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NASA Contractor Report CR-191023

LUNAR ELECTRIC POWER SYSTEMS UTILIZING THE SP-100 REACTOR COUPLED TO DYNAMIC CONVERSION SYSTEMS (TASK ORDER NO. 12)

Rockwell International
Rocketdyne Division
Canoga Park, California

March 1993

' PREPARED FOR
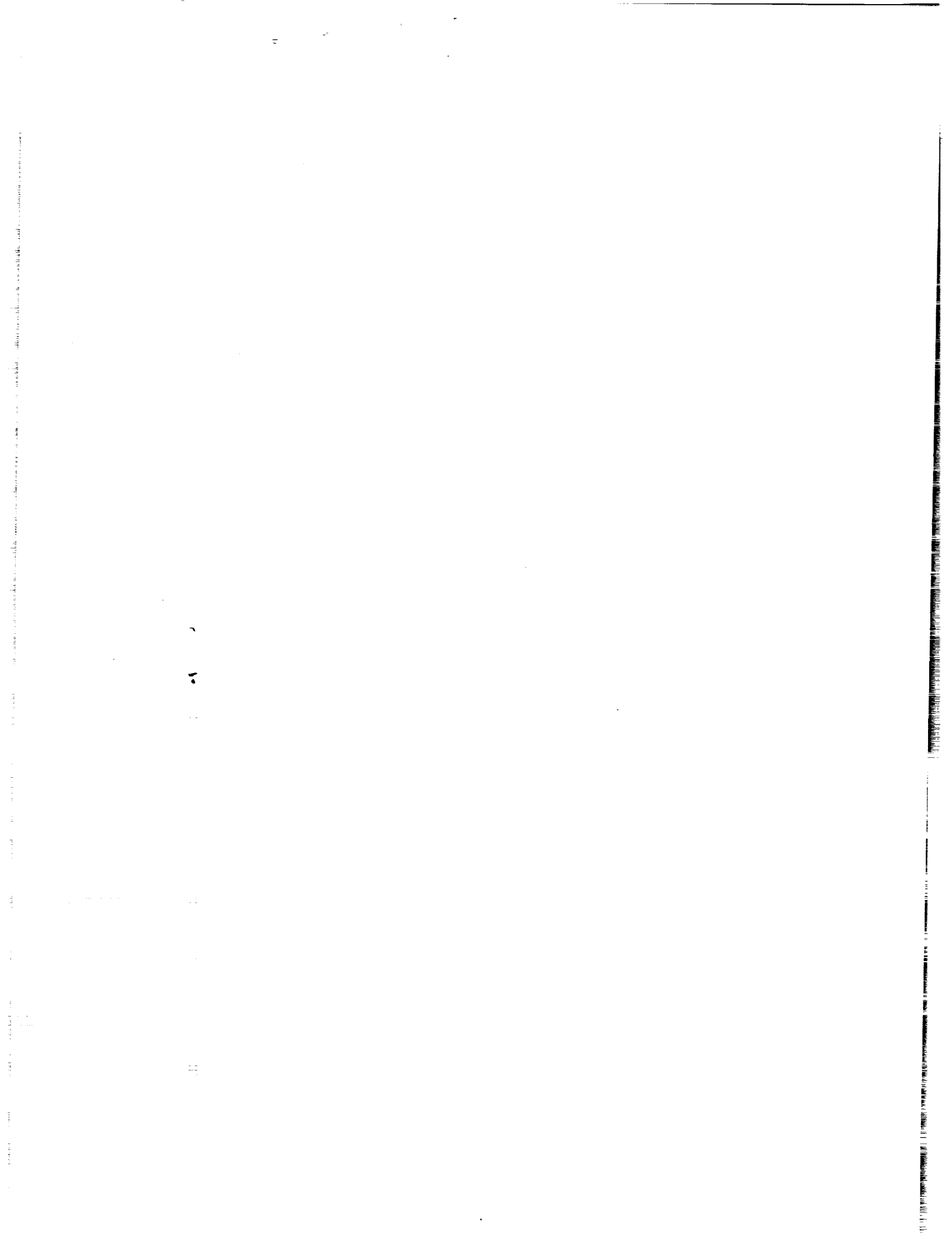LEWIS RESEARCH CENTER
UNDER CONTRACT NAS3 25808

NASA

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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FIGURES

FIGURES (Cont'd)

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1.0 SUMMARY

An integration study was performed by Rocketdyne under contract to NASA-LeRC coupling an SP-100 reactor to either a Brayton or Stirling power conversion system. The application was for a surface power system to supply power requirements to a lunar base. A power level of 550 kWe was selected based on the NASA 90-day study of the Moon and Mars. Reliability studies were initially performed to determine optimum power conversion redundancy. This analysis resulted in selecting three operating engines and one stand-by unit for both the Brayton and Stirling options. Integration design studies indicated that either the Brayton or Stirling power conversion systems could be integrated with the SP-100 reactor. Stirling had a 5% mass advantage for 1000 Vdc output and the Brayton a 2% mass advantage for 1000 Vrms, 1 kHZ output. The Brayton radiator area was 3.2 times larger than the Stirling.

The same SP-100 reactor was used for both the Brayton and Stirling Systems. Because of the higher efficiency of the Stirling cycle (29.7% vs 23.8%), a longer reactor lifetime results (9.6 y for the Stirling and 7.6 y for the Brayton). A description of installation and maintenance operations is also included.

2.0 INTRODUCTION

Under contract to NASA-LeRC, the Rocketdyne Division of Rockwell International performed an integration study coupling an SP-100 reactor to either a Brayton or Stirling power conversion system. The object of the study was to investigate design concepts for integration of a SP-100 reactor to multiple dynamic engines and to assess the ease of integration for both Stirling and Brayton engines. The application was for a surface power system to supply power to a mature or evolved lunar base. General Electric, prime contractor for the SP-100 program, supplied technical information on the Reference Flight System SP-100 reactor. The Allied Signal Corporation, Fluid Systems Division, provided information on the Brayton power conversion components. Mechanical Technology Incorporated provided information for the Stirling engine.

3.0 OBJECTIVES AND TECHNICAL APPROACH

The objective of this task was to investigate design concepts for integration of an SP-100 reactor to multiple dynamic engines, characterize deployment and assembly schemes for such systems, and assess the ease of integration for both Stirling and Brayton engines.

The technical approach employed to achieve this objective is shown schematically in Figure 3-1. The first steps, accomplished in parallel, were to select system state points for the Brayton and Stirling systems, to pick the optimum number of engines for each system, and to make an estimate of power conditioning and pumping losses for each system. These activities made it possible to size the Brayton and Stirling engines and calculate their performance. Allied Signal characterized the Brayton engine and Mechanical Technology, Inc., characterized the Stirling engine. Rocketdyne was responsible for sizing the heat transport system components such as electromagnetic pumps, heat exchangers, and expansion tanks. The SP-100 reactor operating parameters, dimensions, and lifetime vs. power and temperature were provided by General Electric. All of this information was combined to prepare design layouts of the Brayton and Stirling systems. System mass estimates were then made based on these layouts.

FIGURE 3-1
TASK ORDER NO. 12: TECHNICAL APPROACH

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                                                              ┌──────────┐
                                                              │ PREPARE  │
                                                              │          │
                                                              │  TASK    │
                                                              │ SUMMARY  │
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                                          │   EVALUATE   │─────────┤
                                          │   BRAYTON    │         │
                                          │ PERFORMANCE  │         │
                                          └──────▲───────┘         │
                                                 │                 │
                                          ┌──────────────┐         │
                                          │   EVALUATE   │─────────┘
                                          │   STIRLING   │
                                          │ PERFORMANCE  │
                                          └──────▲───────┘
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CHARACTERIZE SP-100 REACTOR REACTOR (GE)

CHARACTERIZE BRAYTON ENGINES

CHARACTERIZE STIRLING ENGINES

SIZE HEAT TRANSPORT COMPONENTS

PREPARE BRAYTON SYSTEM LAYOUTS

PREPARE STIRLING SYSTEM LAYOUTS

ESTABLISH BRAYTON STATE POINTS

ESTABLISH STIRLING STATE POINTS

SELECT NUMBER OF ENGINES

CALCULATE POWER CONDITIONING AND PUMPING LOSSES

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4.0 GROUND RULES AND ASSUMPTIONS

The following ground rules for the study were agreed upon between Rocketdyne and NASA-LeRC and were incorporated in the task work statement.

- **Reactor**. The SP-100 reactor will be utilized as the heat source. The reactor will be operated at a power level consistent with producing 550 kWe net to the output bus, for both the Stirling and Brayton systems.

- **Heat Transport System**. An intermediate heat exchanger will be incorporated in all designs to isolate the primary reactor coolant (lithium) from a secondary loop that either contains the power conversion unit working fluid or contains an intermediate fluid that supplies heat to the power conversion unit working fluid. The purpose of this heat exchanger is to facilitate maintenance, such as removal and replacement, of the power conversion units, and to minimize activation of power conversion components.

- **Power Conversion Units**. The overall system design will incorporate the number of engines needed for production of 550 kWe net to the output bus. The peak cycle temperature shall be consistent with the reactor outlet coolant temperature while taking into account thermal losses in the heat transport system.

  The number of operating and standby engines will be determined by an analysis of the system reliability and mass for various numbers of operating and standby engines, and any technological limits on engine size that may exist.

- **Environment**. Only the Lunar environment will be considered. The effect of the Martian environment on the system design is the subject of a separate proposed study.

- **Initial Thaw and Startup**. A source of auxiliary electrical power will be assumed available for lithium thaw and startup. Lithium thaw shall be accomplished through trace heating.

Based on previous lunar surface nuclear power system studies and features to enhance safety, the following assumptions were made for the integration study:

- Emplacement is in a cylindrical, excavated cavity in the lunar regolith. A cavity liner (guard vessel) is provided as an integral part of the system. The cavity liner incorporates a passive cooling system that transports deposited heat from reactor/primary cooling system heat leakage, neutrons, and gammas to the lunar surface, where

the heat is rejected to space by a dedicated cavity liner radiator.

- The SP-100 reactor, primary coolant loop, and shadow shield is located at the bottom of the cavity. The cavity liner fits closely around the reactor such that the reactor would remain covered with lithium in the unlikely event of a leak in the primary loop.

- Reactor decay heat after shutdown is removed by a free convective branch of the primary heat transport loop. The heat is transferred to the cavity liner, which in turn transfers heat to a dedicated cavity liner surface radiator.

- An expansion tank with a free lithium surface is located at the high point of the primary coolant loop. This allows for expansion of the lithium as it heats up and for collection of helium gas formed by the neutron interaction with the lithium.

- An intermediate heat exchanger, with the primary lithium on the shell side, is located above the reactor shadow shield. This isolates the power conversion heat transfer fluid from the reactor coolant, thereby reducing the possibility of fission product contamination of any components located at the lunar surface.

- All power conversion equipment, reactor control actuators, and heat rejection equipment is located at grade level. Although maintenance was not considered in this study, the design provides accessibility for above grade component maintenance if fesible.

- A power level of 550 kWe at 1000 Vac or dc was selected based on past NASA power system studies and results of the "90-Day Study" of the moon and Mars.

Several radiator configurations were considered before deciding on the configuration shown in this study. The first option provides a dedicated radiator for each engine whether it be operating or stand-by. This design results in the simplest piping system, but with a substantial penalty in mass and area, since there is an extra unused radiator for stand-by engines.

A second option is to provide only one radiator for each _operating_ engine, with piping and valves to permit switching to a standby engine. This option eliminates the mass penalty of the first option, but introduces additional system complexity and failure modes due to the valves.

The third option is to manifold all radiators together, so that they function as a single unit, fed by all operating engines, and with any standby engines also permanently connected to the radiator complex.

Like the second option, this option also avoids a radiator mass penalty, but does introduce some extra mass associated with additional radiator manifolds. However, this additional mass is much less than the mass of a complete engine dedicated radiator. This third option was selected for the integration study to minimize radiator area while retaining a high level of reliability.

5.0 INITIAL STUDIES AND TRADE-OFFS

## 5.1 SYSTEM PERFORMANCE OPTIMIZATION

Initial parametric performance studies were performed to select system operating conditions. These initial operating conditions were used for the power conversion subcontractor design studies. The results of these studies are presented in Figure 5-1, which gives the specific mass as a function of specific radiator area for both Brayton and Stirling systems. The specific mass in this figure is based on previous scaling studies and does not include the mass of the guard vessel. The resultant design points selected, with agreement from the power conversion subcontractors, are shown in the Figure. The peak cycle operating temperature was based on a reactor outlet temperature of 1355K and a heat transport loop ΔT of 79K, which is the current SP-100 reference.

5.2 SELECTION OF NUMBER OF ENGINES

To achieve a high system reliability, it is desirable to provide some extra (standby) power conversion capability over and above that needed to produce the design power level. Unfortunately, extra power conversion capacity comes at the expense of extra system mass, so a compromise must be reached. In making a selection of the number of power conversion units (also called engines), the following conditions were taken into account.

- The reliability of a single engine and its associated power conditioning equipment was assumed to be 0.95 for the operating life of the system (approximately 7 years). Past studies, for example for the SP-100 Stirling and Brayton systems, indicate that 0.95 is an optimistic but reasonable goal.

- Replacement of a failed engine was not considered in selecting the number of engines. Further study is needed to determine the feasibility of engine replacement.

- For a 550 kWe system, capability to produce partial power is probably of greater significance than reliability to produce 100% power. For example, current lunar power architecture studies indicate that much of this power would be used for activities such as production of lunar liquid oxygen. Partial power capability would slow down such an operation, but not shut it down completely. It is also anticipated that these systems would operate initially at partial power. As power requirements increase, the systems would ramp up gradually to full power capacity.

- The fewer the number of engines, the more easily they can be integrated into a complete system.

FIGURE 5-1

INITIAL BRAYTON AND STIRLING PERFORMANCE CHARACTERISTICS
550 kWe
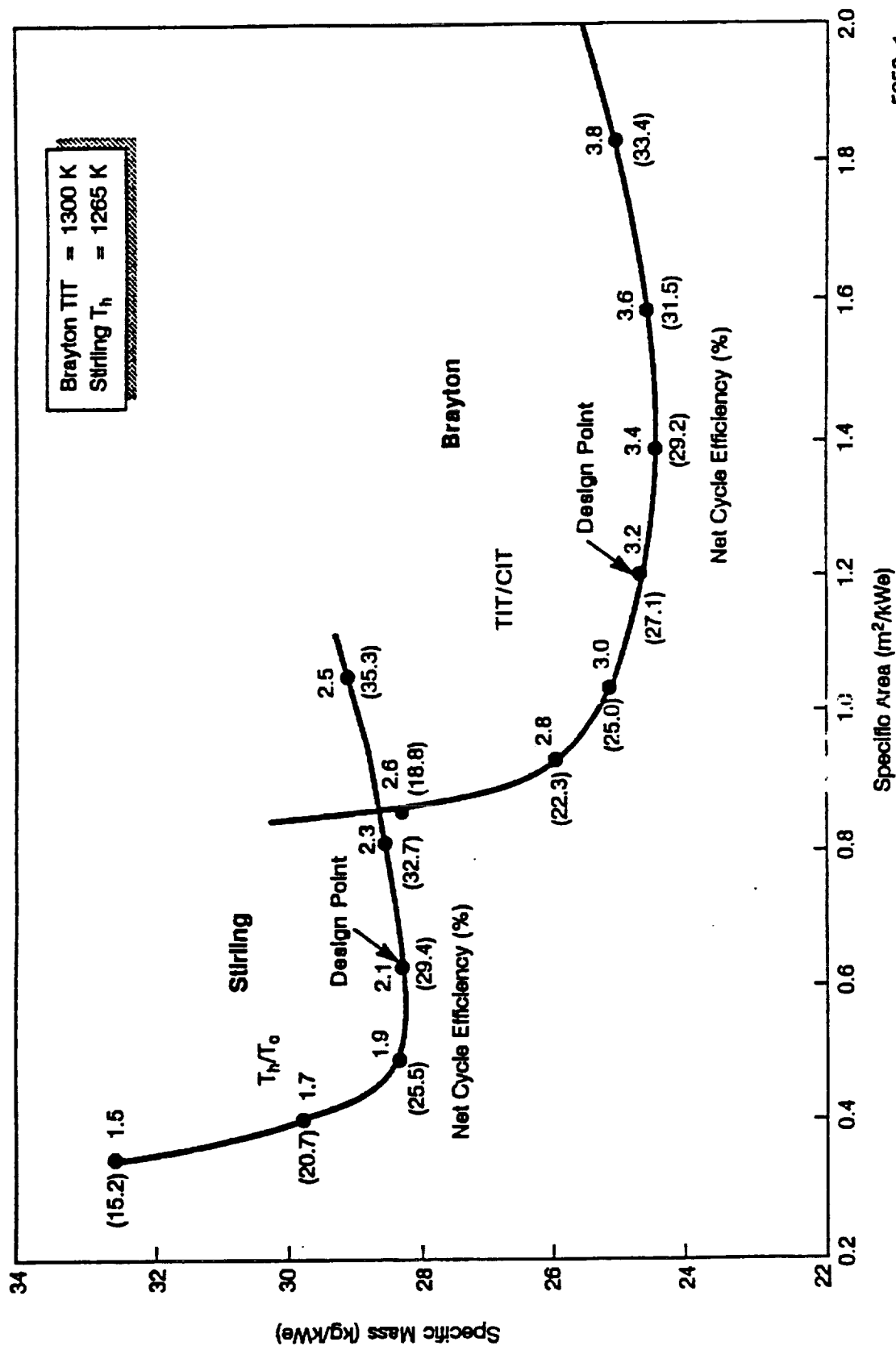
• While there is no technological limit on Brayton engine size in the range encompassed by this study, Stirling engine scalability studies conducted by MTI (reference 1) indicate that for a free piston Stirling engine, power output probably should not exceed about 100 kWe per piston.

