. of Am. Nuc. Soc., Vol. 35, No. 2, (1977). Oak Ridge National Laboratory, Oak Ridge, TN.

Perkins, Capt. D.R. "Preliminary Analysis and Comparison of Recoverable Space Based Orbit Transfer Vehicle for LEO to GEO Missions," (1983), Air Force Rocket Propulsion Laboratory, AFRPL-TR-83-029.

Solon, M. Shuttle Bay drawing by Grumman Aerospace Corp., Bethpage, N.Y., (1985).

FIGURE 1

BASELINE FUEL ELEMENT & MODERATOR BLOCK

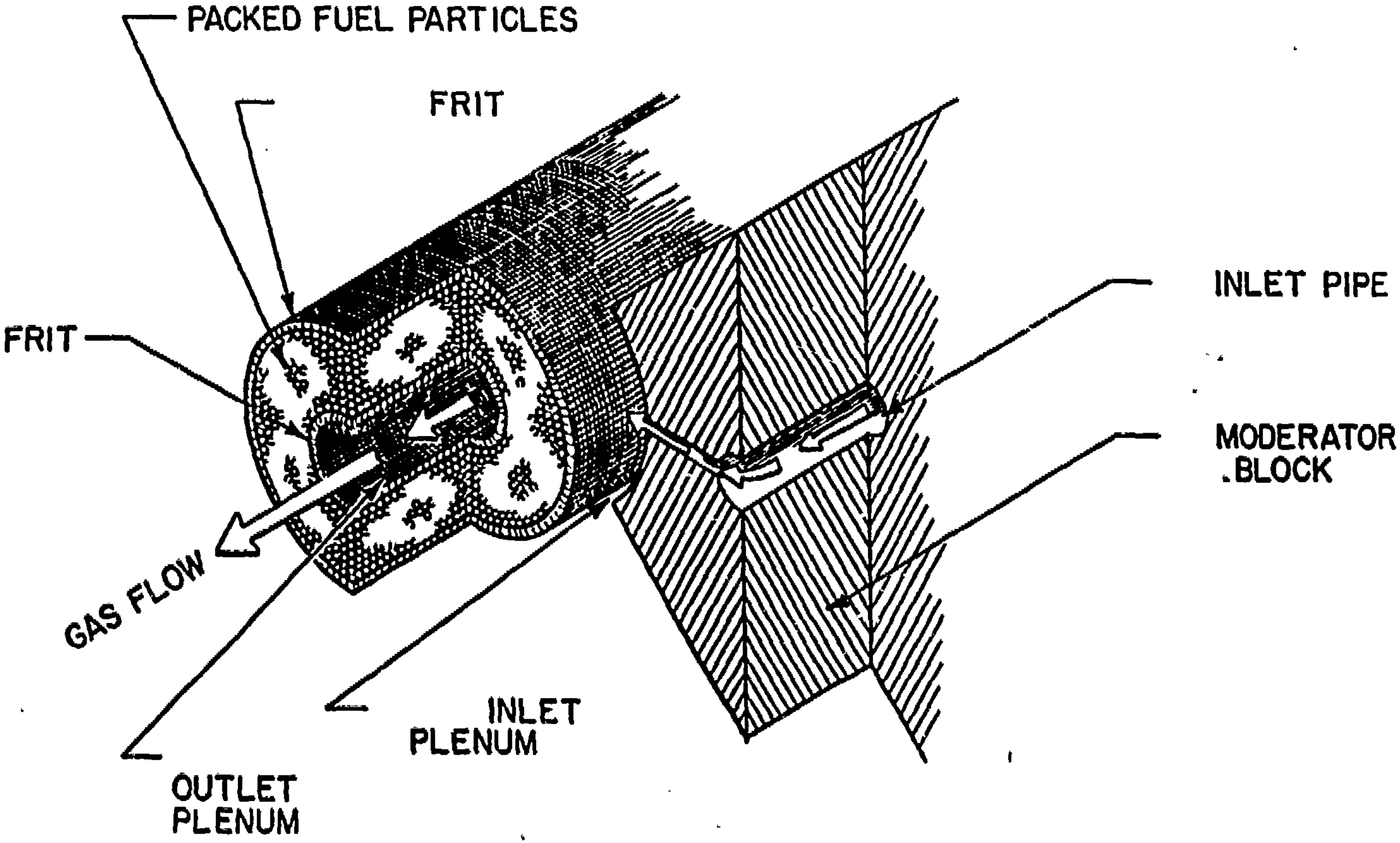


FIGURE 2

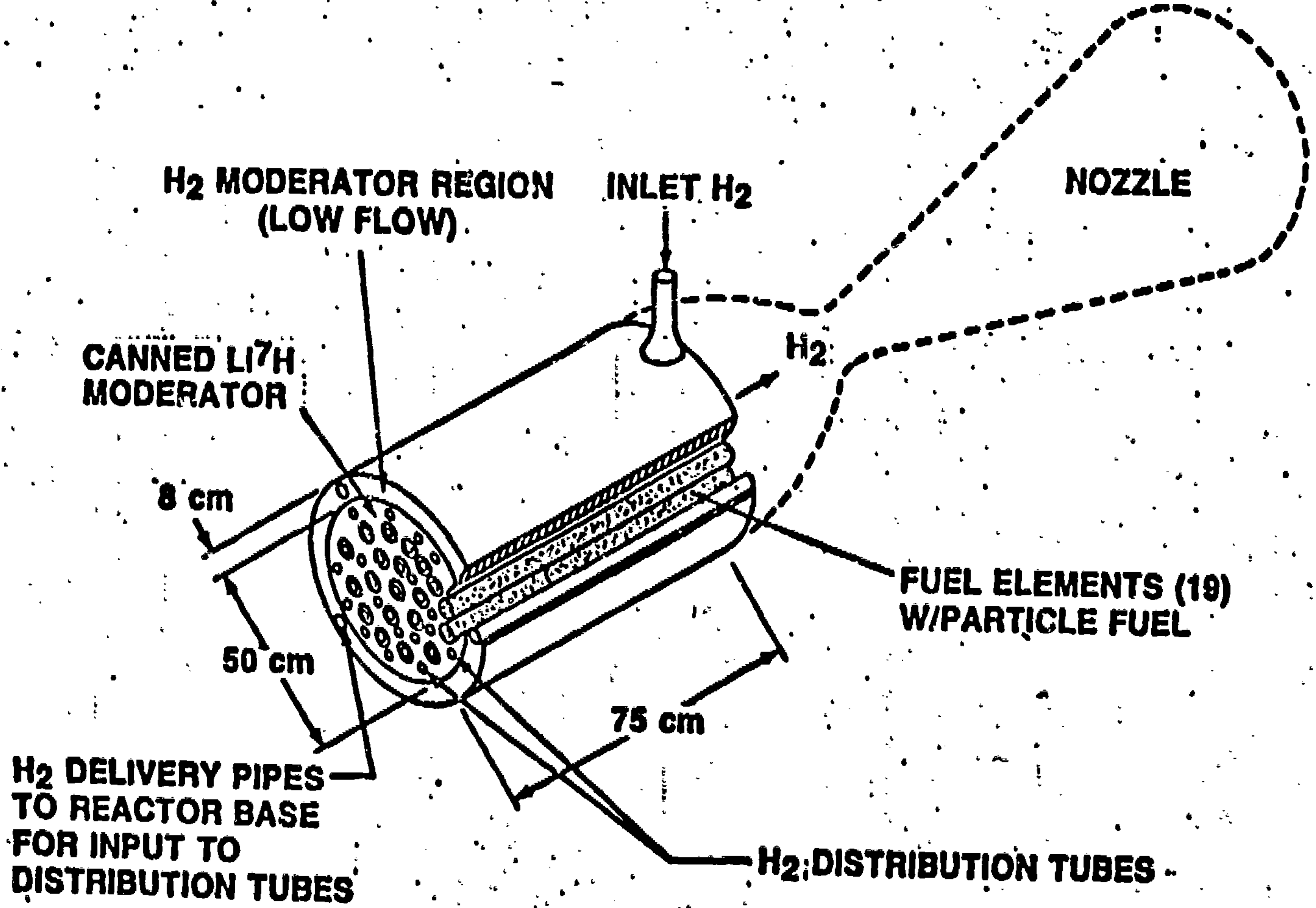
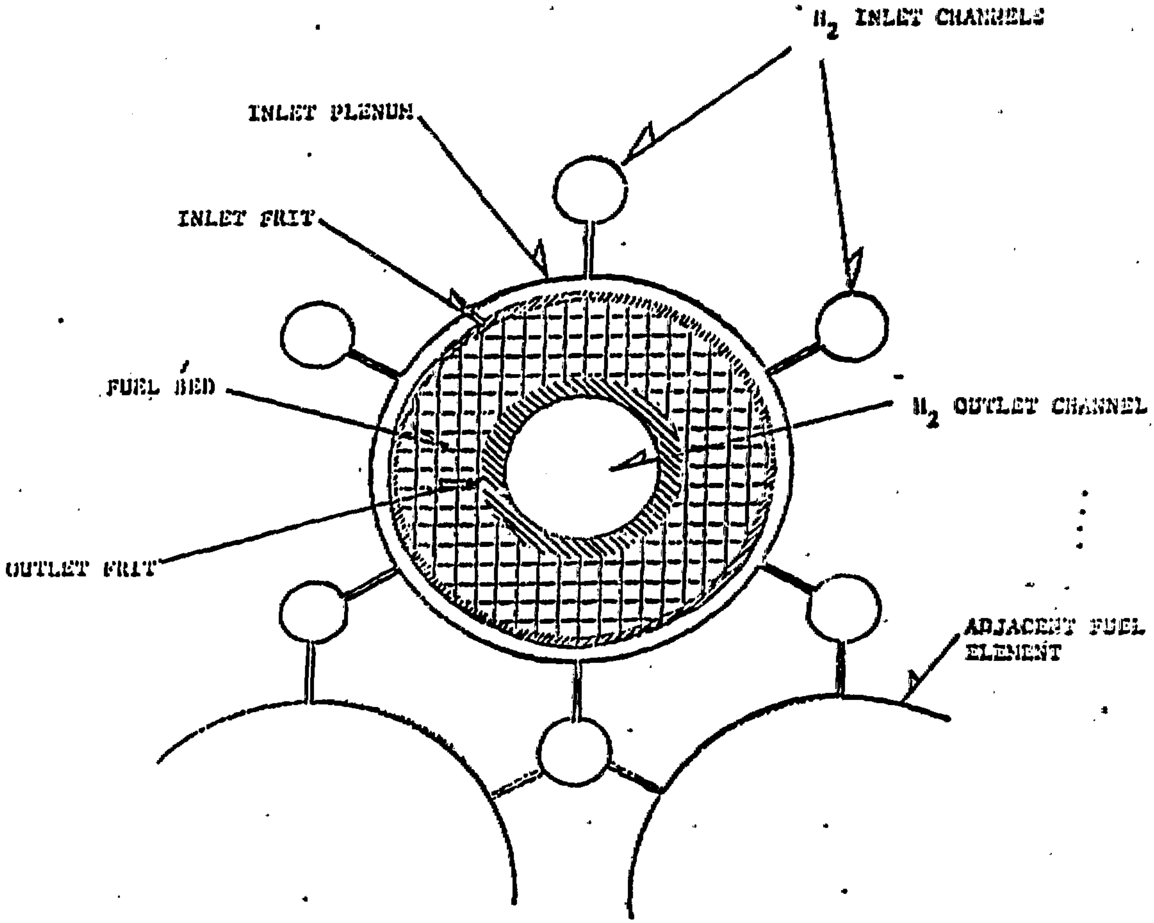

H_2 MODERATOR REGION (LOW FLOW)
INLET H_2
NOZZLE
H_2
CANNED LI^7H MODERATOR
8 cm
50 cm
75 cm
FUEL ELEMENTS (19) W/PARTICLE FUEL
H_2 DELIVERY PIPES TO REACTOR BASE FOR INPUT TO DISTRIBUTION TUBES
H_2 DISTRIBUTION TUBES

