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Reactor Power for Lunar Exploration

This paper is based primarily on results of a joint study conducted for NASA and the AEC by industry. Prime contractor for the NASA study was Lockheed Missiles & Space Co.; Aerojet-General Corp. supported the study as a subcontractor. Certain information on Brayton cycle hardware and performance was supplied by the AiResearch Manufacturing Division of the Garrett Corp. The AEC contractor was Atomics International Division of North American Aviation, Inc. Results of these studies have been reported in references 1 and 2.

STUDY OBJECTIVES

The study of the application of reactor power systems to manned lunar missions upon which the present paper is based was instituted with the following principal objectives:

(1) To evaluate the capabilities of the hardware and technology under development by the SNAP-8 and associated programs.

(2) To identify and evaluate the major operational interfaces between a manned lunar-surface mission and the reactor power systems and to determine the influence of each upon the other.

(3) To determine desirable modifications to the SNAP-8 and other reactor power systems to enhance their applicability to manned lunar-surface missions.

(4) To develop guidelines and design criteria for ongoing reactor power technology development programs.

In order to attain the study objectives, concepts were developed and evaluated for integration into the manned lunar mission of a SNAP-8 reactor, Rankine cycle system; a SNAP-8 reactor, thermoelectric system; and a SNAP-8 reactor, Brayton cycle system. The major emphasis was on the SNAP-8 reactor, Rankine cycle system. Although less emphasis was placed on the thermoelectric and Brayton systems, many results of the Rankine cycle work are applicable to lunar-surface reactor power systems in general.

BACKGROUND

Over the past several years NASA and other organizations have conducted studies of concepts for extension of manned lunar exploration beyond Apollo (refs. 3 to 7). These concepts have ranged from minor extensions of Apollo systems to concepts for semipermanent lunar bases. Lunar bases that can support about 12 men appear feasible from the logistics standpoint with uprated versions of the present Saturn V and reasonable extensions of Apollo spacecraft technology. Apollo Applications Program (AAP) missions currently under study are quite modest extensions of the existing Apollo systems aimed at attaining staytimes on the lunar surface of up to about 12 days, and these concepts project only a very few years beyond the Apollo missions.

AAP-class missions are expected to employ a combination of solar cells and batteries for power. Power requirements on the lunar surface are on the order of 1 to 2 kilowatts, durations are up to 12 days, and operations on the surface will be restricted to daytime. Studies of small expendable bases (two to six men with durations of up to 2 or 3 months) have indicated that for this level of activity, fuel-cell power is the best choice. Larger semipermanent bases are expected to require nuclear reactor power.

Prior studies of nuclear reactor power systems for lunar-base operations have established the basic feasibility of lunar surface reactor power (ref. 8). The study in reference 8 is a conceptual design of an optimized system not based on technology presently in development, and it assumed a requirement for power levels in excess of the capabilities of current technology such as SNAP-8. However, more recent estimates of the power requirements for lunar-base operations have indicated that the previous power requirement estimates were too high.

NASA and the AEC currently have under technology development several systems which could be utilized for nuclear power production on the lunar surface or in other space environments. These include the SNAP-10A and SNAP-8 family of zirconium-uranium hydride reactors, the SNAP-2 and SNAP-8 mercury Rankine turbo generator systems, the Brayton cycle turbo generator systems, and direct radiator and compact converter thermoelectric systems. A recent study directed by the NASA Langley Research Center carried out an investigation of the use of this technology for providing power to a manned orbital laboratory (ref. 9). The study here reported was undertaken to examine the capability of this technology base as support for possible future lunar missions. Whereas no such missions as those postulated for this study are presently planned, the lead time required for development of nuclear technology is quite long, and the study therefore was timely in providing missions application information to the technology development programs. The NASA and AEC space reactor power system technology programs have utilized development guidelines and criteria established primarily for unmanned applications. The presence of man in a mission application will have a substantial impact on reactor power system design criteria, operation techniques, and development requirements. Reliability, operating modes, radiation levels, repair and maintenance capability, and mission integration considerations of unmanned mission cases will be altered.