Figure 5-2 shows the reliability of the power conversion subsystem (engines and associated power conditioning and controls) as a function of subsystem mass for both the Brayton and Stirling power conversion subsystems. A constant power conversion engine reliability of 0.95 was used in these calculations. The total number of engines, including standby engines, is noted next to each data point. It can be seen from examination of Figure 5-2 that there is little advantage from a reliability standpoint to have two standby engines; and a significant mass penalty results for both the Brayton and Stirling systems. In order to satisy high system reliability and low system mass, it appears that four enginees (three required for full power, with one stand-by) would be a reasonable choice for both Brayton and Stirling systems.

To evaluate the partial power capability of systems with various numbers of engines, the concept of capacity factor was utilized. An example of how this was calculated is shown in Figure 5-3. In this example, there are four installed engines, with three required for full power. The probability of achieving 66⅔% power to 100% power is 0.9360. The probability of two engines out of four being in operation is much higher, 0.9995, and the probability of one engine out of four being in operation is essential 1.000. The capacity factor is the total area under the histogram or 99.52%. This is interpreted to mean that, over its lifetime, the power conversion subsystem can be expected to produce 99.52% of the total kilowatt-hours it would produce if it operated at full power 100% of the time.

Similar calculations were made for two, three and five engines, for both the Brayton and Stirling systems, and were plotted against subsystem mass, as shown in Figure 5-4. Inspection of these curves leads to the conclusion that three, four or five engines are all candidates, but two engines introduce a large mass penalty with a relatively small improvement in capacity factor.

For this integration study, four engines were chosen for both the Brayton and Stirling systems. This provides very close to a minimum mass system, potential for acceptable complexity, and keeps the Stirling engine size in the technologically feasible range.

5.3 POWER CONDITIONING LOSSES AND PUMPING POWER

To establish the required engine gross power output to produce 550 kWe net, power conditioning losses and pumping power were estimated, as tabulated in Table 5-1.

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FIGURE 5-2
POWER CONVERSION SUBSYSTEM RELIABILITY CHARACTERICS

Brayton

Stirling
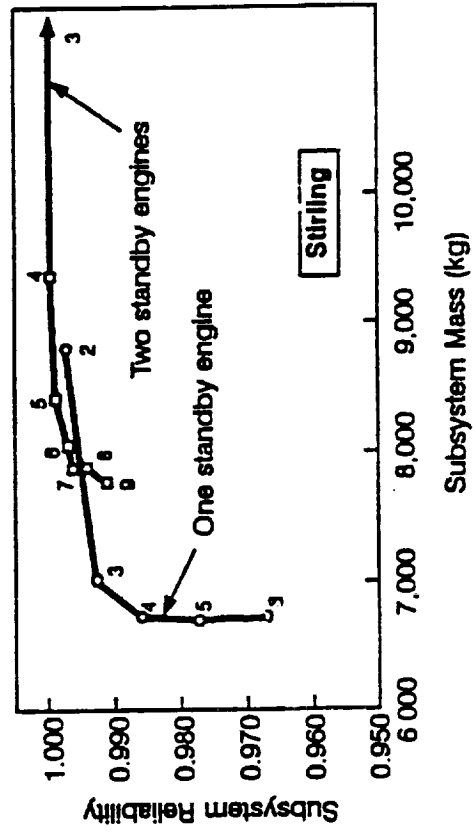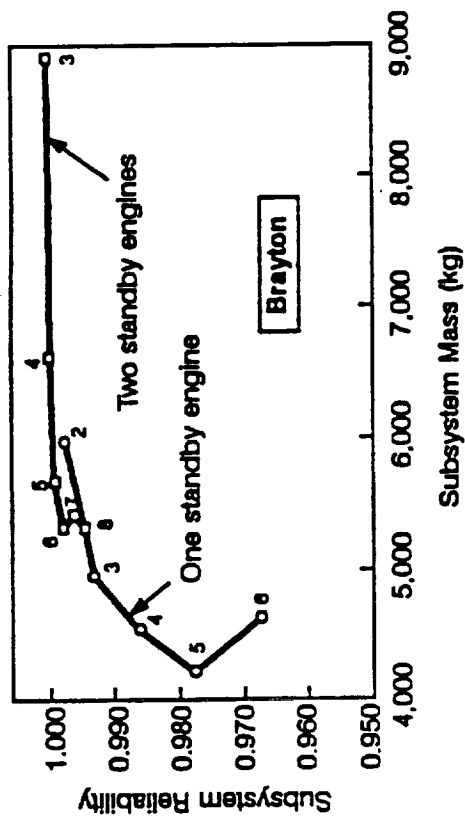
"Reliability" equals probability of producing 100% power over system lifetime.

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FIGURE 5-3
CAPACITY FACTOR OF POWER CONVERSION SUBSYSTEM
4 INSTALLED ENGINES
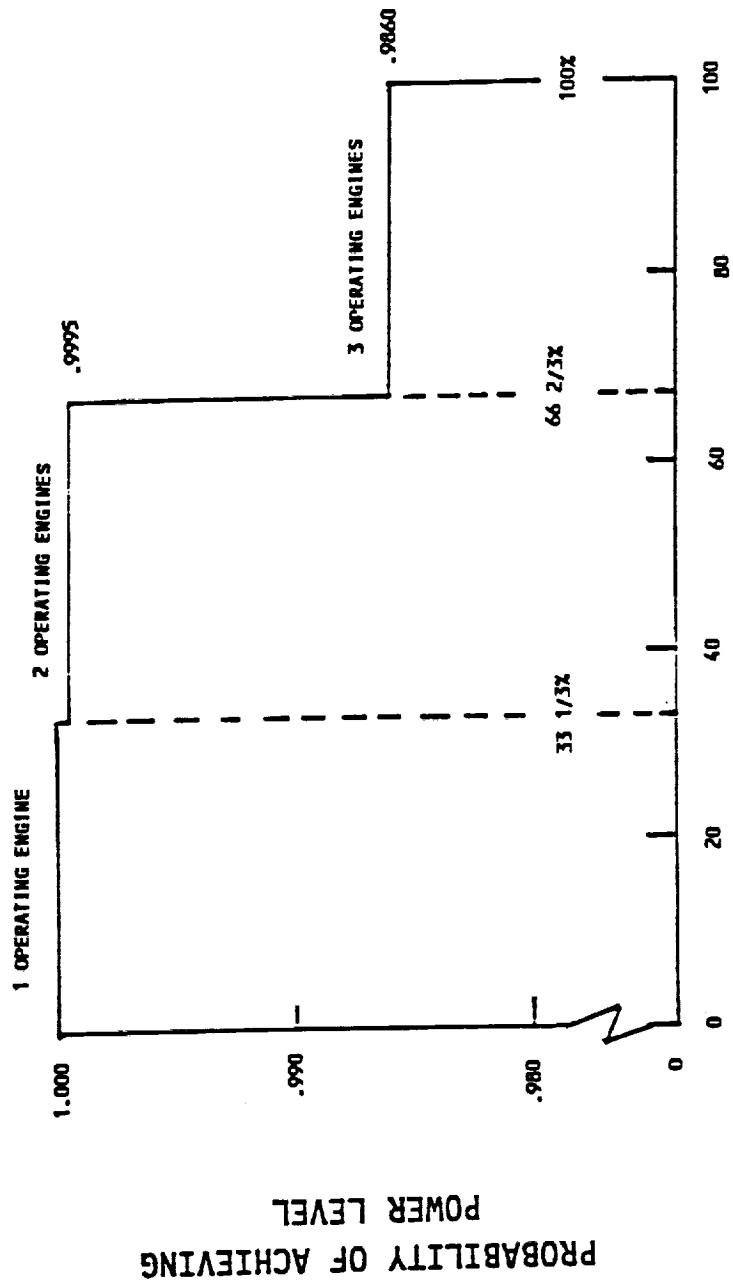
CAPACITY FACTOR = 1.000 X 33 1/3% + .9995 X 33 1/3% + .9860 X 33 1/3% = 99.52%

FIGURE 5-4
POWER CONVERSION SUBSYSTEM CAPACITY FACTOR CHARACTERISTICS

BRAYTON

STIRLING
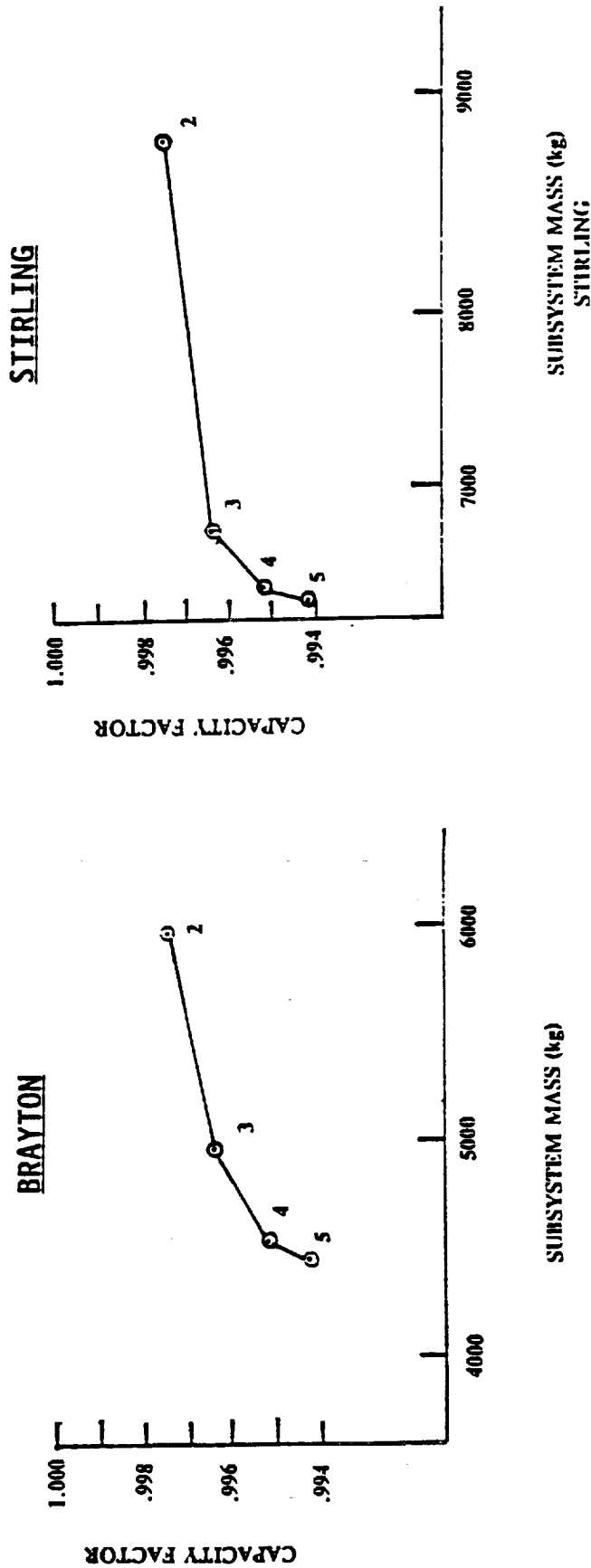
NOTES:
1. SUBSYSTEM CONSISTS OF ENGINES AND POWER CONDITIONING:
2. BRAYTON ENGINE INCLUDES TURBOALTERNATOR-COMPRESSOR AND RECUPERATOR
3. INDIVIDUAL ENGINE RELIABILITY ASSUMED AT .95

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TABLE 5-1
POWER CONDITIONING LOSSES AND PUMPING POWER

SYSTEM	VOLTAGE	POWER LOSS (kWe)	PUMPING POWER (kWe)	TOTAL (kWe)
BRAYTON	1000 VDC	22	10	32
BRAYTON	1000 VAC, 1 kHz	8	10	18
STIRLING	1000 VDC	26	20	46
STIRLING	1000 VAC	46	20	66

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6.0 SP-100 REACTOR CHARACTERIZATION

The SP-100 reactor and shield dimensions, operating parameters, and predicted lifetime as a function of reactor thermal power and temperature were provided by General Electric.

Figure 6-1 shows the key dimensions of the reactor, shield, and control and safety rod drives. These dimensions are for the Generic Flight System (GFS) reactor which is rated at a thermal power of 2.4 mwt.

Nominal operating conditions for the reactor are tabulated in Table 6-1. As noted in the table, the actual operating thermal power is not exactly 2.4 mwt, but somewhat less, since both the Brayton and Stirling systems operate at efficiencies allowing 550 kWe net output at less than 2.4 mwt. The extent to which this can prolong system lifetime is illustrated by Figure 6-2. This figure provides a family of curves depicting reactor full power lifetime vs. reactor outlet temperature and power level. Cladding strain and peak fuel temperature are limiting for fuel lifetime effects at higher reactor outlet temperature (1400K and higher). At the nominal 1355K outlet temperature, the predominant factor is fuel burnup and, therefore, the life increases approximately proportionately as the thermal power decreases.

FIGURE 6-1
SP-100 GENERIC FLIGHT SYSTEM REACTOR

Lithium
Hydride

Reflector and Safety
Rod Drive Envelope

R26.162 cm
R10.3 in.

R38.862 cm
R15.3 in.

R57.82 cm
R22.764 in.

R32.47 cm
R12.783 in.

43.18 cm
17 in.

74.93 cm
29.5 in.

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Beryllium

Tungsten

80.76 cm
31.755 in.

4.73 cm
1.217 in.

Reentry Shield

Hemispherical Head

Reflector

1 m 17.127 cm
46.113 in.

33.79 cm
13.303 in.

42.58 cm
16.764 in.

34.29 cm
13.5 in.

R22.98 cm
R9.047 in.

17.0°

R25.46 cm
R10.024 in.

Core

R17.64 cm
R6.945 in.

31.75 cm
12.5 in.

3.929 cm
1.547 in.

1.27 cm
0.5 in.

1 m 17.127 cm
46.113 in.

2m 3.086 cm
79.955 in.

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TABLE 6-1

SP-100 REACTOR NOMINAL OPERATING CONDITIONS

- REACTOR INLET TEMPERATURE (K)   1276

- REACTOR OUTLET TEMPERATURE (K) 1350

- REACTOR THERMAL POWER (kWt)   2400*

- PRIMARY COOLANT FLOW RATE (KG/SEC) 7.27

* REACTOR OPERATES AT POWER REQUIRED TO PRODUCE 550 kWe NET

FIGURE 6-2
SP-100 REACTOR LIFE CHARACTERISTICS

7.0 BRAYTON CHARACTERISTICS

The flow schematic and state points (temperature and pressure) for the Brayton system are shown in Figure 7-1. A single primary lithium loop transports heat from the SP-100 reactor to the primary heat exchanger, which then heats the helium-xenon working fluid for the four Brayton loops. Only one of the Brayton loops is shown on the flow schematic. Heat is rejected from each of the Brayton power conversion loops by means of a cooler and a NaK heat rejection loop which also cools the Brayton alternator. Each Brayton loop is cross coupled to each of the four radiator panels so that if a power conversion failure occurs, there is no loss of radiator area.

A layout of the tuboalternator compressor (TAC) with overall dimensions is shown in Figure 7-2 and pertinent performance characteristics are shown in Table 7-1. The TAC has a radical inflow turbine and a radical outflow compressor. Both the journal end thrust bearings use compliant pad gas lubricated foil bearings. The gross cycle efficiency is 25.7%.

FIGURE 7-1
550 kWe SP-100 BRAYTON
FLOW SCHEMATIC AND STATE POINTS
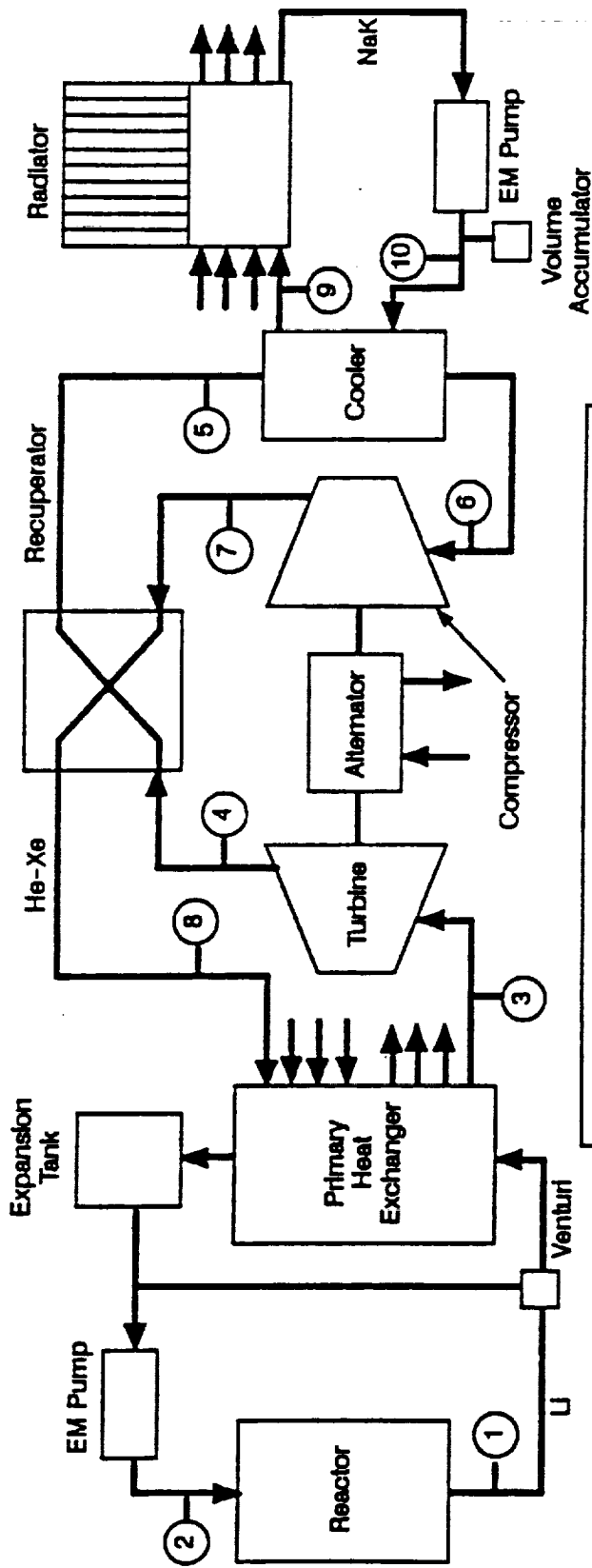
State Point	Fluid	Temperature (K)	Pressure (kPa)
1	U	1355	--
2	U	1276	--
3	He-Xe	1300	1,280
4	He-Xe	1041	690
5	He-Xe	640	680
6	He-Xe	406	675
7	He-Xe	556	1,340
8	He-Xe	957	1,330
9	NaK	631	--
10	NaK	397	--

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Rockwell International
Rocketdyne Division

FIGURE 7-2
TURBOALTERNATOR COMPRESSOR

Turbine Inlet

Turbine Exit

21.8 cm (8.6 in.)