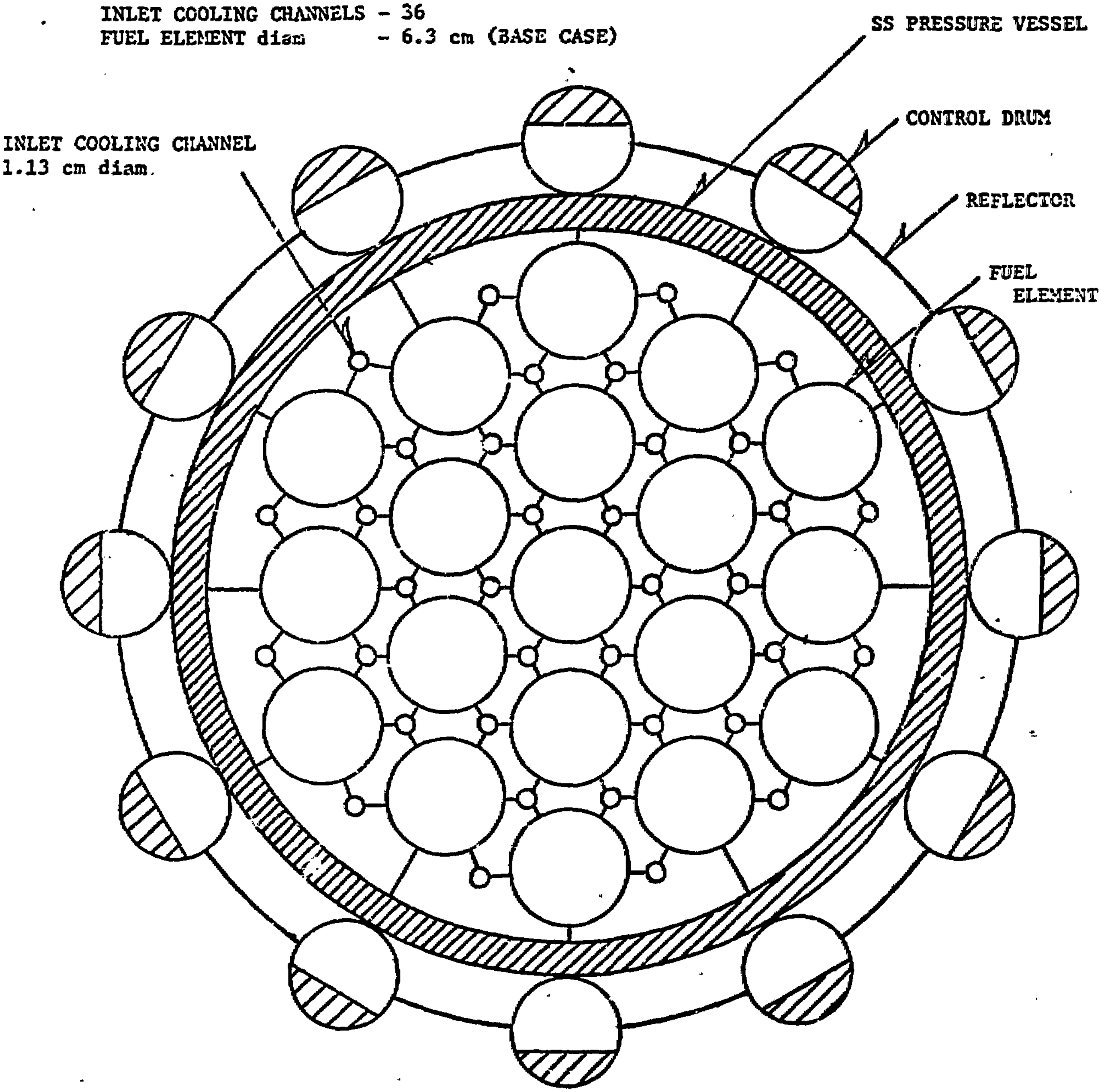
FIGURE 3



BASELINE FUEL ELEMENT FOR PARTICLE BED OTV

FIGURE 4

CORE diam - 40 cm (BASE CASE)
CONTROL DRUMS - 12
INLET COOLING CHANNELS - 36
FUEL ELEMENT diam - 6.3 cm (BASE CASE)



PARTICLE BED OTV (19 FUEL ELEMENT)

FIGURE 5

OTV REACTOR

TABLE 1
BASE CASE DESIGN PARAMETERS

PARAMETERS:

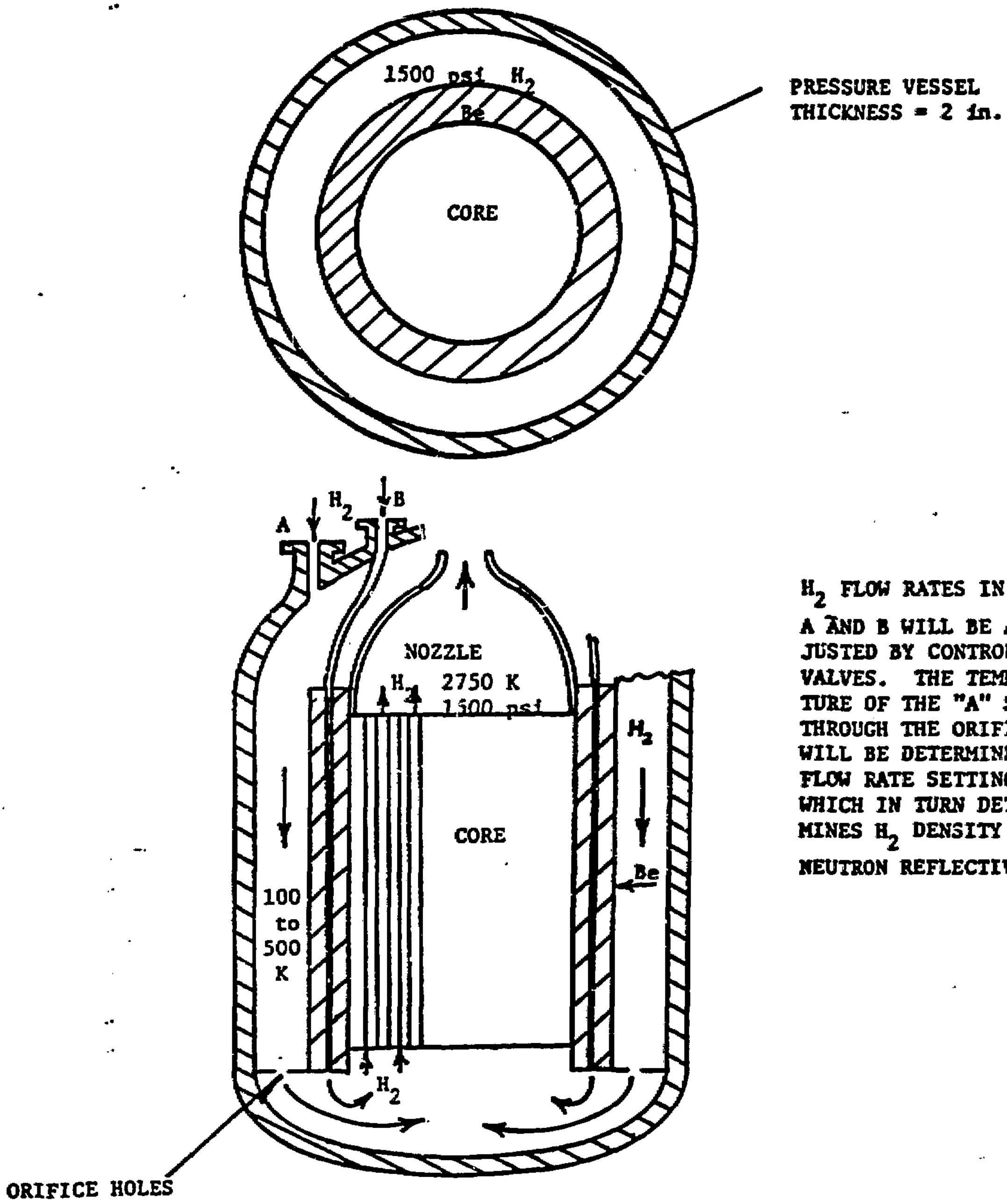
- NUMBER OF FUEL ELEMENTS - 19
- FUEL PARTICLE SIZE - 700 μm
- FUEL VOLUME FRACTION OF CORE - 25%
- RANGE OF ^{235}U (93.5% ENRICHMENT) LOADINGS - 4-10 KG
- POISON FRACTION OF CONTROL ROD - 33%
- NUMBER OF CONTROL RODS - 12