ESTABLISHMENT OF MISSION MODEL

Lunar-base concepts are generally associated with the idea of extensive scientific mission activity on the lunar surface. Deep geologic core drilling, special laboratories utilizing the "hard" lunar vacuum, and large radio or optical telescopes are typical postulated scientific activities. The referenced advanced studies have indicated that these classes of missions could be conducted on the lunar surface with a base crew of about 12 men.

The mission model was formulated around concepts of a 6-to-12-man semipermanent lunar base developed by the aforementioned and contemporary advanced mission studies. These studies have assumed use of the Saturn V launch vehicle and appropriate spacecraft hardware for crew and logistics transport. Estimates of required electric power for such base operations range from about 15 kWe to more than 100 kWe, with estimates above 30 kWe generally associated with assumption of some sort of natural resources processing (e.g., propellant production) on the lunar surface. Although resources processing ultimately may be of importance for lunar operations, it is our opinion that this will not be the case for the first lunar activities extensive enough to require nuclear power. Therefore, for the purpose of the subject study, resources processing was not assumed, and the range of power requirement considered was 20 to 35 kWe. However, a brief examination was made of the capability of the SNAP-8 mercury Rankine system to provide higher power levels.

Before outlining power requirements in somewhat more detail, it is pertinent to summarize the motivation for nuclear power for lunar surface operations. A design for a power system for a lunar base must take into consideration the problem of supplying power during the lunar night; therefore, systems employing solar cells as the primary source of power must provide an alternate source for the night period. The alternate source could employ rechargeable batteries or fuel cells with a regeneration plant powered by the solar cells during the day in order to regenerate the fuel expended at night. Clearly, a battery system which will supply several kilowatts of power for 2 weeks would be quite heavy. The fuel regeneration concept sounds better but becomes unattractive upon examination, principally

TABLE 1.—*Gross Systems Characteristics for Delivery of 30 kWe for 1 Year on Lunar Surface*

Power system	Hardware mass, lb	Expendables mass, lb	Total radiator plus solar array area, sq ft
Solar plus recharged batteries	140 000	0	10 000
Solar plus fuel cells	8 500	60 000	6 000
Solar plus fuel cells with regeneration	50 000	0	31 000
Nuclear (SNAP-8)	28 000	0	1 700

because the regeneration process (electrolysis plus liquefaction of reactants) is rather inefficient and the required solar array becomes very large. Also, the regeneration plant itself is very complex and is more complex than some of the nuclear powerplant concepts investigated in this study. As indicated by table 1, other power concepts investigated to date are not competitive in performance with nuclear power for production of electricity for a lunar-base operation.

Housekeeping functions for support of a lunar base require roughly 1 kilowatt of electric power for each man supported (ref. 10). This value is to some extent dependent on the source of electric power. With a nuclear source, it is economical to expend electric energy in order to regenerate life-support expendables (e.g., water and air). With a chemical source of electric power, this is not necessarily true, and somewhat less electric power per man will be required. Experiment programs and surface operations will require additional power. The electric power requirements assumed for this study are summarized in table 2.

TABLE 2.—*Typical Power Requirements for 12-Man Lunar Base*

Load	Average power, kWe
Housekeeping [a]	12
Deep drilling and trenching	4.5
External lighting	5
Battery charging for various portable equipment	2
Miscellaneous experiments	2
Subtotal	25.5
10 percent design margin	2.6
Total	28.1

[a] Includes life support, communications, and shelter internal lighting.

Logistics delivery to the lunar surface was postulated as being accomplished by an unmanned flight mode of a hypothetical propulsive spacecraft called lunar landing vehicle (LLV), launched to translunar trajectory by Saturn V. Figure 1 shows a typical LLV concept. (This concept is typical of those under study; NASA has no plans at present for initiating development of an LLV.) The LLV flight mode is entry into a lunar orbit, followed by descent and landing.

For the purposes of this study a gross lunar landed payload capability of 29 475 pounds was assumed for the LLV. Mass required for payload support structure must be subtracted from this figure in order to determine net payload capability. Continued study of LLV concepts has indicated that the above payload figure is quite conservative.