17 cm (6.7 in.)

74 cm (29 in.)

150 cm (59 in.)

Compressor Exit

13.7 cm (5.4 in.)

Compressor Inlet

17.8 cm (7.0 in.)
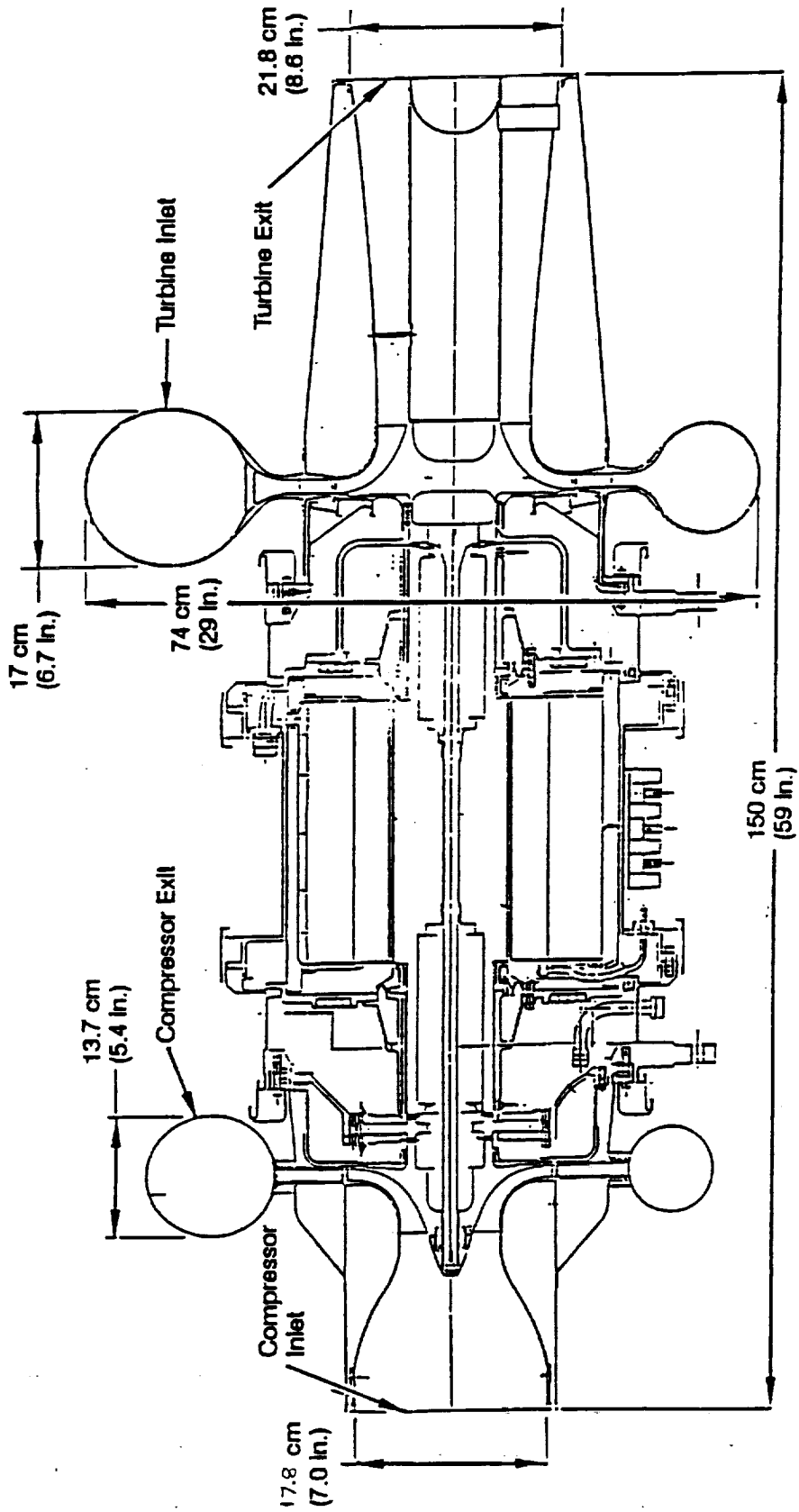
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TABLE 7-1
BRAYTON ENGINE CHARACTERISTICS

CONFIGURATION	SINGLE SHAFT TURBOALTERNATOR-COMPRESSOR
RECUPERATOR	
TURBINE INLET TEMP (K)	1300
COMPRESSOR INLET TEMP (K)	406
PRESSURE RATIO	1.99 TO 1
GROSS CYCLE EFFICIENCY	25.7
WORKING FLUID	He-Xe
WORKING FLUID MOLECULAR WT.	70
FREQUENCY (Hz)	1025
GROSS POWER OUTPUT (kWe)	194 AT 1000 V, 3 PHASE AC

8.0 STIRLING CHARACTERISTICS

The flow schematic and state points for the Stirling system are shown in Figure 8-1. Only one of the four loops is shown. A primary and secondary Li loop are used to transport heat to the Stirling engine heater. Helium is used as the working fluid for the Stirling cycle. Heat is rejected from the Stirling cooler through a NaK heat rejection loop, which is also used to cool the alternator. As with the Brayton system, the heat rejection loops are cross-coupled to each radiator panel. A layout of the Stirling engine with overall dimensions is shown in Figure 8-2 and pertinent performance characteristics are shown in Table 8-1. The Stirling engine is an opposed piston configuration to minimize vibration. The Stirling gross cycle efficiency is 33%.

FIGURE 8-1
550 kWe SP-100 STIRLING
FLOW SCHEMATIC AND STATE POINTS

State Point	Fluid	Temperature (K)
1	Li	1355
2	Li	1276
3	Li	1304
4	Li	1225
5	NaK	625
6	NaK	552
T_h	--	1265
T_c	--	602

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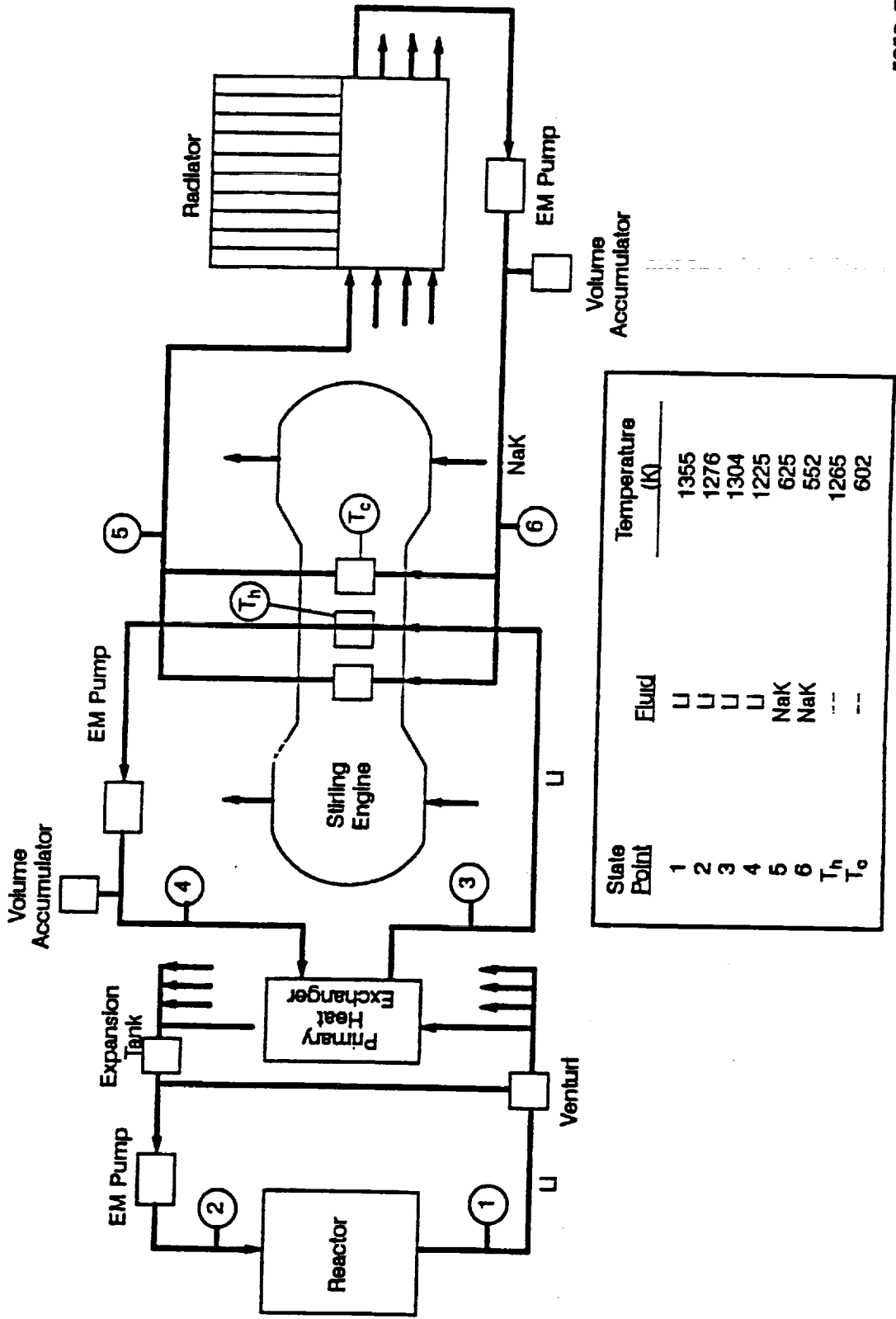
FIGURE 8-2
STIRLING POWER CONVERTER

55 cm

220 cm

Alternator Flange

Heater Flange
Cooler Flange
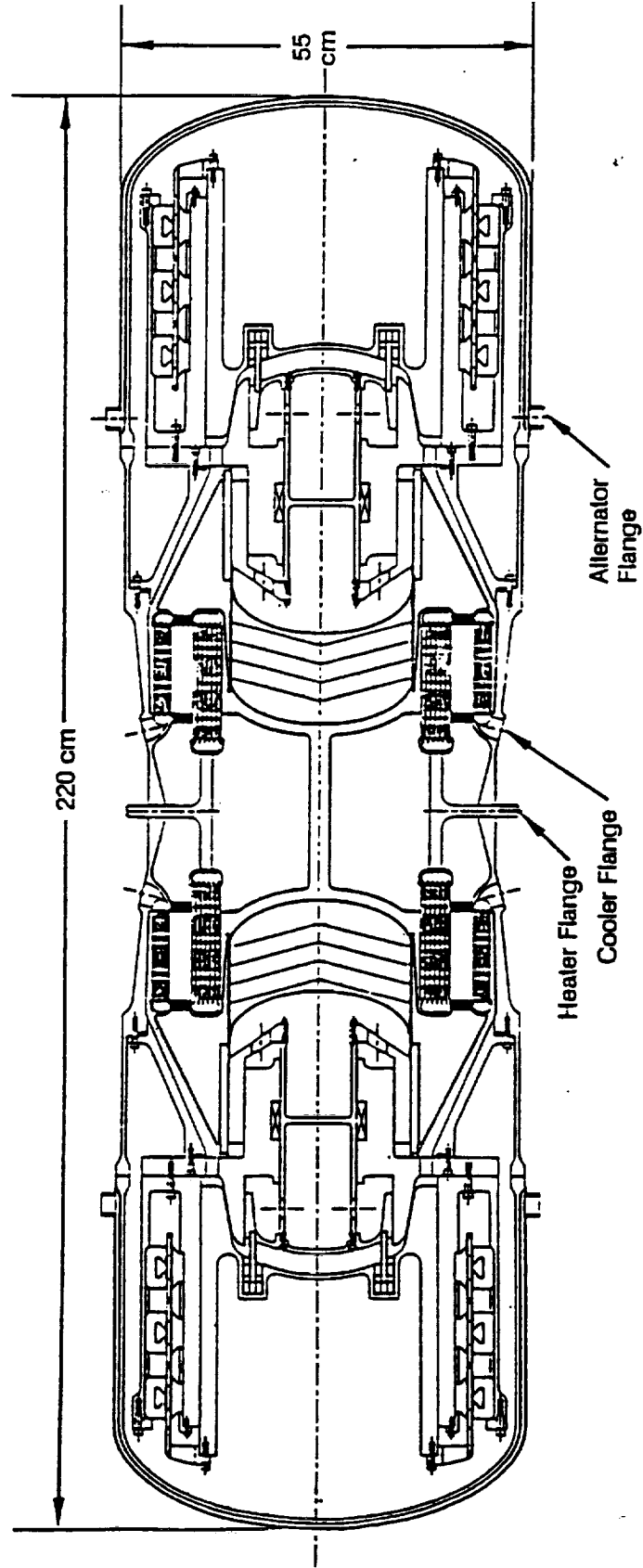
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TABLE 8-1
STIRLING ENGINE CHARACTERISTICS

CONFIGURATION ALTERNATOR	OPPOSED PISTON, LINEAR
HEATER HEAD TEMP (K)	1265
COOLER TEMP	602
TEMPERATURE RATIO	2.1
SPECIFIC MASS (kg/kW)	6.7
GROSS CYCLE EFFICIENCY %	33
WORKING FLUID	He
PRESSURE (bar/psia)	150/2175
FREQUENCY (Hz)	70
POWER OUTPUT (kWe)	199 AT 1000 V, SINGLE PHASE AC

9.0 BRAYTON INTEGRATION AND PERFORMANCE CHARACTERISTICS

9.1 SYSTEM CONFIGURATION

The overall deployed arrangement for the Brayton system is shown in Figure 9-1. The radiator panels are in a vertical cruciform configuration with the NaK headers located on the bottom of the radiator panels. Vertical reflux condenser tubes are connected to the header and reject the waste heat to space. The guard vessel radiators are located between the main radiator panels.

For launch, the radiator panels would be folded like an accordion and therefore the individual panels would require flexible connections between them for the NaK piping. The details of these radiator connection were not worked out as part of this study.

The SP-100 Brayton nuclear power system, without the radiator panels, is shown in plan and elevation in Figure 9-2. The overall height of the integrated system is 9 meters and the diameter is 2.3 meters.

The reactor, shield and primary Li heat transport loop is shown in Figure 9-3. The reactor shadow shield is used to prevent activation of secondary loop components and coolants. The primary loops includes the reactor, primary loop heat exchanger, dual wound EM pump, gas accumulator/expansion tank, flow control venturi (not shown--see flow diagrams), decay heat removal heat exchanger, and interconnecting piping. The primary loop heat exchanger is Li to He-Xe. The primary loop EM pump is a flat linear induction pump with redundant stators and power supplies. The gas accumulator/expansion tank is of a flow-through configuration to provide disengagement of the helium gas generated in the reactor and to provide volume expansion of the Li in going from cold to hot operating conditions. The decay heat removal heat exchanger rejects reactor decay heat when the power conversion system is shut down. This heat is transferred to the guard vessel, which in turn is rejected to space. Flow to the decay heat exchanger during normal operation is prevented by flow control venturi (see flow diagrams). All primary loop components are electrically trace heated to provide for controlled Li thaw during startup.

The entire primary loop is contained within a stainless steel guard vessel. This vessel is closed fitting around the reactor to prevent uncovering the reactor, should a breach in the Li primary loop occur. The vessel is borated in the vicinity of the reactor to minimize the effect on reactor control from back scattered neutrons. The guard vessel is passively cooled by reflux condenser pipes bonded to the outer surface. Heat generated in the vessel is dissipated in a separate radiator located above grade.