MATERIALS:

- FUEL - UC IN ZRC
- POISON - B_4C
- INLET FRIT - INCONEL, 50% POROSITY
- OUTLET FRIT - RHENIUM, 50% POROSITY
- MODERATOR - $ZrH_{1.7}$ CANNED IN 10 MIL SS
- REFLECTOR - STAINLESS STEEL

FIGURE 6

MARK-2 OTV WITH H_2 CONTROL/REFLECTOR



H_2 FLOW RATES IN A AND B WILL BE ADJUSTED BY CONTROL VALVES. THE TEMPERATURE OF THE "A" STREAM THROUGH THE ORIFICES WILL BE DETERMINED BY FLOW RATE SETTING, WHICH IN TURN DETERMINES H_2 DENSITY AND NEUTRON REFLECTIVITY.

FIGURE 7

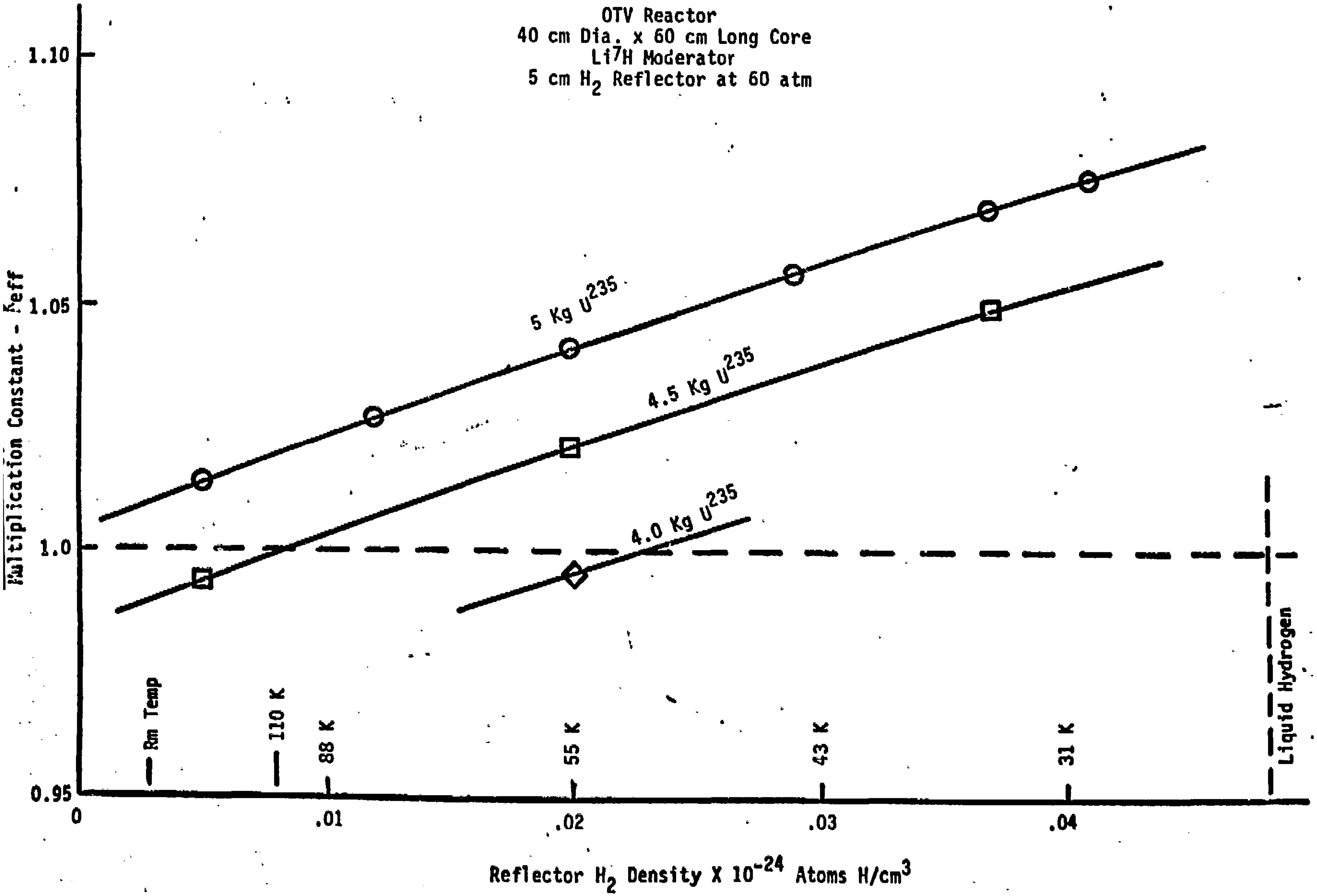

OTV Reactor
40 cm Dia. x 60 cm Long Core
Li^7H Moderator
5 cm H_2 Reflector at 60 atm
5 Kg U^{235}
4.5 Kg U^{235}
4.0 Kg U^{235}
Multiplication Constant - Keff
1.10
1.05
1.0
0.95
0
.01
.02
.03
.04
Rm Temp
110 K
88 K
55 K
43 K
31 K
Liquid Hydrogen
Reflector H_2 Density X 10^{-24} Atoms H/cm^3