The lunar-base crew was assumed to occupy one or two six-man shelters delivered from Earth by Saturn V/LLV. It was assumed that necessary control panel space for control and monitoring of the powerplant would be available within the shelter. It was also assumed that no advantage could be taken of lunar terrain for shielding between the powerplant and the shelters and that the base would be located at a place near the lunar equator, this area being the most severe thermal environment. An excursion area around the powerplant was assumed permissible. The major emphasis for this study was placed on a 12-man base for

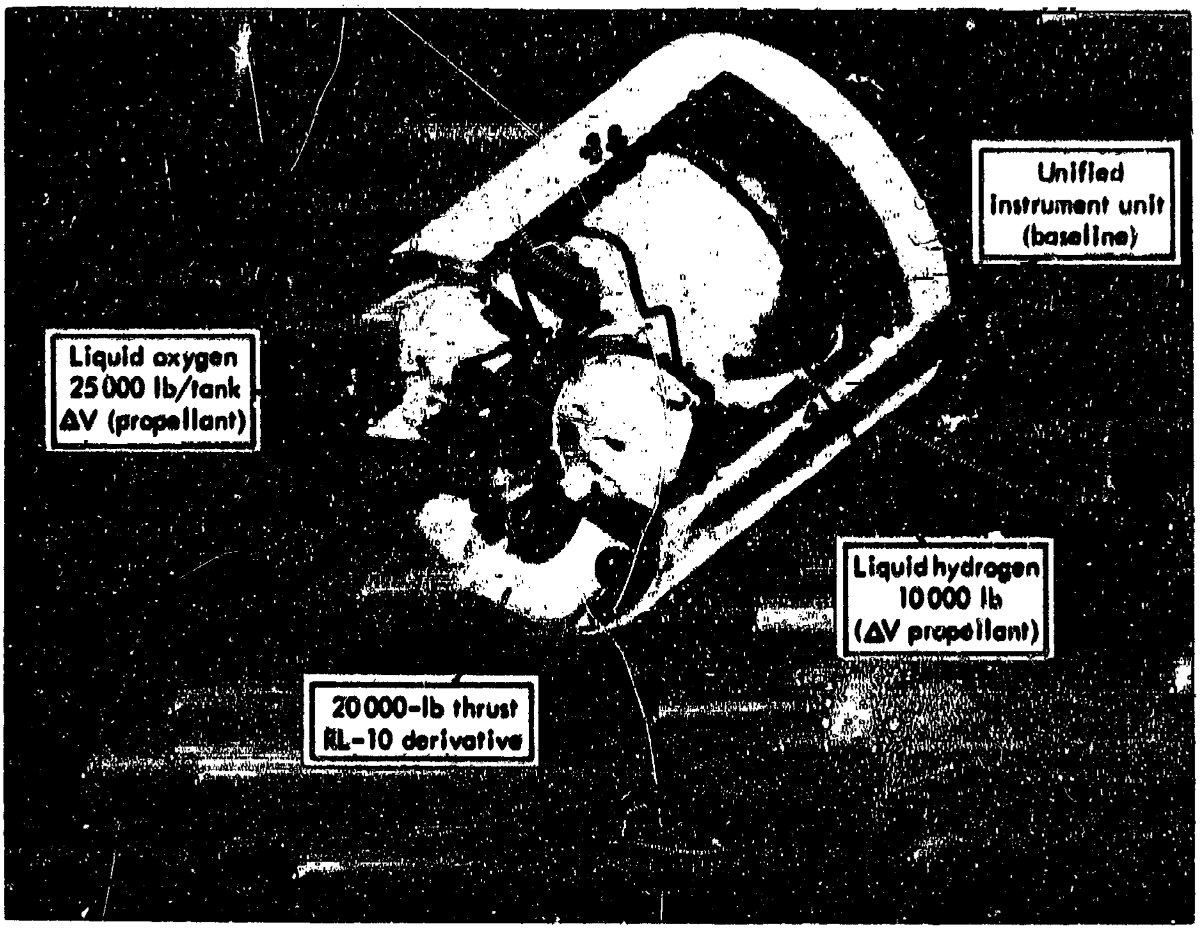

FIGURE 1.—Early cargo stage lunar landing vehicle concept.