FIGURE 9-1
550 kWe SP-100 BRAYTON
RADIATOR CONFIGURATION

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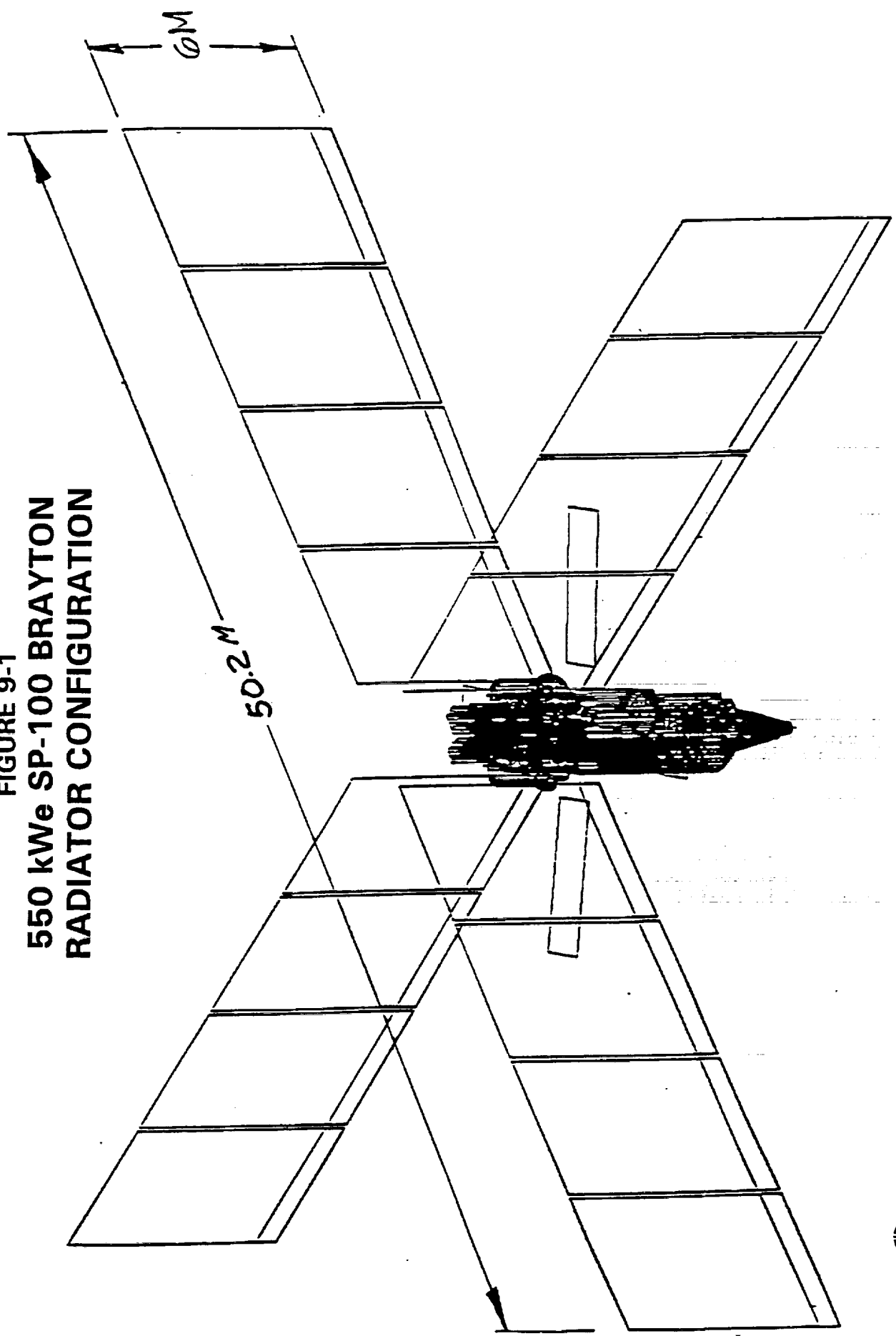
FIGURE 9-2
550 kWe SP-100 BRAYTON

9M.

2.3M

PLAN A-A   **PLAN B-B**
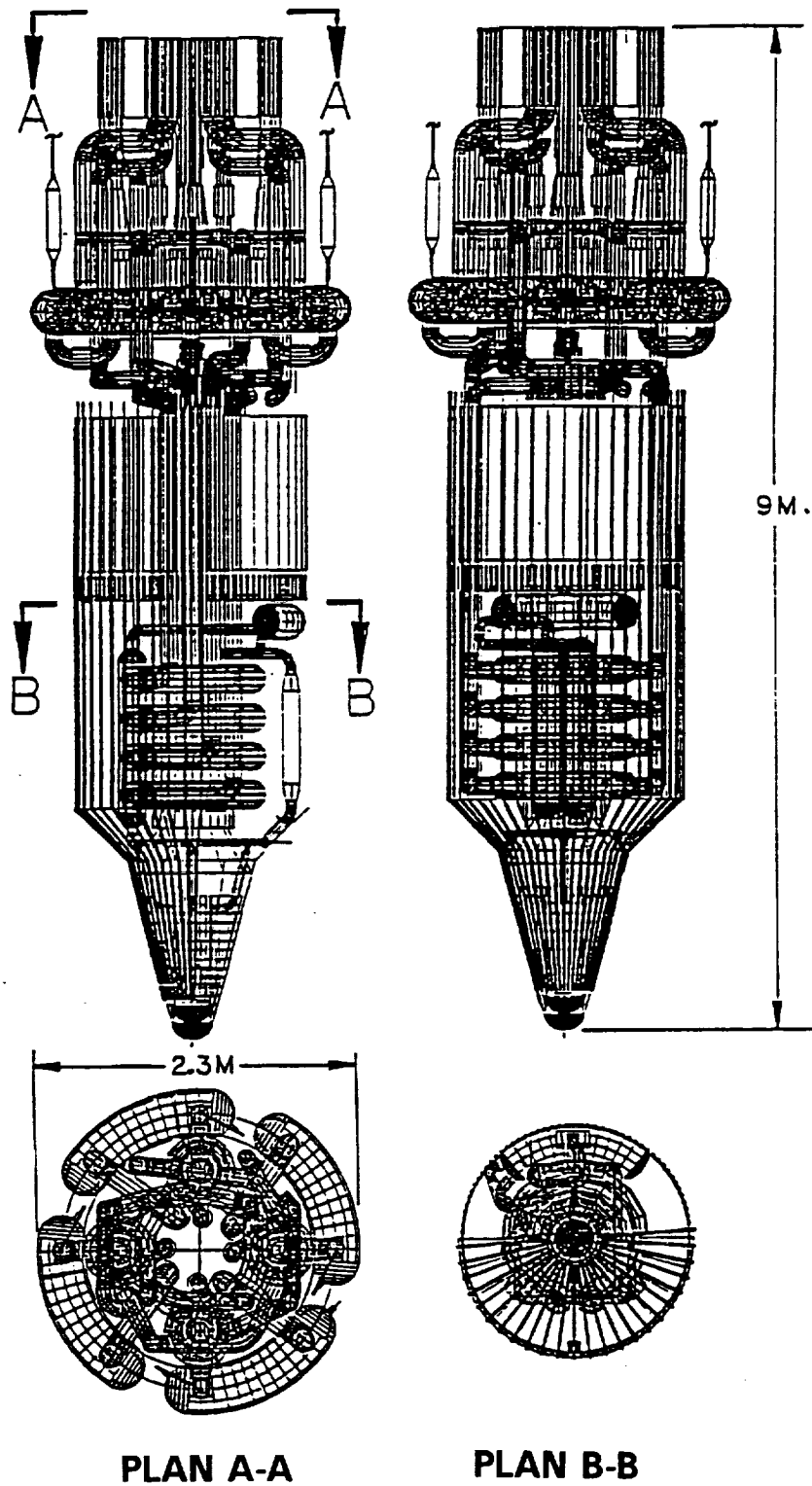
FIGURE 9-3
550 kWe SP-100 BRAYTON
PRIMARY HEAT TRANSPORT LOOP

CONTROL/SAFETY DRIVES

DECAY HEAT REMOVAL
HEAT EXCHANGER

GUARD VESSEL

GAS ACCUMULATOR/
EXPANSION TANK

GUARD VESSEL
COOLING PIPES

PRIMARY LOOP
HEAT EXCHANGER
(LI TO HEXE)

PRIMARY LOOP
LI EM PUMP

ACTIVATION SHIELD

REACTOR
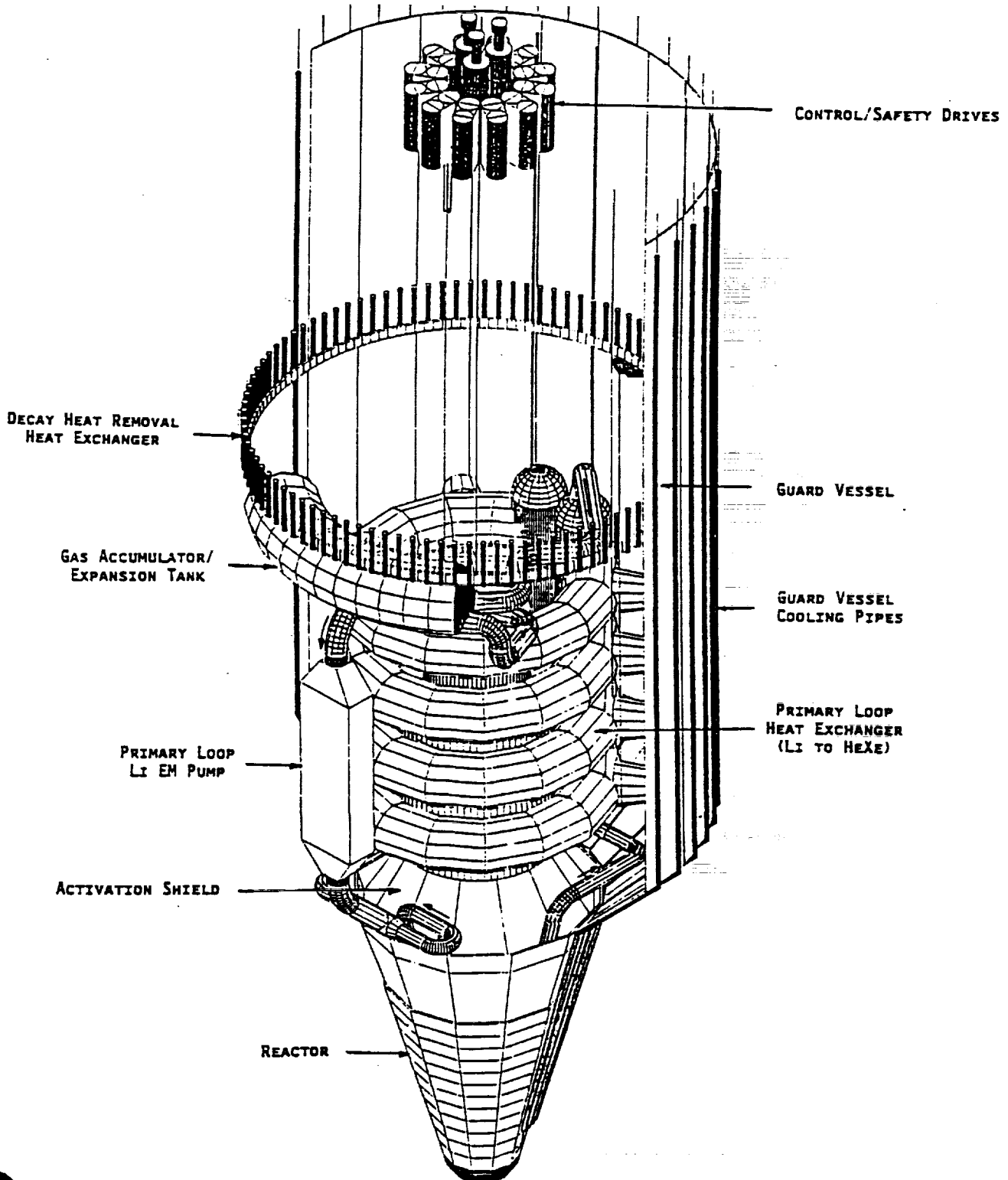
The power conversion equipment and associated gas ducting are shown in Figure 9-4. Ducts leading to and from the primary loop heat exchanger pass through the *regolith shield tank and are routed to the turbines, compressors and gas coolers as shown in the figure. The turboalternator-compressors are mounted vertically with the recuperators at the upper end. Control and safety rod drives, hidden in this view, are located just above the regolith shield.

The regolith shield tank, located between the primary loop equipment gallery and the power conversion equipment, is filled with the local regolith during installation and functions as a shutdown shield. The shielding thickness was sized to provide an operating dose rate at grade levels of 50 rem/hr and a dose rate of 1 mrem/hr at 200 m from the reactor (which includes scattering from above grade components). The dose rate at components located above grade after shutdown is less than 10 mrem/hr, which is sufficiently low to allow extended maintenance. If above grade access for maintenance is not required the regolith shield can be eliminated.

9.2 BRAYTON COMPONENT CHARACTERISTICS

Additional detail on the Brayton system components alluded to in the preceding system description is provided in Table 9-1 which includes a capsule description of each component along with pertinent dimensions as appropriate. For the main radiator, H_2O heat pipes were used up to a temperature equivalent to an internal pressure of 6.9 mpa (1000 psia). For the Brayton system this resulted in only a few Hg heat pipes (1%). Small cycle changes could be made that would result in an all H_2O radiators.

9.3 BRAYTON SYSTEM MASS BREAKDOWN

A detailed mass estimate was made for the Brayton system, as tabulated in Table 9-2. It can be noted that the total mass is different depending if the output is 1000 Vdc or 1000 Vrms, 1 kHz.

9.4 BRAYTON SYSTEM PERFORMANCE SUMMARY

Performance parameters for the 550 kWe SP-100 Brayton system are tabulated in Table 9-3. The net cycle efficiency of 23.8% permits the reactor to operate at about 2.3 mwt instead of 2.4 mwt, thereby extending its life from a nominal 7 years to 7.6 years. It should be noted that this is a mass-optimized design point and operating characteristics could be varied (at the expense of increased mass) to increase efficiency or decrease radiator area. This was illustrated in the initial optimization analysis shown in Figure 5-1. As the radiator area is increased, efficiency of the cycle increases. This results since the cycle temperature ratio increases (compressor inlet temperature decreases).

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FIGURE 9-4
550 kWe SP-100 BRAYTON
GAS WORKING FLUID LOOPS

RECUPERATOR (4)

HEAT REJECTION LOOP
NaK EM PUMP (4)

TURBOALTERNATOR
COMPRESSOR (4)

GAS COOLER
(HeXe TO NaK)

REGOLITH SHIELD TANK

PRIMARY LOOP
HEAT EXCHANGER
(Li TO HeXe)

Rockwell International

Rocketdyne Division
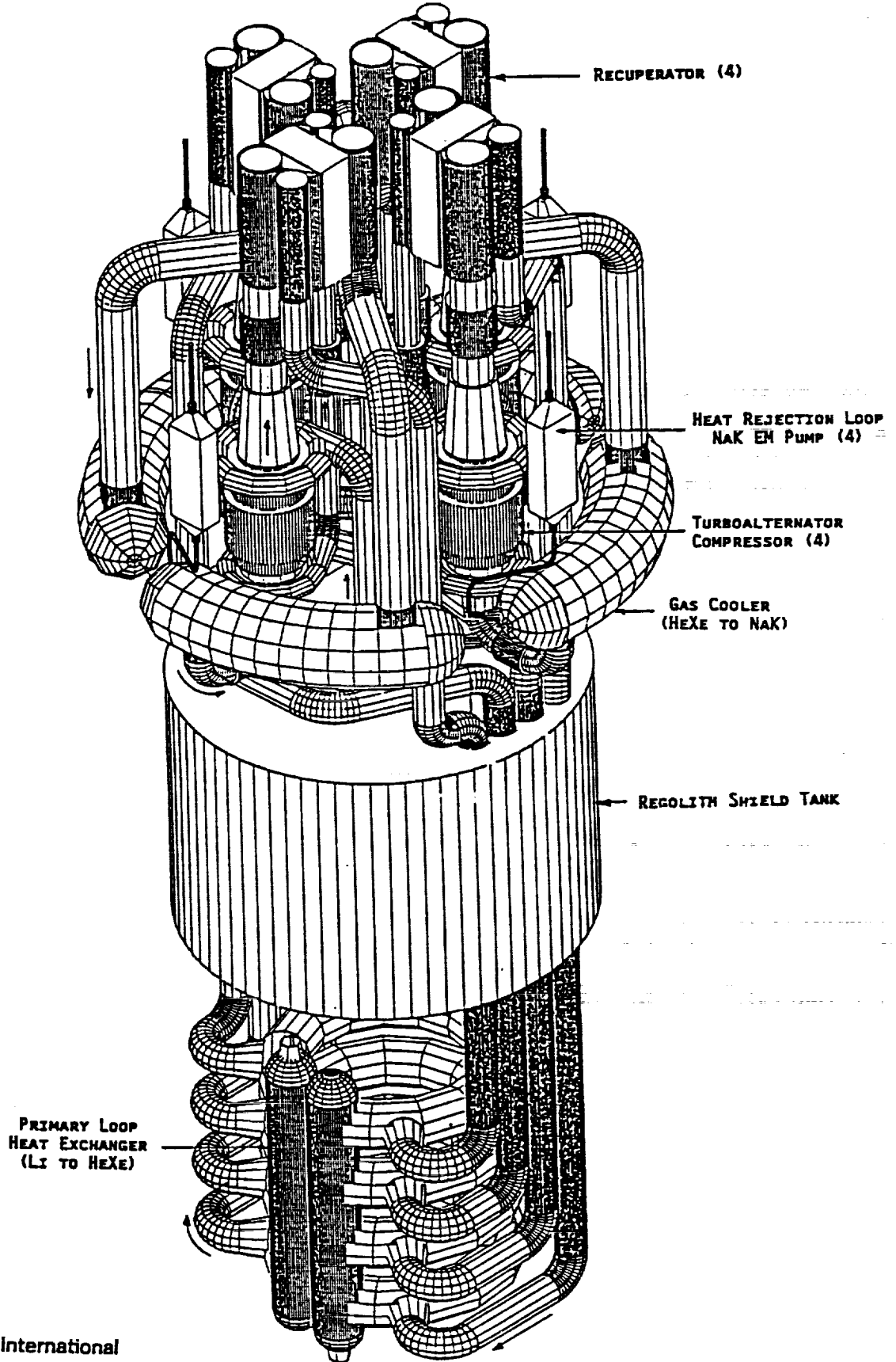
TABLE 9-1
BRAYTON SYSTEM COMPONENTS