FIGURE 8

OTV REACTOR CHARACTERISTICS

POWER - 200 MW

GAS OUTLET TEMPERATURE - 2750 K

COOLANT PRESSURE - 60 ATM H_2, 80 ATM NH_3

POWER DENSITY - 10 KW/cm^3

FUEL BED VOLUME - 25% OF REACTOR CORE

FUEL BED MATERIAL - 700 μ, ZrC-COATED, UC_2 SPHERES

NUMBER OF FUEL ELEMENTS - 19

DIAMETER OF CORE - 40 cm

LENGTH OF CORE - 60 cm

MODERATOR - Li^7H (CANNED)

REFLECTOR - COLD HYDROGEN

THICKNESS OF REFLECTOR - 5 cm

REACTIVITY CONTROL - REFLECTOR HYDROGEN DENSITY
TEMPERATURE CONTROL

ALUMINUM PRESSURE VESSEL - 3 cm THICK

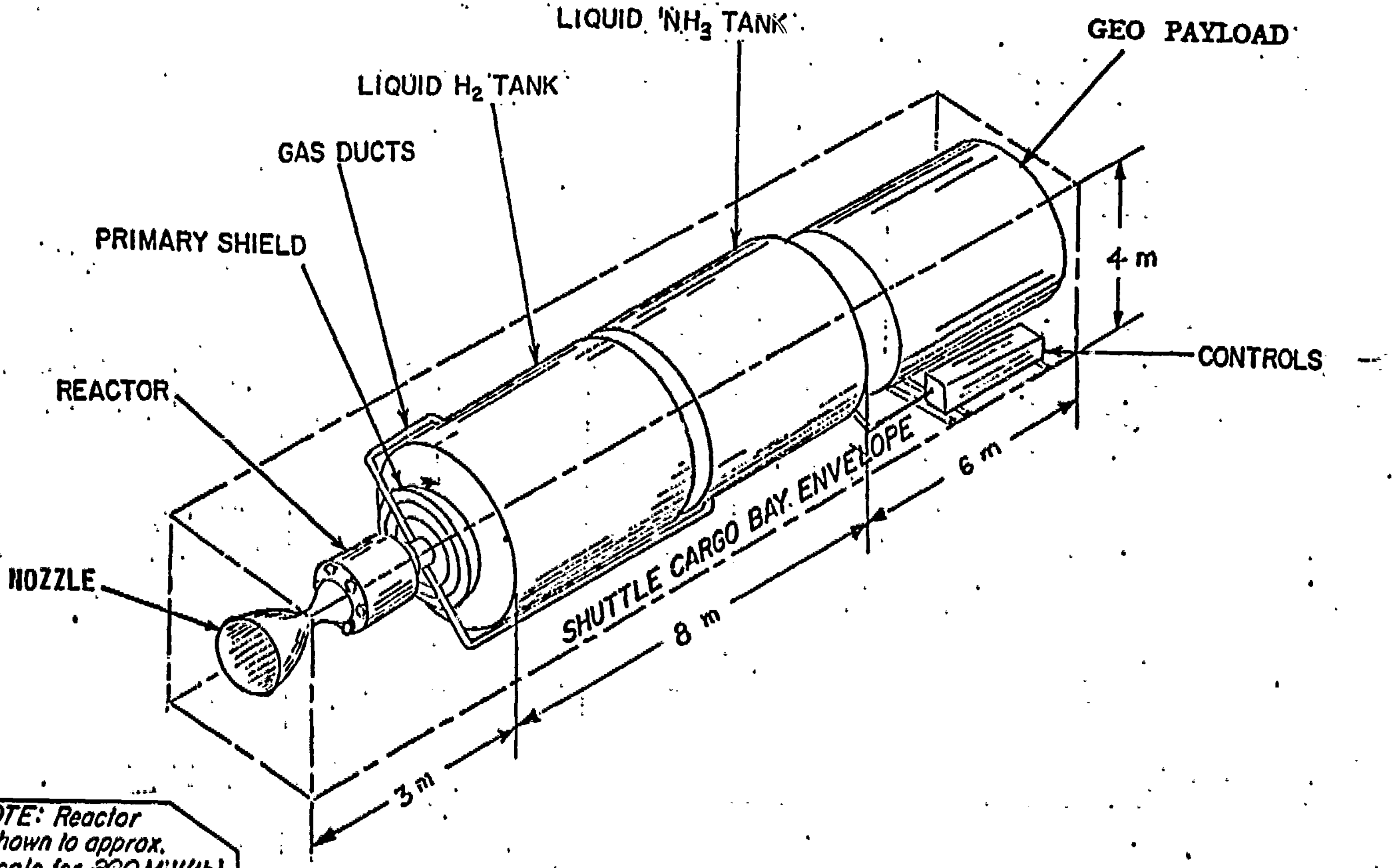
OVERALL SIZE - 100 cm x 56 cm DIA.

OVERALL WT. = 300 Kg

	DESIGN A	DESIGN B
COOLANT	HYDROGEN (LIQUID & GAS)	AMMONIA (LIQUID & GAS)
CORE PRESSURE DROP	0.50 atm	1.4 atm

FIGURE 9

ORBITAL TRANSFER VEHICLE



NOTE: Reactor shown to approx. scale for 200 MW(th)

WEIGHTS(KG)									
INERT WEIGHT				PROPELLANTS			WEIGHT SUMMARY		
HYDROGEN TANK	400	460	2,735	HYDROGEN	6,810	14,810	INERT WEIGHT	2,735	OTV GROSS WEIGHT= 29,545
INSULATION	50			AMMONIA	7,900		PROPELLANTS	14,810	
PUMP & PIPING	10			ATTITUDE CONTROL	100		PAYLOAD	12,000	
AMMONIA TANK	100	125							
INSULATION	10								
PUMP & PIPING	15								
REACTOR	200	2,150							
NOZZLE	30								
STRUCTURE	1,500								
CONTROL SYSTEMS (GUIDANCE & ATTITUDE)	350								
THERMAL SHIELD	30								
POWER SUPPLY	40								