10 000 hours or more of continuous operation. The base crew staytime was fixed at a maximum of 1 year for the purpose of analysis of shielding and calculation of crew exposure to radiation from all sources.

The radiation dose allowable to each astronaut on the lunar surface was based upon criteria suggested by the NASA Manned Spacecraft Center. These criteria allow a maximum, fractionated, annual, whole-body dose to the astronaut of 100 rem and a single, acute dose of 50 rem. These criteria are reasonable extrapolations of the Apollo criteria for longer duration missions.

The total dose to the astronaut is the summation of the doses from the reactor sources and from solar flares and other natural sources. The solar-flare dose was selected on the basis of a tradeoff analysis of base separation distance from the powerplant when the total astronaut dose from all sources is maintained at 100 rem. A solar-flare dose of 30 rem was selected, since the separation distance from the power system to the base sharply increases for larger solar-flare dosages. The maximum allowable dose from the reactor sources is 70 rem. This exposure allowance is allocated as: normal operation, 46 rem; maintenance and repair on the powerplant, 24 rem. Additional shielding on the outer airlock of the lunar shelter (about 3000 pounds) may be added in order to reduce the solar flare dose to 30 rem; it is assumed that this outer airlock will be used as a storm shelter in the event of a hazardous solar flare. A problem arises in the probabilities of incurring exposure from various sources. The probability of incurring the dose within the shelter from the operating reactor is essentially 100 percent. The probability of incurring a radiation dose during maintenance and repair will be smaller, while the probability associated with the 30-rem solar flare dose is in the 1-percent range. Therefore, the expected dose will be well below the 100-rem limit. It could be reasonably argued that the solar-flare dose allocation could be set at approximately 100 rem at a 1-percent probability, thus avoiding the added shielding in the shelter which this mission model requires. However, a generally conservative approach was used for this study.

Further contribution to the problem of exposure criteria comes from the disagreement in the technical community regarding allowed dose. Arguments have been voiced ranging from use of industrial standards to allowing doses as high as 1000 rem per year. No universally accepted set of criteria exists. In this study, as in many others dealing with nuclear systems, shielding mass is highly significant and the establishment of firm criteria substantially at variance with those used herein would change results and alter conclusions.

The power system may be landed on the lunar surface up to 6 months before it is brought into operational status. During the preoperational storage period, the lunar base presumably will be unoccupied and the crew will arrive at the base prior to the power system's being brought to full power. The initial startup of the powerplant will be scheduled for the lunar day in order to minimize problems with thermal conditioning of the system.

For the purpose of maintenance, repair, and redundancy studies, it was assumed that, if the nuclear power system fails, there will be a backup emergency power system to permit withholding a decision for 14 days as to aborting the lunar-base mission. The backup power system will have the capability of assuring survival of the crew but will not necessarily permit continuance of any experiments. Therefore, the maximum allowable downtime of the power system is 14 days. The power system should have the capability for restart during the lunar night. It was further assumed that a 2-day cooldown period with the reactor subcritical would be employed prior to manned repair activities. This procedure substantially reduces gamma-shielding requirements.

Surface mobility vehicles are assumed to be available at the lunar base for purposes of exploration, experimentation, aid in various maintenance and repair tasks, aiding an astronaut in distress should he become stranded somewhere on the lunar surface, and other purposes. Two lunar scientific survey modules (LSSM) (ref. 11) and one large mobile exploration vehicle (ref. 12) were assumed. For off-loading and radiator deployment tasks, the large vehicle can be modified by mounting an onboard crane or other device.

In the absence of any measurements or other available data concerning the density and composition of the lunar surface material, it was assumed that the material is an anhydrous [1] sandstone, rocklike surface constituted mainly of silicon dioxide. A density of 1.6 gm/cm^3 was assumed when the lunar material is used in the form of block or bricks.