COMPONENT	DESCRIPTION	DIMENSIONS, ETC.
CAVITY LINER	STAINLESS STEEL FINNED HEAT PIPE ASSEMBLY. H_2O WORKING FLUID. RADIATORS TILTED AT 15°. .076 CM SS CAVITY LINER.	RADIATOR AREA 25 M^2. TEMPERATURE 500K.
DECAY HEAT REMOVAL SUBSYSTEM	MANIFOLD COOLED BY 100 CARBON-CARBON H_2O HEAT PIPES, RADIATING TO CAVITY LINER.	5 CM. RISER AND DOWNCOMER. 3.7 METERS ABOVE REACTOR. .25 METER LONG HEAT PIPES.
VENTURI	PROVIDES STATIC PRESSURE DROP EQUAL TO REACTOR PRESSURE DROP TO MINIMIZE FLOW THRU DECAY HEAT REMOVAL SYSTEM WHILE PRIMARY LOOP/REACTOR IS OPERATING.	4 CM. THROAT DIAMETER.
PRIMARY EM PUMP	FLAT LINEAR INDUCTION PUMP WITH 2 STATORS.	16.0 CM. HIGH X 32 CM. WIDE X 127 CM. LONG.
INTERMEDIATE HEAT EXCHANGER	LITHIUM TO HE/XE HEAT EXCHANGER, FOUR CIRCULAR TUBE BUNDLES, MANIFOLDED TO RISER AND DOWNCOMER PIPES.	200, 1.3 CM. TUBES PER TUBE BUNDLE.

tskord12.rbh

TABLE 9-1

BRAYTON SYSTEM COMPONENTS (CONT'D)

COMPONENT	DESCRIPTION	DIMENSIONS, ETC.
PRIMARY EXPANSION TANK	CURVED CYLINDRICAL TANK TO ACCOMMODATE LITHIUM EXPANSION AND HELIUM GAS GENERATION.	.13 M^3 VOLUME.
HEAT REJECTION HEAT EXCHANGER (4)	HE/XE TO NAK SHELL AND TUBE HEAT EXCHANGER.	535, .95 CM. TUBES. TUBE BUNDLE 38 CM. DIA. x 193 CM. LONG.
HEAT REJECTION LOOP EM PUMPS. (4)	FLAT LINEAR INDUCTION PUMP.	13 CM. HIGH x 23 CM. WIDE x 58 CM. LONG.
HEAT REJECTION LOOP EXPANSION TANKS (4)	CYLINDRICAL NAK TANK.	.035 M^3 VOLUME.
RADIATOR MANIFOLD	4 COMPARTMENT NAK MANIFOLD, RUNNING LENGTH OF RADIATOR.	EACH COMPARTMENT CROSS SECTION 15 CM. x 1.5 CM.
MAIN RADIATOR	CARBON-CARBON FINNED HEAT PIPE VERTICALLY ORIENTED 922 H_2O HEAT PIPES 10 HG HEAT PIPES	565 M^2 TOTAL AREA, 471 AVE RADIATION TEMPERATURE

TABLE 9-2
BRAYTON SYSTEM MASS BREAKDOWN SUMMARY
550 kWe LUNAR SURFACE POWER SYSTEM

	Mass (kg)		Mass (kg)
Reactor Assembly	**703**	**Secondary Heat Transport**	**1157**
Fuel Pins	315	Gas to Nak Cooler (4)	764
Reactor Vessel & Internals	193	EM Pump (4)	209
Reflectors	125	Volume Accumulator (4)	32
Safety Rods	25	Piping	112
Reentry Shield	45	Bleed Cooler (4)	40
Activation Shield	**975**	**Heat Rejection**	**4960**
Neutron (LiH)	260	Radiator Panels & Manifolds	4460
Gamma (W)	215	Deployment/Structure	500
Be Conduction, Shell	300		
Structure/Vessel	200	**Power Processing & Control**	**2369**[1]
		Power System	2175
Primary Heat Transport	**1124**	Speed Regulator/Filter	660
Heat Source Heat Exchanger	209	Parasitic Load Radiator	140
EM Pump	300	Rectifier	865
Expansion Tank	17	Pump Power Supplies	20
Decay Heat Removal HX	18	Cables	50
Flow Control Venturi	2	Instrumentation & Control	185
Piping	54	Electronics Radiator	255
Insulation	94		
Li Coolant	330	**Reactor System**	**194**
Trace Heaters	100	Safety Rod Drive Assembly	54
		Control Drive Assembly	83
Power Conversion	**3302**	Control Sensors	47
Engine/Alternator (4)	1495	Neutron Monitor	10
Recuperator (4)	659		
Ducting (4)	675	**Structure/Containment**	**1178**
Insulation (4)	352	Guard Vessel	488
Inventory Control (4)	121	Internal Structure	200
		Heat Pipes/Radiator	490
		TOTAL	**15,768**[2]
			14,903[3]

(1) Mass can be reduced by 865 kg using 1000 Vrms, 1 kHz output
(2) 1000 Vdc
(3) 1000 Vrms, 1kHz

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TABLE 9-3
550 kWe SP-100 BRAYTON
PERFORMANCE SUMMARY

NET POWER OUTPUT (kWe)	550
GROSS POWER OUTPUT (kWe)	582
REACTOR THERMAL POWER (kWt)	2309
NET CYCLE EFFICIENCY (%)	23.8
REACTOR FULL POWER OPERATING LIFE (Y)	7.6
NUMBER OF OPERATING/REDUNDANT POWER CONVERTERS	3/1
TEMPERATURES (K)	
REACTOR OUTLET	1355
TURBINE INLET	1300
COMPRESSOR INLET	406
RADIATOR PLATFORM AREA (M^2)	
MAIN	565
VESSEL COOLING	25
TOTAL POWER SYSTEM MASS (kg)	
1000 Vdc	15,768
1000 Vrms, 1 kHz	14,903

10.0 STIRLING INTEGRATION AND PERFORMANCE CHARACTERISTICS

The overall deployed arrangement for the Stirling system is shown in Figure 10-1. This arrangement is similar to that for the Brayton system. The guard vessel radiators are not shown in this illustration. Because of the smaller size of the Stirling main radiators vs. the Brayton, folding the panels for launch would be expected to be substantially easier from an assembly standpoint.

The SP-100 Stirling nuclear power system, without the radiator panels, is shown in elevation in Figures 10-2 and 10-3. The overall height of the integrated system is 7.9 meters and the diameter is 2.45 meters.

The reactor, shield, and primary Li heat transport loop is shown in Figure 10-4. The components of the primary Li loop are essentially the same as for the Brayton system except for the four primary loop heat exchangers which are Li to Li and therefore more compact than the Li to He-Xe heat exchangers of the Brayton system.

The power conversion equipment and associated Li piping are shown in Figure 10-5. Li pipes leading to and from the primary loop heat exchangers pass through the optional regolith shield tank and are routed to the Stirling engines as shown in the figure. Control and safety rod drives, not shown in the illustration, are located just above the regolith shield, which is sized to the same radiation dose rates as the Brayton shield.

10.1 STIRLING COMPONENT CHARACTERISTICS

Additional detail on the Stirling system components is provided in Table 10-1 which includes a capsule description of each component, along with pertinent dimensions as appropriate. It can be noted for the main radiator about 30% of the heat pipes use Hg as the working fluid.

10.2 STIRLING SYSTEM MASS BREAKDOWN

A detailed mass estimate was made for the Stirling system, as tabulated in Table 10-2. It can be noted that the total mass is different depending on whether the output voltage is 1000 Vdc or 1000 Vrms, 1kHz.

10.3 STIRLING SYSTEM PERFORMANCE SUMMARY

Performance parameters for the 550 kWe SP-100 Stirling system are tabulated in Table 10-3. Because the Stirling system optimizes at 29.7% efficiency (higher than the Brayton system), the reactor full power operating life is extended to 9.6 years. As with the Brayton system, the Stirling system is mass-optimized and therefore efficiency could be increased or radiator area decreased with a concomitant increase in system mass.

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FIGURE 10-1
550 kWe SP-100 STIRLING
RADIATOR CONFIGURATION
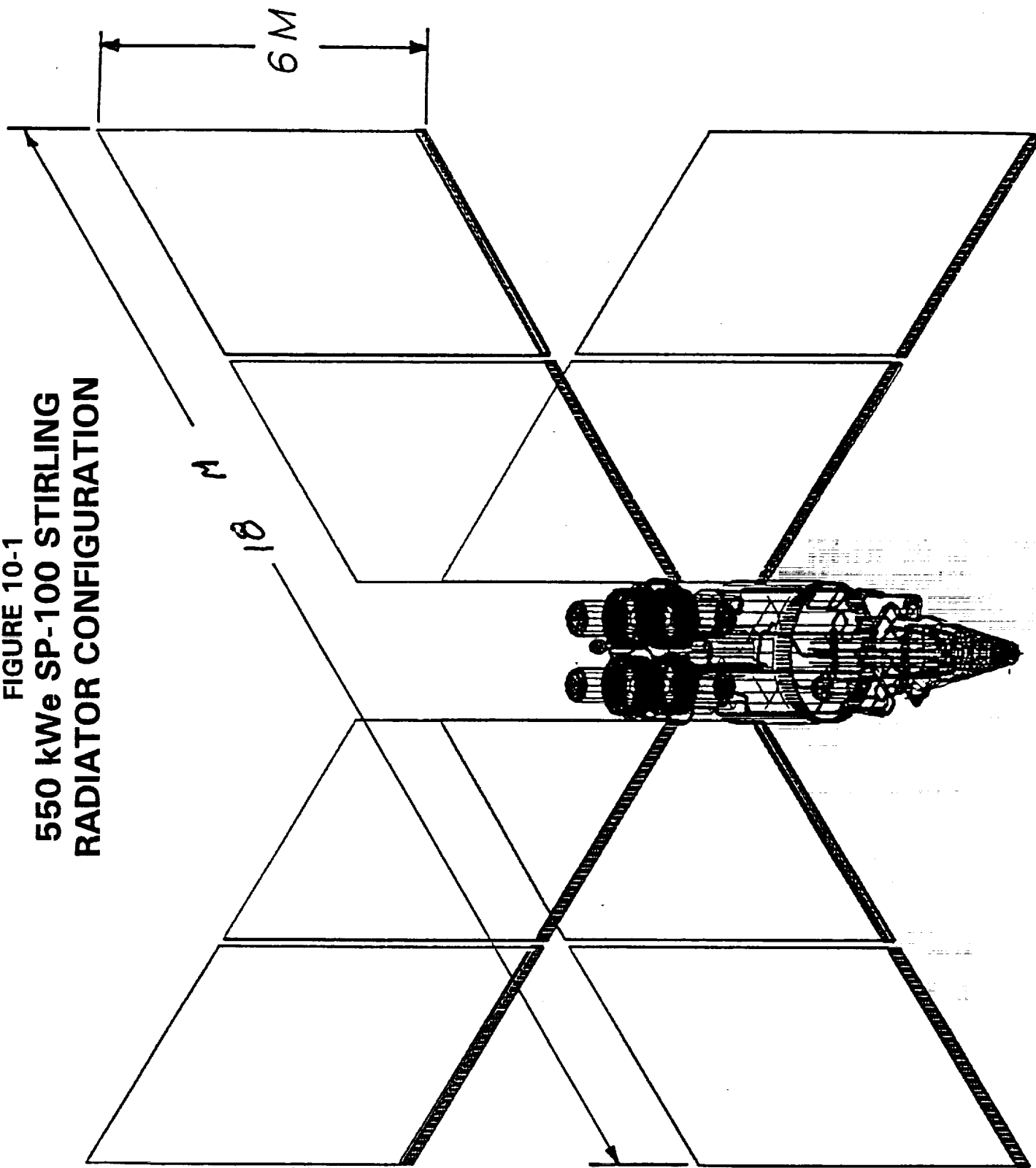
FIGURE 10-2
550 kWe SP-100 STIRLING

2.45 M

7.9 M
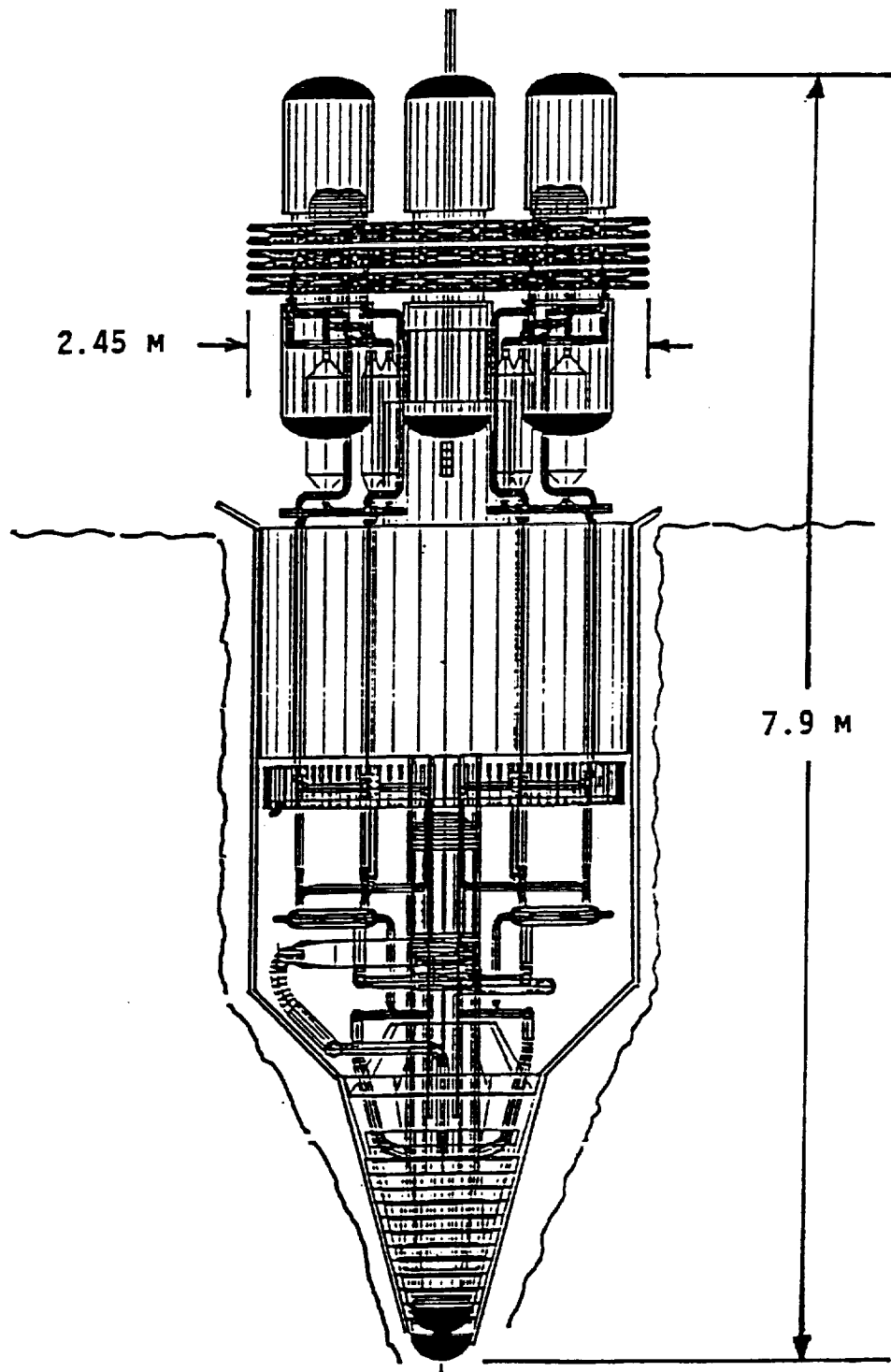
VIEW B

FIGURE 10-3
550 kWe SP-100 STIRLING

STIRLING ENGINE (4)

SECONDARY LOOP
Li EM PUMP (4)

REGOLITH SHIELD TANK

DECAY HEAT REMOVAL
HEAT EXCHANGER

GAS ACCUMULATOR/
EXPANSION TANK

PRIMARY LOOP
Li EM PUMP

GUARD VESSEL

PRIMARY LOOP
HEAT EXCHANGER (4)
(Li TO Li)

ACTIVATION SHIELD

REACTOR

40
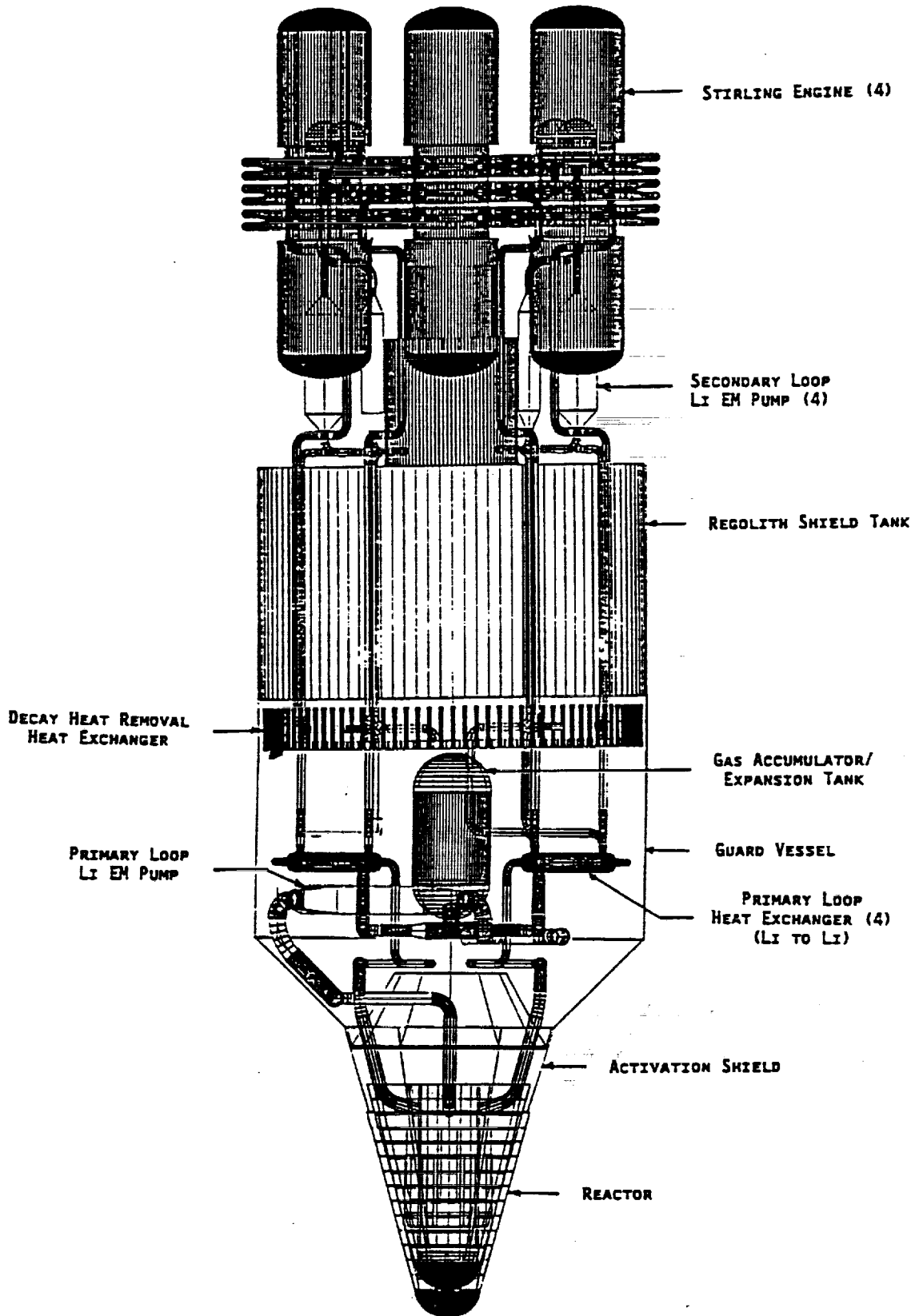
FIGURE 10-4
550 kWe SP-100 STIRLING
PRIMARY HEAT TRANSPORT LOOP