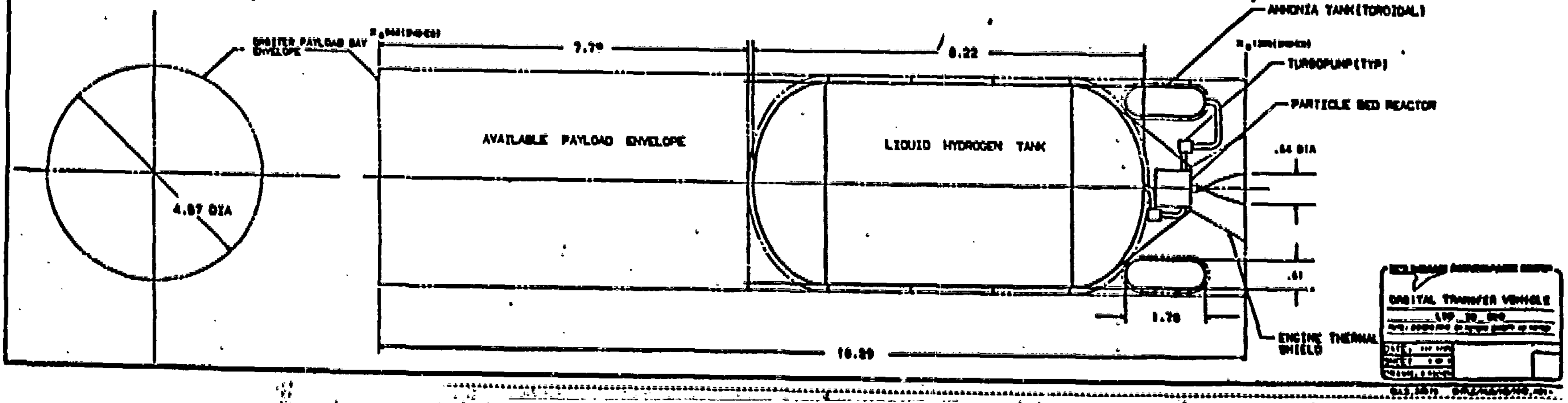


FIGURE 10

FIGURE 11

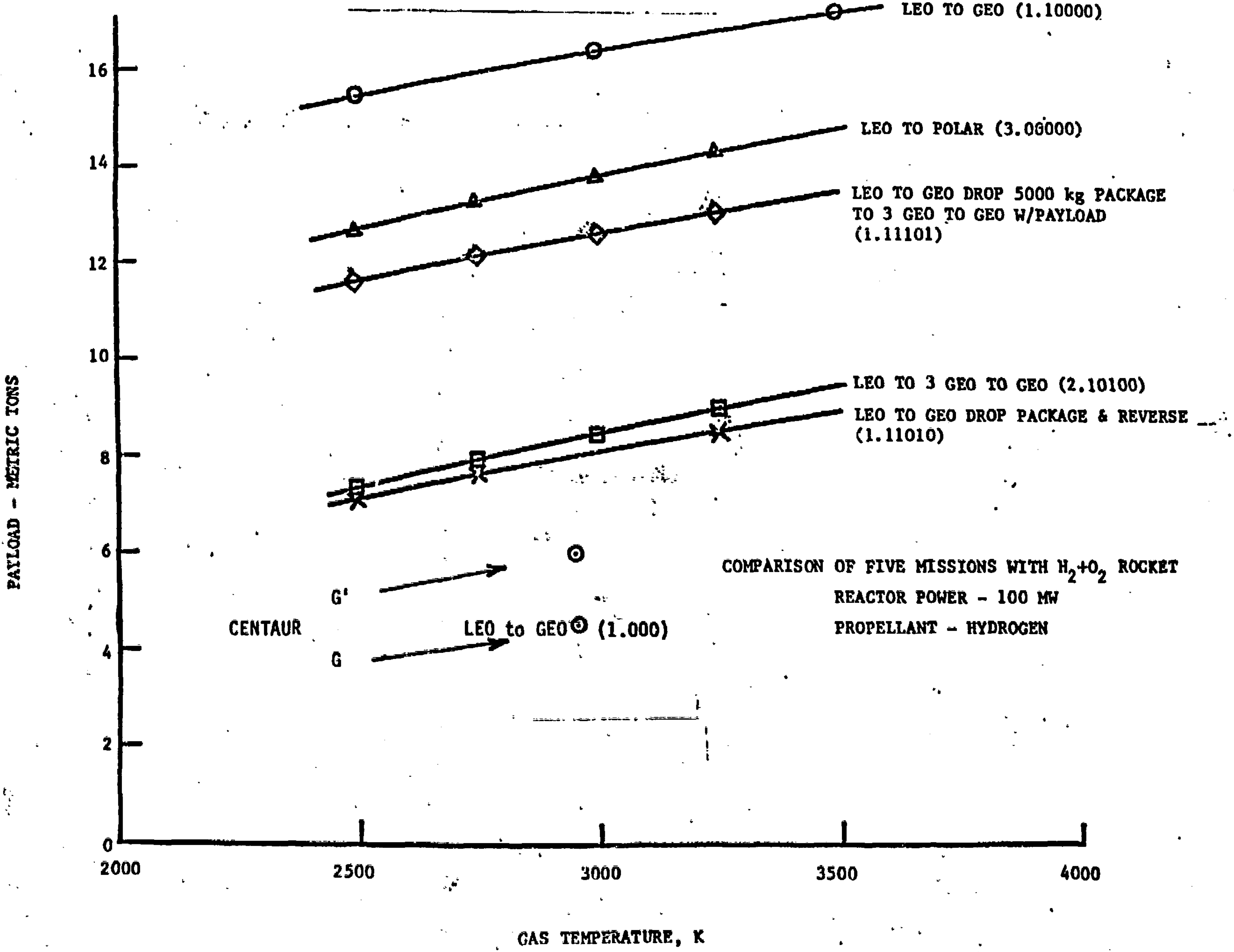
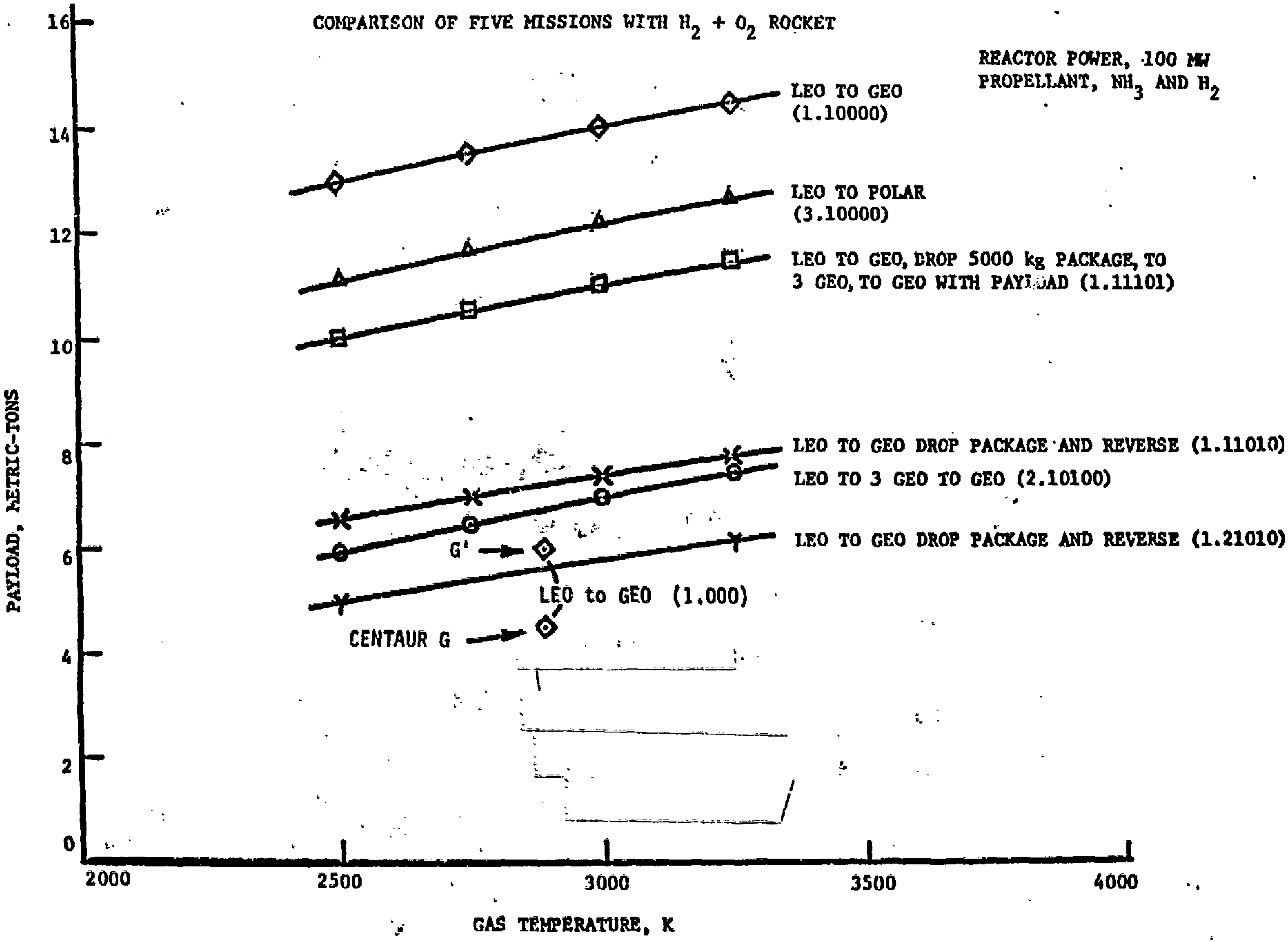