The evidence obtained from approximately 3 weeks of operation with the Surveyor I spacecraft indicates that the visible spacecraft surfaces show no noticeable covering of dust that might be caused by either lunar surface ejecta or electrostatic charges on the lunar surface. Consequently, it was assumed that no significant covering of lunar material will collect on any external surfaces of the power system or on any of its auxiliary structures during the mission.

The lunar thermal environment used as a guideline for this study is specified in reference 13. The basis for the meteoroid environment is given in reference 14. This reference was used to obtain a working curve of single-thickness aluminum for various probabilities of no puncture. For application to the lunar mission, the product of area to be protected and time is multiplied by 0.5 to account for shielding by the Moon.

REACTOR AND SHIELD

he present SNAP-8 S8-DR core with 211 ments has been operated for a 10 000-hour

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[1] The shielding effectiveness of soil is sensitive to hydrogen content; for conservatism, none was assumed.

test at power levels up to 600 kilowatts and would be adequate for a 1-year lifetime for reactor power levels up to about 800 kWt.

A reactor core larger than the S8–DR would provide greater capability. The larger core can be achieved by increasing the number of fuel-moderator elements and the length of the S8–DR core. A 20-inch-long core made up of 241 fuel-moderator elements, which could be produced by a minimal design change from the present S8–DR core, provides a significant increase in performance margins of the reactor system. The reflector thickness and control drum diameter have been reduced in order to reduce the shielded volume. The design and performance characteristics of the reference reactor are shown in table 3. This reactor core design was approved by the AEC as the reactor design for the lunar-base reactor power systems for the purposes of the subject study. The outlet NaK temperature from this core is approximately 1300° F, and at 600 kWt the reactor has a design lifetime of approximately 20 000 hours.

Two shielding concepts were investigated for the power system integration concepts studied. The baseline concept was a 4π shield design integral with and completely surrounding the reactor (fig. 2). The gamma-ray shield is composed of tungsten and the neutron shield of LiH. A tungsten shield in the shape of a hat was placed around the power conversion system containing the primary loop. The purpose of this shield was attenuation of the gamma-ray

TABLE 3.—*Reference Reactor Design and Performance Characteristics*

Design characteristics

Item	Value
Number of fuel elements	241
Active fuel length, in	20.2
Vessel outside diameter, in	10.2
Fuel material	$U\text{-}ZrH_x$
Uranium loading, wt percent	10.5
Hydrogen content, $N_H \times 10^{22}$	6.3
Fuel element diameter, in	0.560
Element separation, mils	30
Hydrogen barrier material	SCB–1
Cladding material	Hastelloy N
Core vessel material	316 SS
Coolant	NaK–78
Control drum diameter, in	4.0
Reflector material	BeO
Poison material	B_4C

Performance characteristics

Item	Value		
Power, kW	400	600	1000
Outlet temperature, °F	1300	1300	1300
Coolant temperature rise, °F	200	200	200
Design lifetime, hr	~26 000	~20 000	~12 000
Coolant flow rate, lb/sec	9.0	13.5	22.5
Pressure drop, psi	0.34	0.75	2.06