CONTROL/SAFETY DRIVES

REGOLITH SHIELD TANK

GAS ACCUMULATOR/
EXPANSION TANK

DECAY HEAT REMOVAL
HEAT EXCHANGER

PRIMARY LOOP
HEAT EXCHANGER (4)
(LI TO LI)

PRIMARY LOOP
LI EM PUMP

ACTIVATION SHIELD

REACTOR
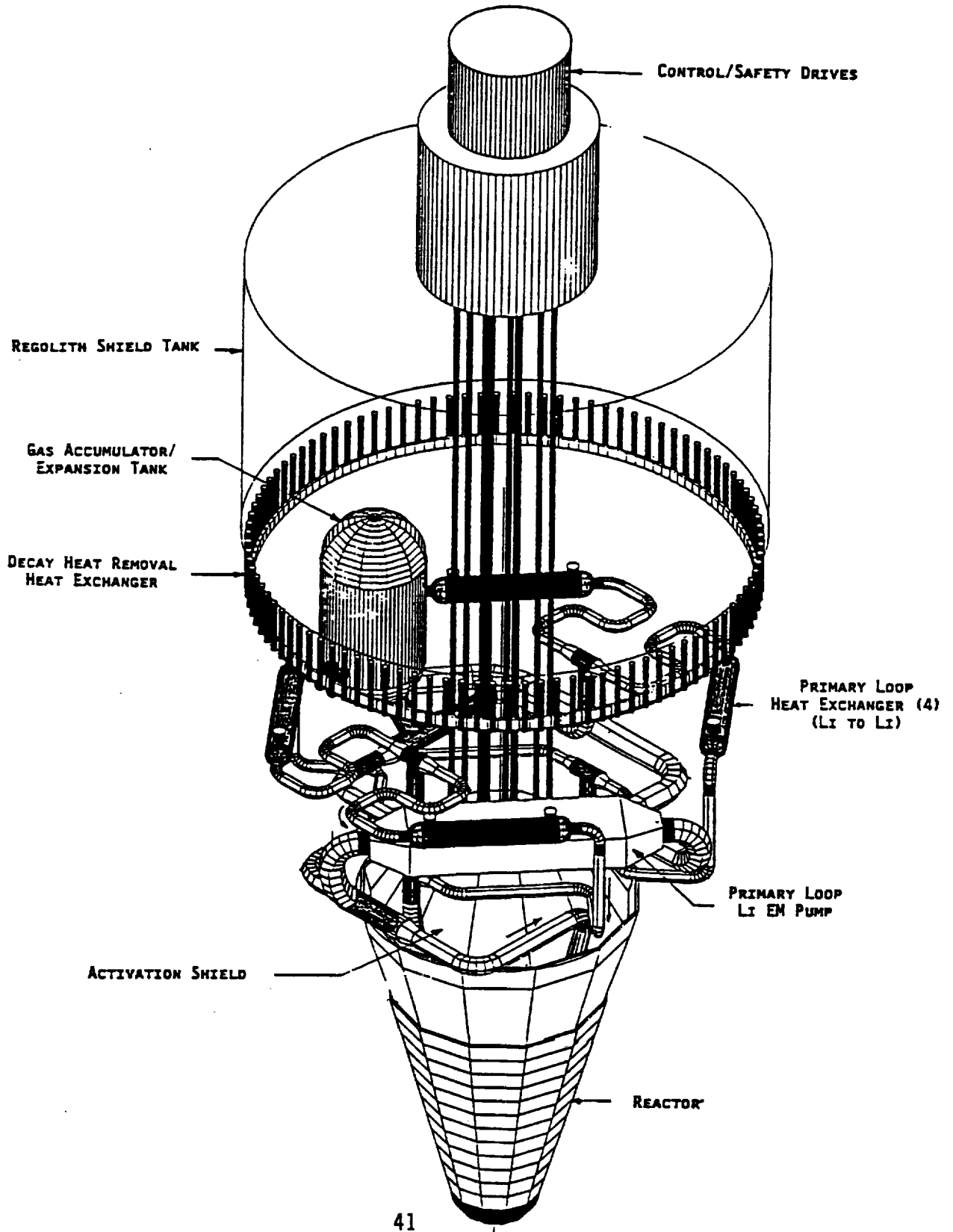
FIGURE 10-5
550 kWe SP-100 STIRLING
SECONDARY LOOP AND
POWER CONVERSION SYSTEM

VOLUME
ACCUMULATOR (4)

STIRLING ENGINE (4)

SECONDARY LOOP
LI EM PUMP (4)

REGOLITH
SHIELD TANK

SECONDARY
LI LOOP (4)

PRIMARY LOOP
HEAT EXCHANGER (4)
(LI TO LI)

42
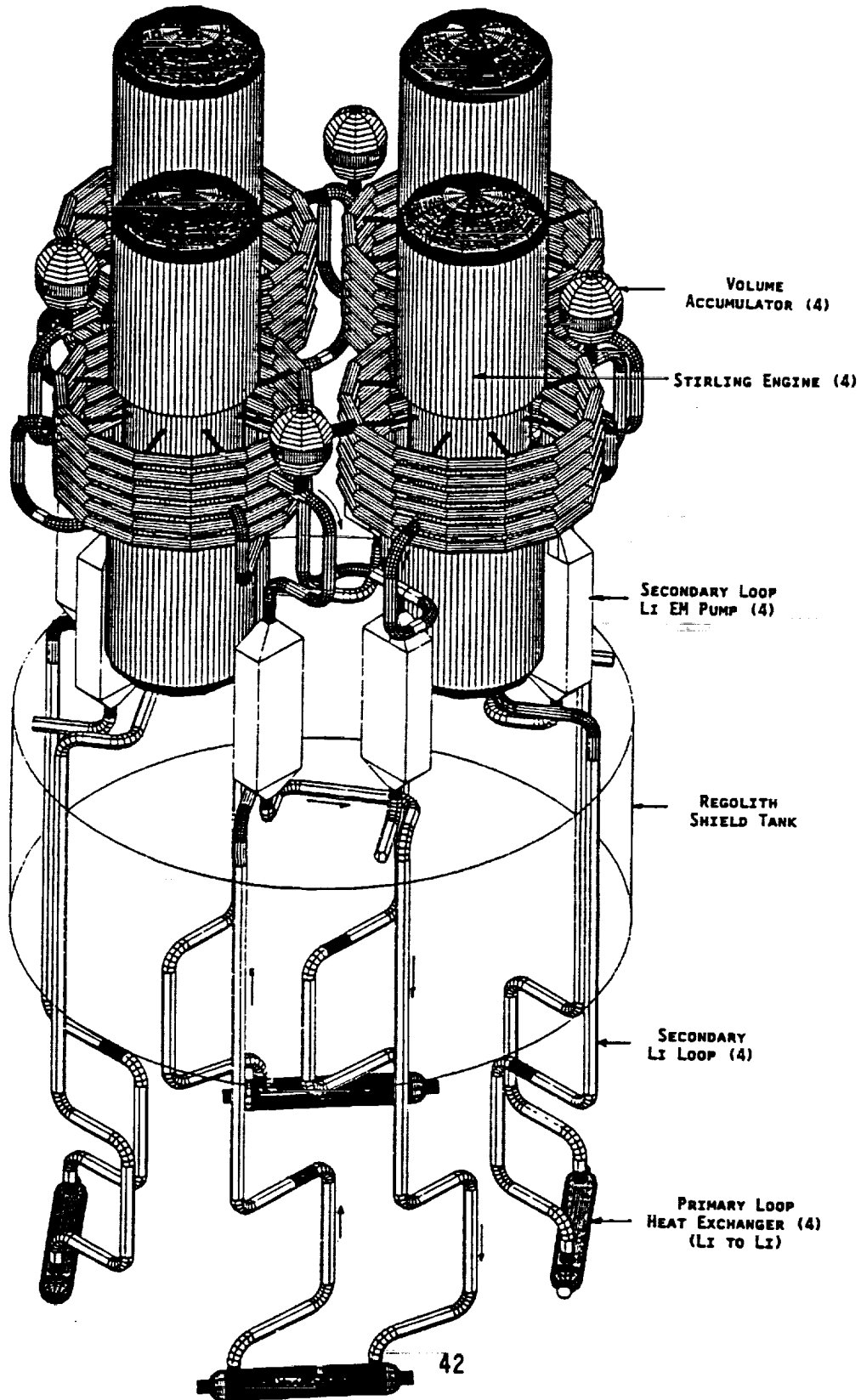
TABLE 10-1
STIRLING SYSTEM COMPONENTS

COMPONENT	DESCRIPTION	DIMENSIONS, ETC.
CAVITY LINER	SAME AS BRAYTON	----
DECAY HEAT REMOVAL SUBSYSTEM	SAME AS BRAYTON	----
VENTURI	SAME AS BRAYTON	----
PRIMARY EM PUMP	SAME AS BRAYTON	----
INTERMEDIATE HEAT EXCHANGERS (4)	LI TO LI SHELL AND TUBE HX	60, .95 CM. TUBES IN EACH TUBE BUNDLE.
PRIMARY EXPANSION TANK	CYLINDRICAL LI TANK. SAME FUNCTION AS FOR BRAYTON SYSTEM.	.13 M^3 VOLUME.

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TABLE 10-2

STIRLING SYSTEM COMPONENTS (CONT'D)

COMPONENT	DESCRIPTION	DIMENSIONS, ETC.
SECONDARY EM PUMPS (4)	FLAT LINEAR INDUCTION LI PUMP	13 CM. HIGH X 23 CM. WIDE X 58 CM. LONG
SECONDARY EXPANSION TANK	CYLINDRICAL LI TANK	$.009 \ M^3$ VOLUME
HEAT REJECTION LOOP EM PUMPS (4)	SAME AS BRAYTON	- - -
HEAT REJECTION LOOP EXPANSION TANKS (4)	SAME AS BRAYTON	- - -
RADIATOR MANIFOLD	SAME AS BRAYTON	- - -
MAIN RADIATOR	CARBON-CARBON FINNED SUBSTITUTE. HEAT PIPES VERTICALLY ORIENTED 294 H_2O HEAT PIPES 121 HG HEAT PIPES	185 M^2 TOTAL AREA, 567K AVERAGE RADIATION TEMPERATURE

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TABLE 10-2
STIRLING SYSTEM MASS BREAKDOWN SUMMARY
550 kWe LUNAR SURFACE POWER SYSTEM

	Mass (kg)			Mass (kg)	
Reactor Assembly	703		**Power Conversion**	5433	
Fuel Pins		315	Engine/Alternator (4)		5333
Reactor Vessel & Internals		193	Insulation (4)		100
Reflectors		125			
Safety Rods		25	**Heat Rejection Heat Transport**	420	
Reentry Shield		45	EM Pump (4)		210
			Volume Accumulator (4)		35
Activation Shield	975		Piping		60
Neutron (LiH)		260	NaK		115
Gamma (W)		215			
Be Conduction, Shell		300	**Heat Rejection**	2025	
Structure/Vessel		200	Radiator Panels & Manifolds		1675
			Deployment/Structure		350
Primary Heat Transport	827				
Heat Source Heat Exchanger		100	**Power Processing & Control**	2609[1]	
EM Pump		300	Power System	2415	
Expansion Tank		17	Pf Capacitors		100
Decay Heat Removal HX		18	Speed Regulator/Filter		660
Flow Control Venturi		2	Parasitic Load Radiator		140
Piping		60	Rectifier		975
Insulation		50	Pump Power Supplies		20
Li Coolant		220	Cables		70
Trace Heaters		60	Instrumentation & Control		145
			Electronics Radiator		305
Secondary Heat Transport	860		Reactor System	194	
EM Pump (4)		210	Safety Rod Drive Assembly		54
Volume Accumulator (4)		20	Control Drive Assembly		83
Piping		265	Control Sensors		47
Insulation (4)		100	Neutron Monitor		10
Li Coolant		140			
Trace Heaters		125	**Structure/Containment**	1080	
			Containment Vessel		430
			Internal Structure		180
			Heat Pipes/Radiator		470
			TOTAL	14,932[2]	
				15,217[3]	

(1) Mass will increase by 285 kg using 1000 Vrms, 1 kHz output
(2) 1000 Vdc
(3) 1000 Vrms, 1 kHz

TABLE 10-3
550 kWe SP-100 STIRLING
PERFORMANCE SUMMARY

NET POWER OUTPUT (kWe)	550
GROSS POWER OUTPUT (kWe)	596
REACTOR THERMAL POWER (kWt)	1850
NET CYCLE EFFICIENCY (%)	29.7
REACTOR FULL POWER OPERATING LIFE (Y)	9.6
NUMBER OF OPERATING/REDUNDANT POWER CONVERTERS	3/1
TEMPERATURES (K)	
REACTOR OUTLET	1355
AVERAGE HOT SIDE	1265
AVERAGE COLD SIDE	602
RADIATOR PLATFORM AREA (M^2)	
MAIN	185
VESSEL COOLING	25
TOTAL POWER SYSTEM MASS (kg)	
1000 Vdc	14,932
1000 Vrms, 1kHz	15,217

11.0 SYSTEM COMPARISON

As shown by this study, either a Brayton or a Stirling power conversion subsystem can be integrated with the SP-100 reactor to produce 550 kw of electrical power continuously for more than 7 years.

Figures 11-1 through 11-3 show the layouts of the two systems side-by-side to facilitate comparison of their characteristics. The salient differences between the two systems are:

- Radiator area for the Stirling system is only 40% of that for the Brayton system. This would make the Stirling system easier to package for launch, transit, and landing on the moon. Radiator deployment would also be simplified.

- The Stirling system is less congested than the Brayton system because the lithium piping is much smaller in size than the corresponding He-Xe ducting, and there are fewer (and smaller) components in the power conversion system. As a result, the Stirling system envelope is over a meter shorter than the Brayton system envelope. These Stirling system characteristics probably would render it more maintainable than the Brayton system, although it should be emphasized that a maintenance study has not yet been performed. The Stirling engine, however, is more complex containing the Brayton equivalent of the primary loop heat exchanger, recuperator, and cooler. This presents not only an engineering challenge, but results in a more massive engine than the Brayton turboalternator, compressor, and recuperator combination.

- The Brayton system has gas lines penetrating the regolith shield while the Stirling has much smaller liquid metal lines. While no detailed shielding calculations were performed, the Brayton would have a significantly increased streaming problem, which would result in a larger shield.

Finally, the performance parameters of the two systems are tabulated in Table 11-1. On a mass basis, the Brayton system offers a 2% advantage for 1000 Vrms, 1 kHz output, and the Stirling a 5% advantage at a 1000 Vdc output. The Stirling system has a factor of 3.2 area advantage and provides a 26% longer reactor full power operating life.