LEO TO GEO (1.10000)
LEO TO POLAR (3.00000)
LEO TO GEO DROP 5000 kg PACKAGE TO 3 GEO TO GEO W/PAYLOAD (1.11101)
LEO TO 3 GEO TO GEO (2.10100)
LEO TO GEO DROP PACKAGE & REVERSE (1.11010)
COMPARISON OF FIVE MISSIONS WITH H_2+O_2 ROCKET
REACTOR POWER - 100 MW
PROPELLANT - HYDROGEN
G'
CENTAUR
G
LEO to GEO (1.000)
PAYLOAD - METRIC TONS
0
2
4
6
8
10
12
14
16
2000
2500
3000
3500
4000
GAS TEMPERATURE, K

FIGURE 12



COMPARISON OF FIVE MISSIONS WITH $H_2 + O_2$ ROCKET

FIGURE 13

MISSION PERFORMANCE

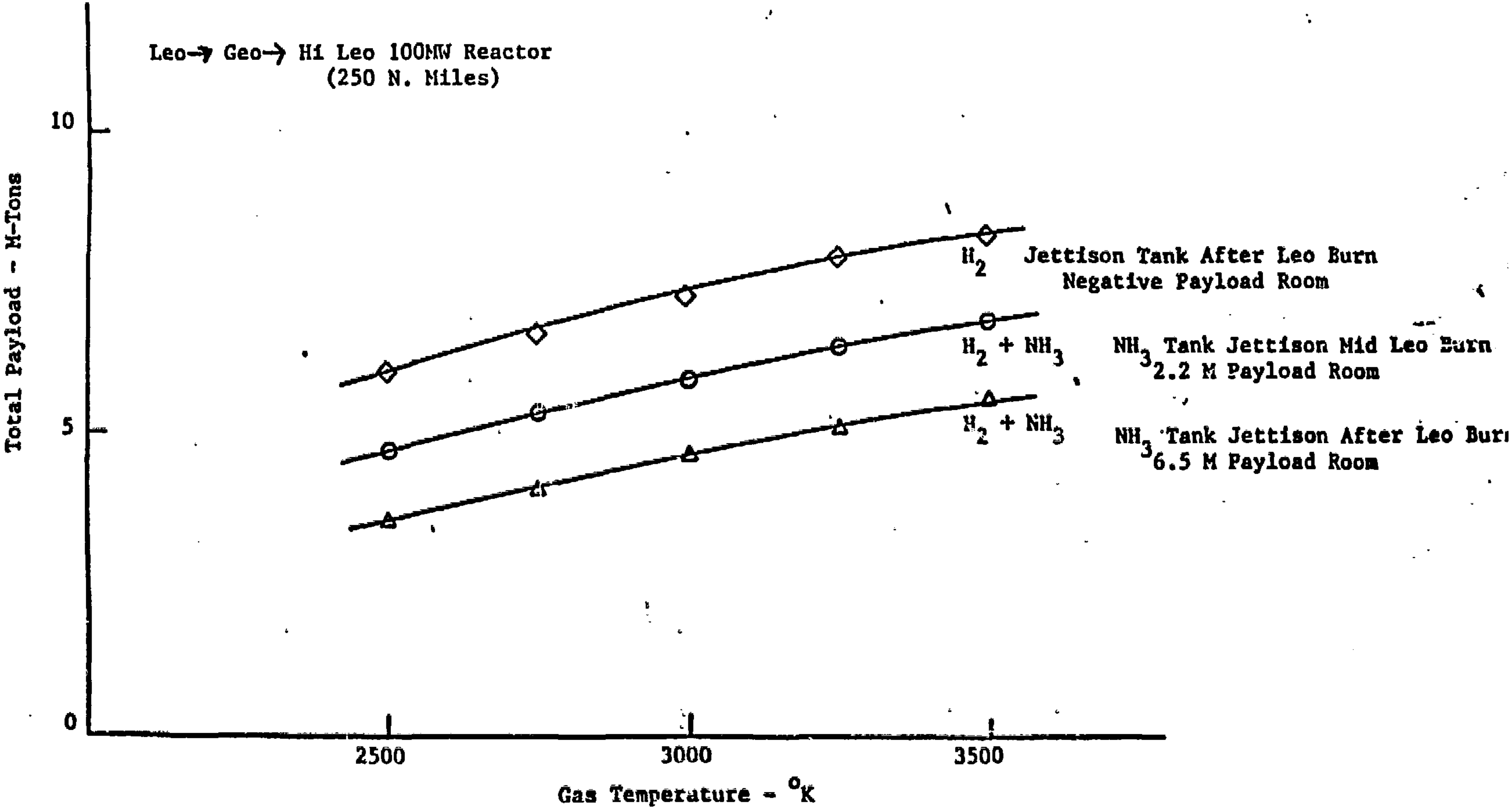
100 MW REACTOR, 2750 K GAS OUTLET TEMPERATURE