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FIGURE 11-1
550 kWe LUNAR SURFACE POWER SYSTEM
OVERALL SYSTEM CONFIGURATION

6M

18.0M

48

STIRLING

ØM

50.2M
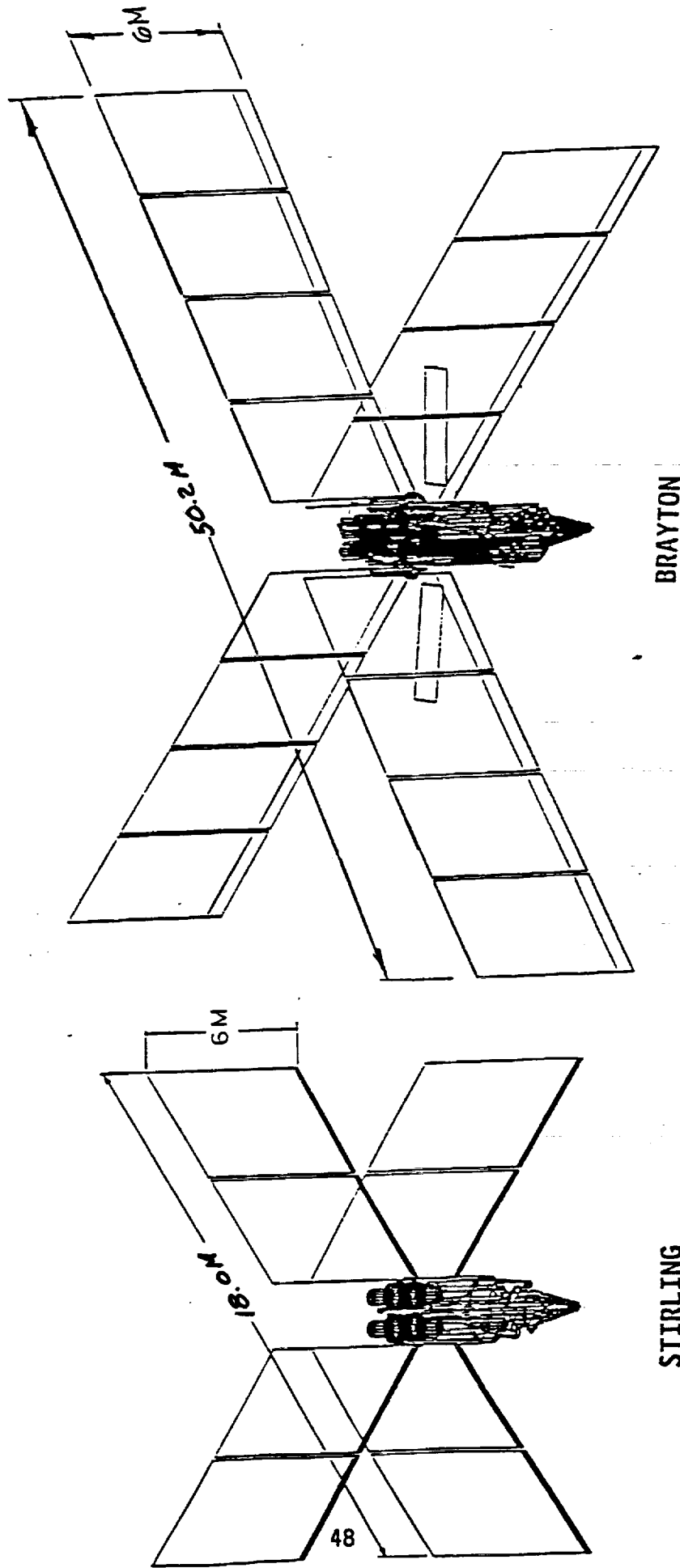
BRAYTON

FIGURE 11-2
550 kWe LUNAR SURGACE POWER SYSTEM
REACTOR AND PRIMARY LOOP

Control/Safety Drives

Guard Vessel

Guard Vessel Cooling Pipes

Primary Loop Heat Exchanger (Li to He-Xe)

Decay Heat Removal Heat Exchanger

Gas Accumulator/Expansion Tank

Primary Loop Li EM Pump

Activation Shield

Reactor

Brayton

5953-10

Control/Safety Drives

Primary Loop Heat Exchanger (4) (Li to Li)

Primary Loop Li EM Pump

Reactor

Regolith Shield Tank

Gas Accumulator/Expansion Tank

Decay Heat Removal Heat Exchanger

Activation Shield

Stirling

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FIGURE 11-3
550 kWe LUNAR SURFACE POWER SYSTEM
POWER CONVERSION LOOP

Recuperator (4)

Heat Rejection Loop NaK EM Pump (4)

Turboalternator Compressor (4)

Gas Cooler (He-Xe to NaK)

Regolith Shield Tank

Primary Loop Heat Exchanger (Li to He-Xe)

Brayton

Volume Accumulator (4)

Stirling Engine (4)

Secondary Loop Li EM Pump (4)

Regolith Shield Tank

Secondary Li Loop (4)

Primary Loop Heat Exchanger (4) (Li to Li)

Stirling

5953-11

50
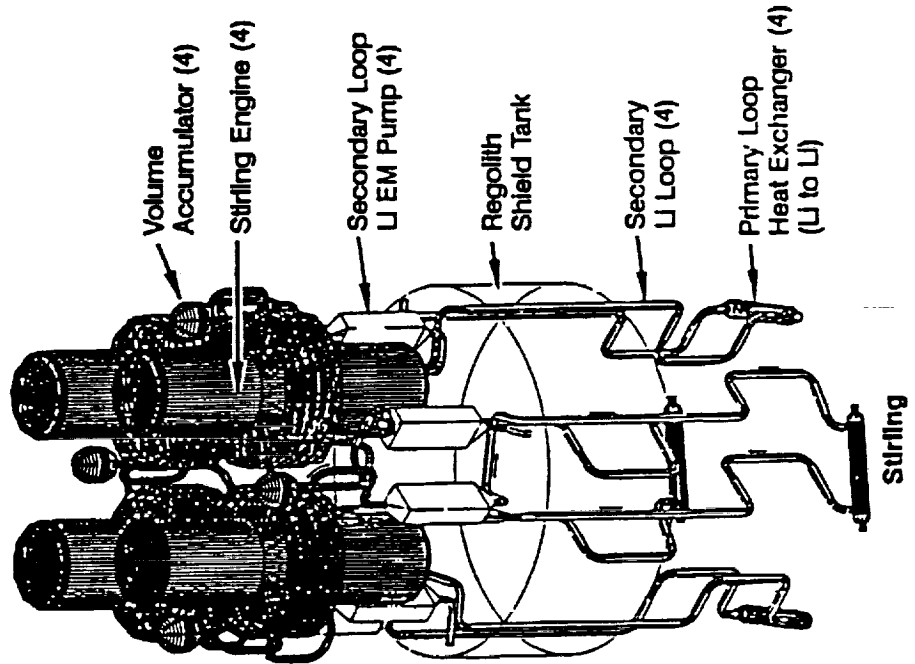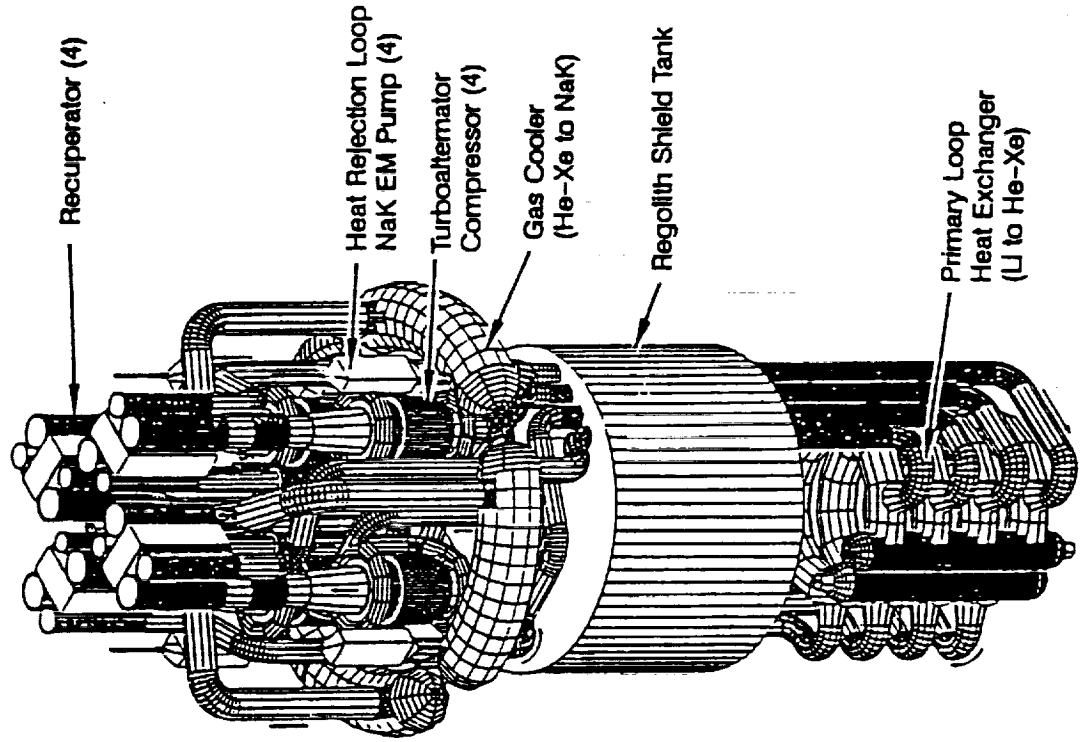
TABLE 11-1
PERFORMANCE COMPARISON
550 kWe LUNAR SURFACE POWER SYSTEMS

	BRAYTON	STIRLING
Net Power Output (kWe)	550	550
Gross Power Output (kWe)	582	596
Reactor Thermal Power (kWt)	2,309	1,850
Net Cycle Efficiency (%)	23.8	29.7
Reactor Full-Power Operating Life (yr)	7.6	9.6
Number of Operating/Redundant Converters	3/1	3/1
Temperatures (K)		
Reactor Outlet	1,355	1,355
Hot Side	1,300	1,265
Cold Side	406	602
Radiator Planform Area (m²)		
Main plus Auxiliaries	304	185
Vessel Cooling	25	25
Power System Mass (kg)		
Reactor	703	703
Shield	975	975
Primary Heat Transport	1,124	1,687
Power Conversion	3,302	5,433
Heat Rejection Heat Transport	1,157	420
Heat Rejection	4,960	2025
Power Processing and Control	2,369[1]	2,609[2]
Structure/Containment	1,178	1,080
TOTAL 1000 Vdc	15,768	14,932
1000 Vrms, 1 kHz	14,903	15,217

[1] 1000 Vdc, Reduce by 856 Kg for 1000 Vrms, 1 KHz
[2] 1000 Vdc, increase by 285 Kg for 1000 Vrms, 1 kHz

12.0 SYSTEM CONTROL AND PARTIAL POWER OPERATION

12.1 REACTOR CONTROL

The primary control for the reactor is with outlet coolant temperature. Outlet coolant temperature is sensed and control segments are adjusted to maintain a value within certain set point limits. Since the reactor has a negative temperature coefficient of reactivity, power demand from the reactor is automatically adjusted. For example, if the power system were operating at full power and one of the engines were turned off, the power demand from the reactor would be reduced by about one-third. This lower power demand is reflected in a lower coolant ΔT (higher average temperature). This higher average coolant temperature reduces the reactor thermal power because of the strong negative temperature coefficient of reactivity. Some trim of the control segments would most likely occur to maintain a constant reactor outlet temperature.

12.2 STARTUP AND SHUTDOWN

The reactor startup is initiated by first thawing the lithium loops using electrical trace heaters. With all the lithium thawed, the primary loop pump(s) are turned on to about 25% flow rate and the safety rods are withdrawn. Reactivity (from the control segments) is then inserted at a rather rapid rate until just before criticality. The reactivity insertion is then adjusted to a moderate rate. This rate is selected to allow the reactor's negative temperature coefficient of reactivity to modify the rate of reactor power increase. When criticality is achieved and sensible heat occurs, reactivity continues to be inserted to increase coolant temperature. During this period, reactor power is controlled by the loop heat losses.

As this portion of the reactivity insertion sequence continues, an engine start command is triggered when the reactor outlet coolant temperature reaches the engine self-sustaining temperature ratio. Each engine module is started using the alternator as a motor. Reactivity insertion continues until full power is achieved. The electrical power generated is dissipated in a parasitic load radiator.

About 25K before the reactor set point is reached, the central control processor switches the control mode from startup to operating (reactor outlet temperature). The reactivity insertion is changed to a slow rate to prevent temperature overshoot.

Shutdown is just the reverse of startup. Reactivity is withdrawn until the engines shut down. Reactivity is further withdrawn until the reactor is subcritical or it can be maintained in a warm standby condition.

12.3 PARTIAL POWER OPERATION

The power systems can be operated at less than the normal power of 550 kWe by one or a combination of the following methods:

- Use of a parasitic load resistor (PLR) bank to dissipate excess power by radiating it to space at a high temperature.

- Complete shutdown of individual engines can achieve net power output steps of 183 kWe, 367 kWe, and 550 kWe.

- Engines can be "throttled", causing them to operate at less than rated power.

- Reactor outlet temperature to lower cycle efficiency.

The simplest control scheme uses a parasitic load radiator for partial power operation, with the reactor and power conversion engines operating at a constant full rated power. The disadvantage of this scheme is that, even if the required electrical output is substantially less than full power much of the time, the reactor operating lifetime remains the same since it is operating at full power all of the time.

To improve reactor lifetime for reduced electrical power demand, a combination of parasitic load control and shutdown of individual engines can be used. For this type of power control, the reactor thermal power could be reduced in one-third increments. Such a control scheme would not require additional controls since these functions are required for other reasons. Such a scheme is suited for wide savings in electrical power demand over long periods of time.

For finer control each engine can be individually throttled. For the Brayton engine, this is accomplished by a gas management sytem that varies the inventory of He-Xe working fluid. For the Sirling engine, this is best accomplished by having split alternator field windings (usually thre). Thus, three discrete power levels for each engine could be obtained. Such a system would be most effective for minimizing reactor thermal power for a given electrical power demand. A parasitic load control would most likely still be required since it may not be possible to throttle engines at a rate consistent with rapid load changes. This control scheme would require the addition of a gas management system for the Brayton system and addition field windings with switching circuits for the Brayton system.

The final scheme for reduced power operating is to reduce the reactor outlet temperature set point. Reducing the reactor outlet temperature effectively reduces the power system cycle efficiency. A parasitic load would still be required since the reactor temperature response is much slower than electrical load change transients. Since the cycle efficiency is being reduced at reduced power demand, the reactor thermal power will not be proportional to the electrical output power.

The most optimum power control scheme will require additional studies and more information on the lower base architecture and power duty cycle. For the purpose of this study a parasitic load radiator was included in the mass estimate capable of dissipating the full 550 kWe load.

12.4 FAILED ENGINE OPERATION

There are two possible modes of operation for a system having redundant power converters. These two modes for a system with four installed engines, any three of which could supply full power, are as follows:

1. Operate three engines at full power and maintain the fourth shutdown in a standby condition.

2. Operate all four engines at 75% of full power (for full power output)

In the first option, should an operating engine failure occur, it would be positively shutdown (using the alternator as a brake). The standby engine could then be started up using the alternator as a motor. In the second option, should one of the engines fail, it would be positively shutdown and the remaining three engines brought to full power. For the purpose of this study, performance predictions were based on having three engines operating at full power.

As with the partial power options, additional studies are required to determine the optimum engine operating mode. Previous studies performed on similar systems favor the three operating, one standby operating mode from a reliability standpoint, however, this is dependent on the failure rates used. With this mode, the standby engine would be started up every few months to assure operability. Many people favor operating all engines at reduced power to assure full power can be achieved should an operating engine fail.

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13.0 SYSTEM INSTALLATION AND MAINTENANCE

Previous studies (Reference 1) were performed to evaluate methods to install the power systems on the lunar surface. In addition, separate studies (Reference 2) were conducted to evaluate methods to robotically perform maintenance. The following reviews the results of these studies.

13.1 SYSTEM INSTALLATION

The typical steps in installing the power system are shown schematically in Figure 13.1. The first step is to excavate a crater in the lunar regolith. One method of making this excavation is the use of pyro-technic devices or shaped charges. After the rough crater is made, the hole is cleared and the power system installed. Installation can be made by either a lunar excursion vehicle payload unloader (LEVPU) or using a block and tackle arrangement as discussed in Reference 1. After the installation in the crater is completed, the hole is back-filled. Some compaction may be required depending on the soil conditions. After back-filling, the radiators are deployed, the regolith shield tank filled, and the electrical and control connections made. The system is then ready for startup and operation.
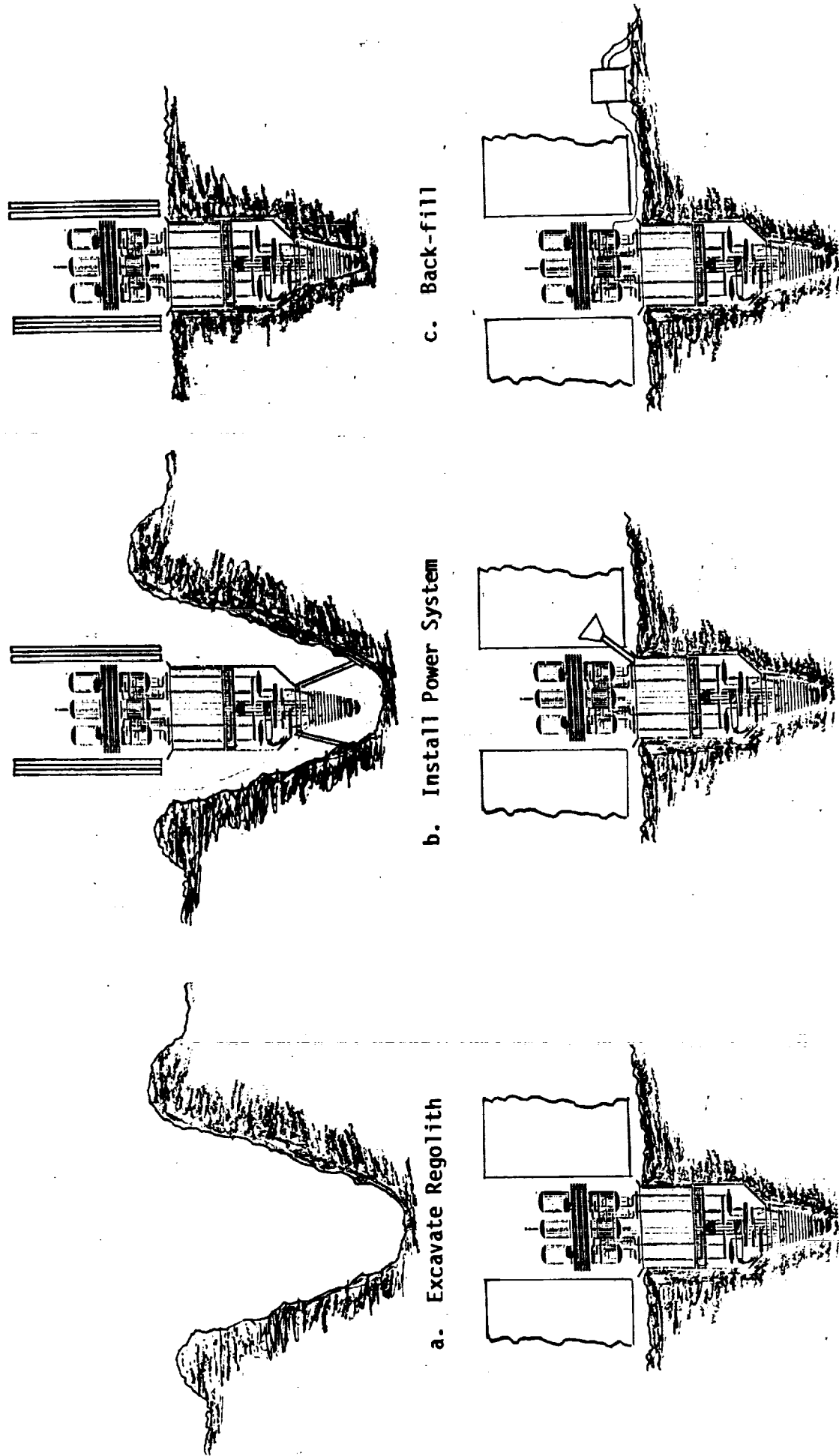
It was assumed that the installation operations would be performed robotically. Astronauts would be used as backup in the event of a failure or unplanned occurrence. Operations required of the robot are as follows:

1.   Placement of pyro-technic devices - requires drilling small holes and installing pyro-technics.

2.   Digging - Requires cleaning up of excavated hole, back-filling of regolith, scoping regolith for filling the shield tank, and digging and back-filling trenches for buried power cables.