	H_2 PROPELLANT		$NH_3 + H_2$ PROPELLANT*		H_2/O_2 CENTAUR G'	
BASIC MISSION	PAYLOAD WT Kg	PAYLOAD LENGTH m	WT Kg	LENGTH m	WT Kg	LENGTH m
LEO TO GEO (equatorial)	15,422	3.37	12,748	8.68	5,993	9.2
LEO TO POLAR	13,268	1.36	10,927	6.98	3,000	9.0
LEO TO GEO, TO 3 GEO, TO GEO (equatorial)	10,143	-1.56	8,288	4.52	-	-
LEO TO 3 GEO TO GEO (inclined)	12,976	0.97	9,468	6.77	-	-
LEO TO GEO AND REVERSE (equatorial)	3,828	-7.45	** 2,126	4.54	-	-

* Jettison of NH_3 tank at mid-LEO

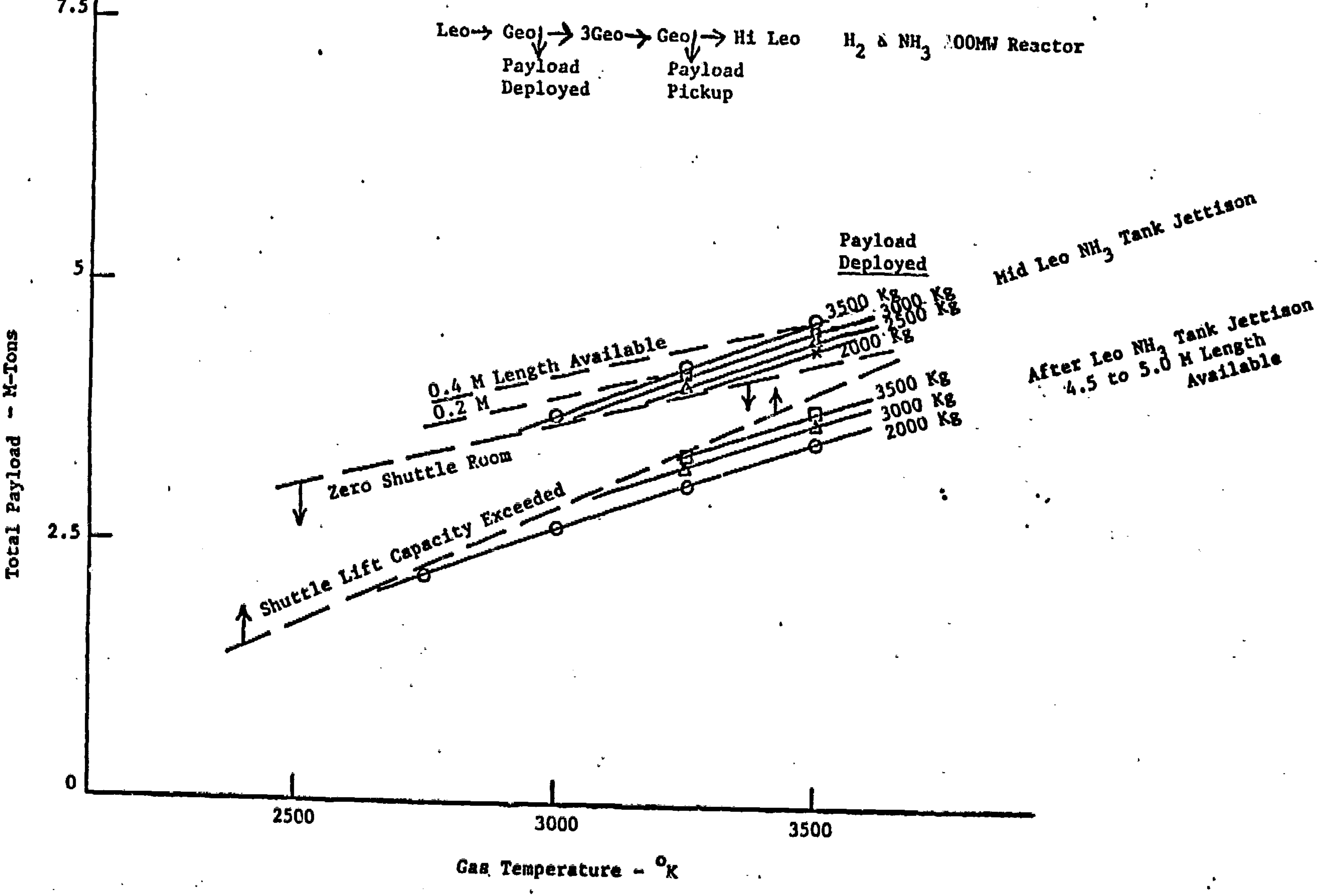
** Jettison after LEO

FIGURE 14



Leo→ Geo→ Hi Leo 100MW Reactor
(250 N. Miles)
Total Payload - M-Tons
10
5
0
2500
3000
3500
Gas Temperature - °K
H_2
Jettison Tank After Leo Burn
Negative Payload Room
$H_2 + NH_3$
NH_3 Tank Jettison Mid Leo Burn
2.2 M Payload Room
$H_2 + NH_3$
NH_3 Tank Jettison After Leo Bur
6.5 M Payload Room

FIGURE 15


Leo→ Geo → 3Geo→ Geo → Hi Leo
Payload Deployed
Payload Pickup
H_2 & NH_3 00MW Reactor
7.5
5
2.5
0
Total Payload - M-Tons
2500
3000
3500
Gas Temperature - °K
Payload Deployed
Mid Leo NH_3 Tank Jettison
3500 Kg
3000 Kg
2500 Kg
2000 Kg
0.4 M Length Available
0.2 M
Zero Shuttle Room
After Leo NH_3 Tank Jettison 4.5 to 5.0 M Length Available
3500 Kg
3000 Kg
2000 Kg
Shuttle Lift Capacity Exceeded