3.   Lifting and Placing - Requires lifting the power system and placing it in the excavated hole and beating the power and electronic equipment.

4.   Manipulation - Requires making electrical connections and radiator deployment.

5.   Cable Laying - Requires laying of power and control cables.

13.2 MAINTENANCE

A study was performed in Reference 2 to evaluate maintenance of various components on the power systems described in this report. The Brayton system was selected for this study because of the more complex integration compared to the Stirling system. All maintenance described below could be performed on the Stirling system, however it would be more easily performed.

Figure 13-1. Typical Power System Installation Steps

a. Excavate Regolith

b. Install Power System

c. Back-fill

d. Deploy Radiator

e. Fill Regolith Shield Tank

f. Make Electrical Connections

To perform the maintenance, it was assumed to be performed robotically and the robot would contain two 7 degree-of-freedom manipulator arms attached to a single body, all of which were mounted on a four wheeled surface vehicle. The manipulator arms were similar to that being developed by Spar Aerospace Ltd's (Toronto, Ontario Canada) Special Purpose Dexterous Manipulator (SPDM). The wheeled surface vehicle was assumed to be similar to "Robie", a four-wheeled surface vehicle being developed by the Jet Propulsion Laboratory. It was also assumed that all operations would be performed autonomously, however, telerobotic methods could be used if autonomous technology is not sufficiently advanced.

Based on the robotic capabilities described above and the Brayton power system described in this report, the following maintenance tasks appear feasible of being performed.

1. Removal and replacement of a failed reactor PCU such as a Brayton or Stirling engine.

2. Removal and replacement of a failed control rod/drum's electro-mechanical actuator.

3. Removal and replacement of damaged radiator panels.

4. Removal and replacement of liquid metal coolant pumps.

5. Removal and replacement of failed power conditioning and control units.

For Tasks 1, 3, and 4, the following steps to be performed by the robot would most likely be required:

a. Drain and scavenge working fluids from component subsystem to be replaced.

b. Cut pipe lines and disconnect electrical wiring from component being replaced.

c. Cover/cap exposed piping to prevent lunar dust contamination.

d. Remove and replace component.

e. Reconnect pipe lines and electrical wiring.

f. Pull a vacuum down on all process piping to remove contaminant gases trapped inside.

g. Refill process piping with working fluid and cover gas.

Tasks 2 and 5 require no cutting of piping lines and handling of working fluids. Hence these tasks require fewer steps and would be simpler to perform.

The removal and replacement of a power conversion unit and control rod/drum actuator was investigated in more detail.

The design of the Brayton power system presented in this report was performed on a computer aided design program called "Autocad". The robot design was also loaded on to "Autocad" to study various views and configurations. The robot can be moved to allow the designer to mechanically check for clearances, interferences, and fit-ups. Figure 13-2 gives the design features that must be incorporated into the power conversion unit assembly for enabling that component to be removed and replaced. These features are broken down into structural support features and power conversion unit features. It was found the rover could fit between radiator panels, however, the vessel cooling radiators would have to be relocated or removed to allow this access. It was concluded that with some minor design modifications, the power conversion unit could be removed robotically.

Figure 13-3 shows the design features of the upper reactor system assembly for removal and replacement of a drive control/safety rod actuator mechanism using the Robie/SPDM rover/manipulator robot. Here the end effector is a specialized socket racket driver attached directly to the manipulator's wrist (replacing the welding/cutting head attachment discussed in the paragraph above for power conversion unit R&R). The figure shows that one of the two SPDM 7 degree-of-freedom arms is used for SPDM stabilization by reacting out applied loads near the bolt location rather than transmitting them all the way back through the wheels of the rover. It appears from the preliminary layout that the current reactor system design is adequate for providing robotic access to the internal control/safety drive mechanisms buried within the four power conversion units.
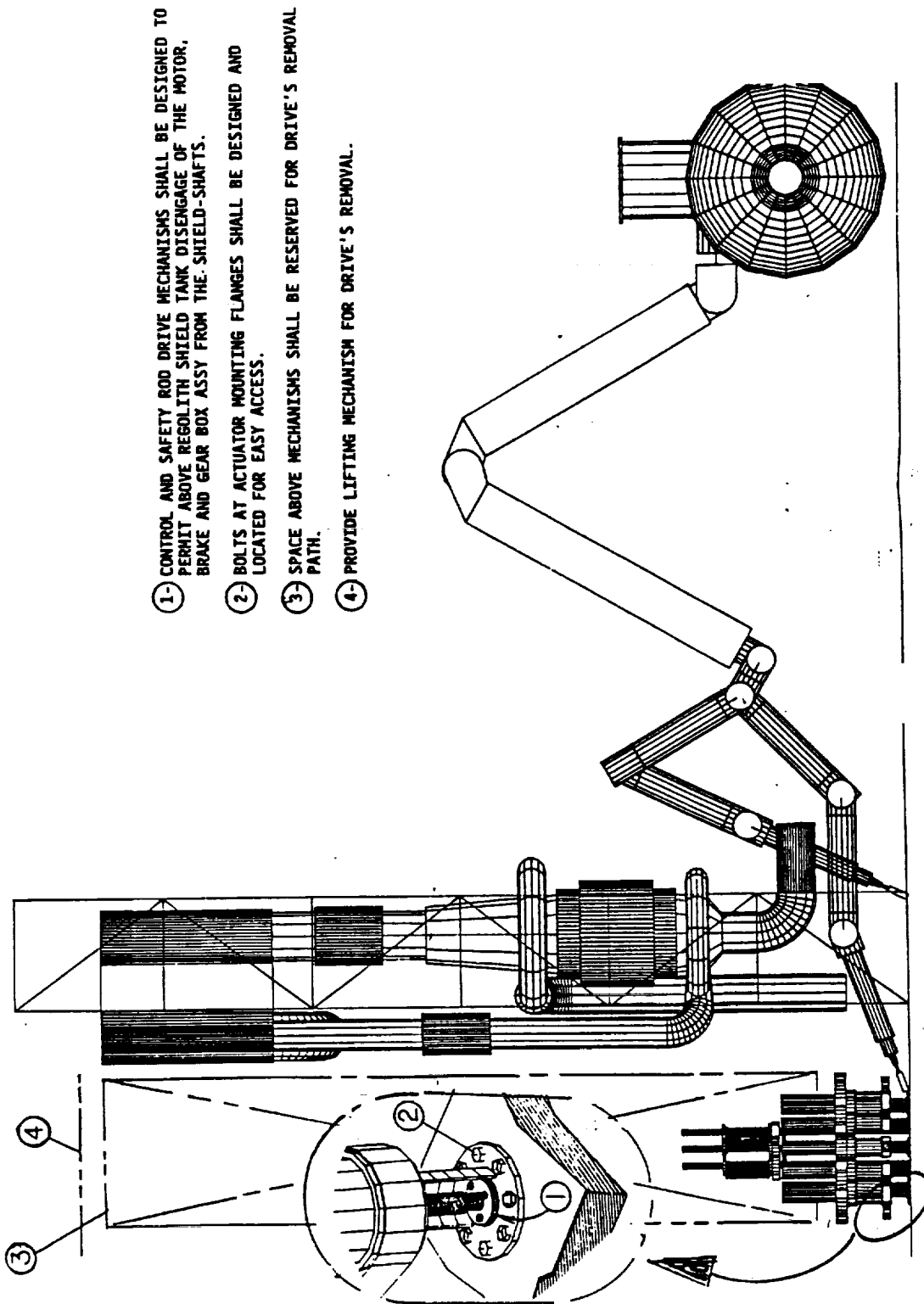
1. CONTROL AND SAFETY ROD DRIVE MECHANISMS SHALL BE DESIGNED TO PERMIT ABOVE REGOLITH SHIELD TANK DISENGAGE OF THE MOTOR, BRAKE AND GEAR BOX ASSY FROM THE SHIELD-SHAFTS.

2. BOLTS AT ACTUATOR MOUNTING FLANGES SHALL BE DESIGNED AND LOCATED FOR EASY ACCESS.

3. SPACE ABOVE MECHANISMS SHALL BE RESERVED FOR DRIVE'S REMOVAL PATH.
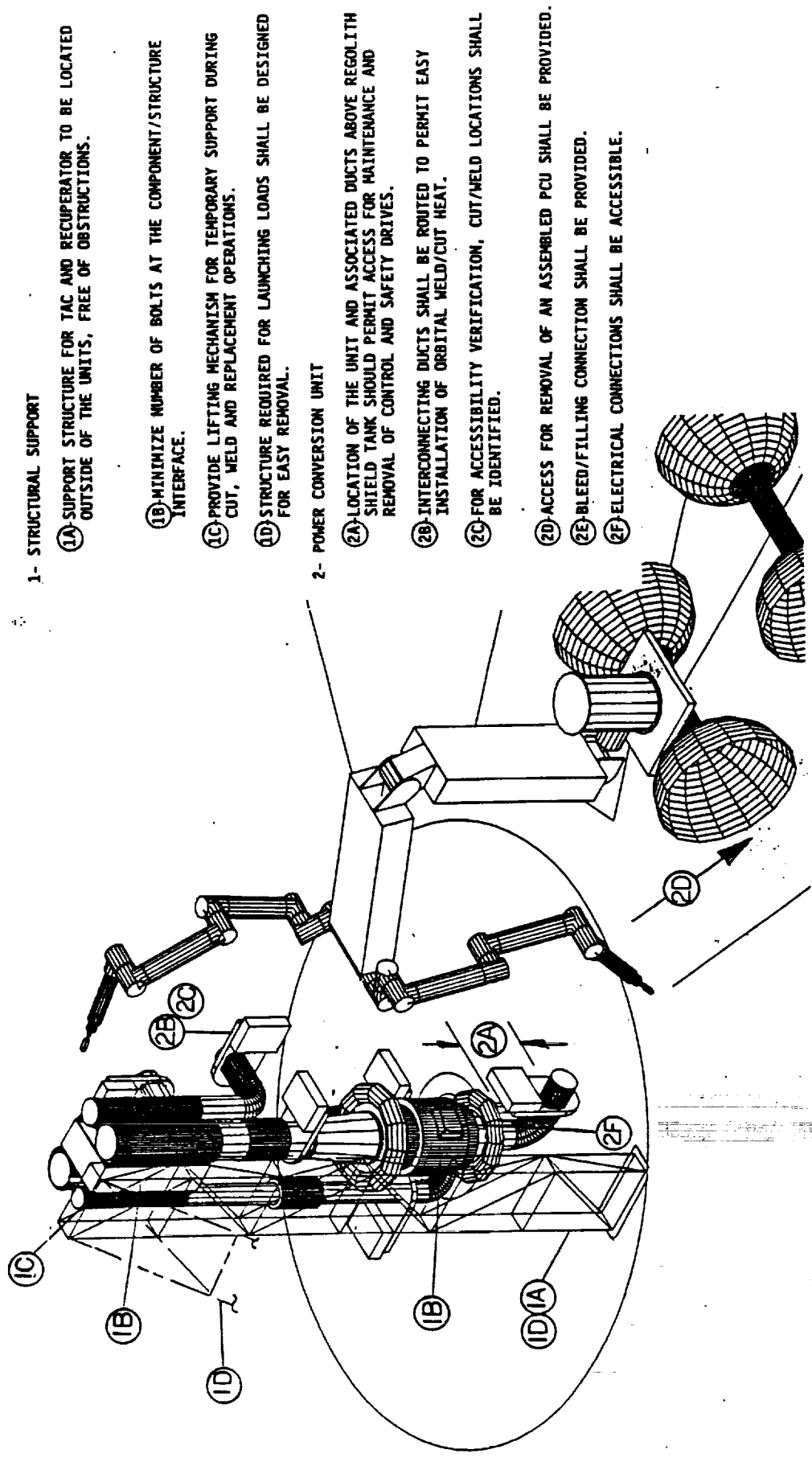
4. PROVIDE LIFTING MECHANISM FOR DRIVE'S REMOVAL.

Figure 13-2. Control and Safety Rod Drives -- Design Considerations for Maintenance and Repair

1- STRUCTURAL SUPPORT

1A- SUPPORT STRUCTURE FOR TAC AND RECUPERATOR TO BE LOCATED OUTSIDE OF THE UNITS, FREE OF OBSTRUCTIONS.

1B- MINIMIZE NUMBER OF BOLTS AT THE COMPONENT/STRUCTURE INTERFACE.

1C- PROVIDE LIFTING MECHANISM FOR TEMPORARY SUPPORT DURING CUT, WELD AND REPLACEMENT OPERATIONS.

1D- STRUCTURE REQUIRED FOR LAUNCHING LOADS SHALL BE DESIGNED FOR EASY REMOVAL.

2- POWER CONVERSION UNIT

2A- LOCATION OF THE UNIT AND ASSOCIATED DUCTS ABOVE REGOLITH SHIELD TANK SHOULD PERMIT ACCESS FOR MAINTENANCE AND REMOVAL OF CONTROL AND SAFETY DRIVES.

2B- INTERCONNECTING DUCTS SHALL BE ROUTED TO PERMIT EASY INSTALLATION OF ORBITAL WELD/CUT HEAT.

2C- FOR ACCESSIBILITY VERIFICATION, CUT/WELD LOCATIONS SHALL BE IDENTIFIED.

2D- ACCESS FOR REMOVAL OF AN ASSEMBLED PCU SHALL BE PROVIDED.

2E- BLEED/FILLING CONNECTION SHALL BE PROVIDED.

2F- ELECTRICAL CONNECTIONS SHALL BE ACCESSIBLE.

Figure 13-3. Power Conversion Unit -- Design Considerations for Maintenance and Repair

14.0 CONCLUSIONS AND RECOMMENDATIONS

The results of this study concluded that both the Brayton and Stirling systems integrate reasonably well with the SP-100 reactor. The Stirling power system was somewhat easier to integrate because it had fewer components and smaller pipe sizes. By folding the radiator panels, both systems could be launched in a single package.

The design of the power system was such that no component assembly was required at the lunar site. There are, however, significant installation operations that need to be performed prior to startup. These operations will require multiple robotic skills such as digging, placement, cable laying, and manipulation. Separate studies performed on maintenance indicated that, with modest extrapolation of robotic technology, all the above grade components could be removed and replaced. To perform these operations, modest design changes would have to be made to the power system.

Performance estimates made for both systems indicated their masses are about equal. The Stirling system has a smaller radiator area and a longer full power reactor lifetime because of its higher efficiency. The study concluded that there was no clear advantage of either the Brayton or Stirling system.

Based on the results of this study, it is recommended that alternate configurations be evaluated to minimize the installation operations. These include such things as having an integral shield to eliminate the need to excavate and sue local regolith shield material. The power system could also be integral with a lunar lander to eliminate the need for surface handling equipment.

Recent tests by General Electric have shown that the lunar regolith is not compatible with the refractory alloys of construction. Consequently, the design shown in this report must be modified so that all refractory alloy components are contained in a dust tight enclosure. Such on enclosure would complicate maintenance, consequently, this area needs to be reevaluated.

15.0 REFERENCES

1. Kenneth M. Sprouse, "Infrastructure for Deployment of Power Systems", NASA Contractor Report CR-18716, June 1991

2. Kenneth M. Sprouse and Francisco P. Cubillos, "Remote Maintenance for Planetary Surface Nuclear Power Systems", <u>Nuclear Technologies for Space Exploration</u>, Jackson, Wyoming, August 16-19, 1992

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15. Supplementary Notes

16. Abstract

An integration study was performed by Rocketdyne under contract to NASA-LeRC coupling an SP-0100 reactor to either a Brayton or Stirling power conversion system. The application was for a surface power system to supply power requirements to a lunar base. A power level of 550 kWe was selected based on the NASA Space Exploration Initiative 90-day study. Reliability studies were initially performed to determine optimum power conversion redundancy. This study resulted in selecting three operating engines and one stand-by unit. Integration design studies indicated that either the Brayton or Stirling power conversion systems could be integrated with the SP-100 reactor. The Stirling system had an integration advantage because of smaller piping size and few components. The Stirling engine, however, is more complex and heavier than the Brayton rotating unit, which tends to off-set the Stirling integration advantage. From a performance consideration, the Brayton had a 9% mass advantage and the Stirling a 50% radiator advantage.

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