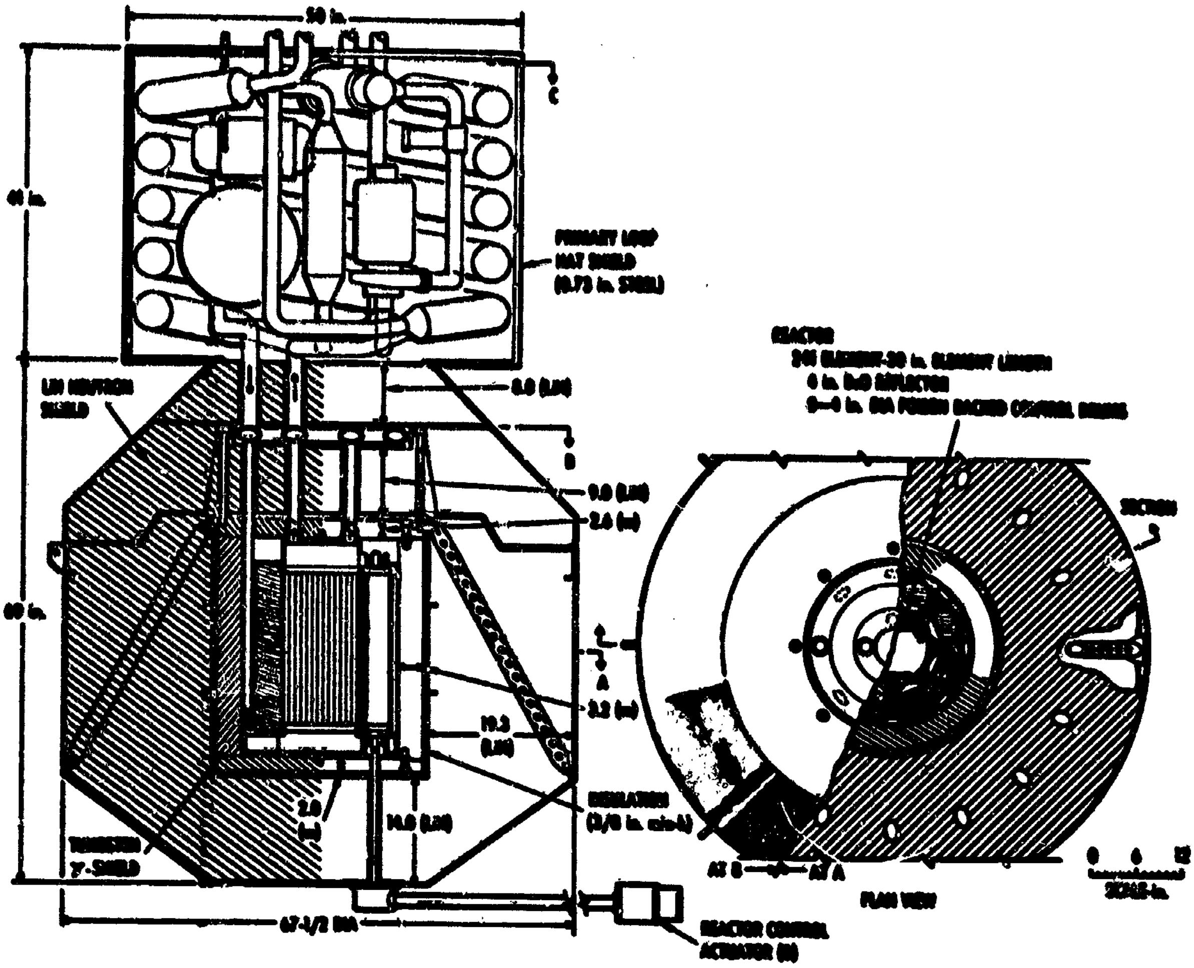

Figure 2.—Lunar-base reactor shield assembly. SNAP-8 mercury Rankine system.

radiation from the radioactive NaK and from possible fission products in the primary NaK loop, both during operation and during maintenance and repair after shutdown. Figure 2 shows the design concept.

The other concept was an "off-loaded" mode, with the reactor assembly removed from the LLV and buried in a hole prepared in the lunar surface. Reactor burial to a sufficient depth reduces the radiation dose rate at the surface to acceptable levels for the power conversion system during reactor operation and for the astronauts after power system shutdown by virtue of the shielding effect of the lunar soil. However, additional shielding is required between the reactor and primary loop to reduce the radiation to the primary loop components to acceptable levels. The design for the off-loaded concept provided this added shielding as part of the reactor and primary loop package.

INTEGRATION CONCEPTS

Three concepts for integration of the SNAP-8 mercury Rankine system were developed: integral, deployed radiator, and off-loaded. All concepts employed the SNAP-8 cycle shown in figure 3. For the mercury Rankine system there was no advantage in radiator deployment, since adequate radiator area was

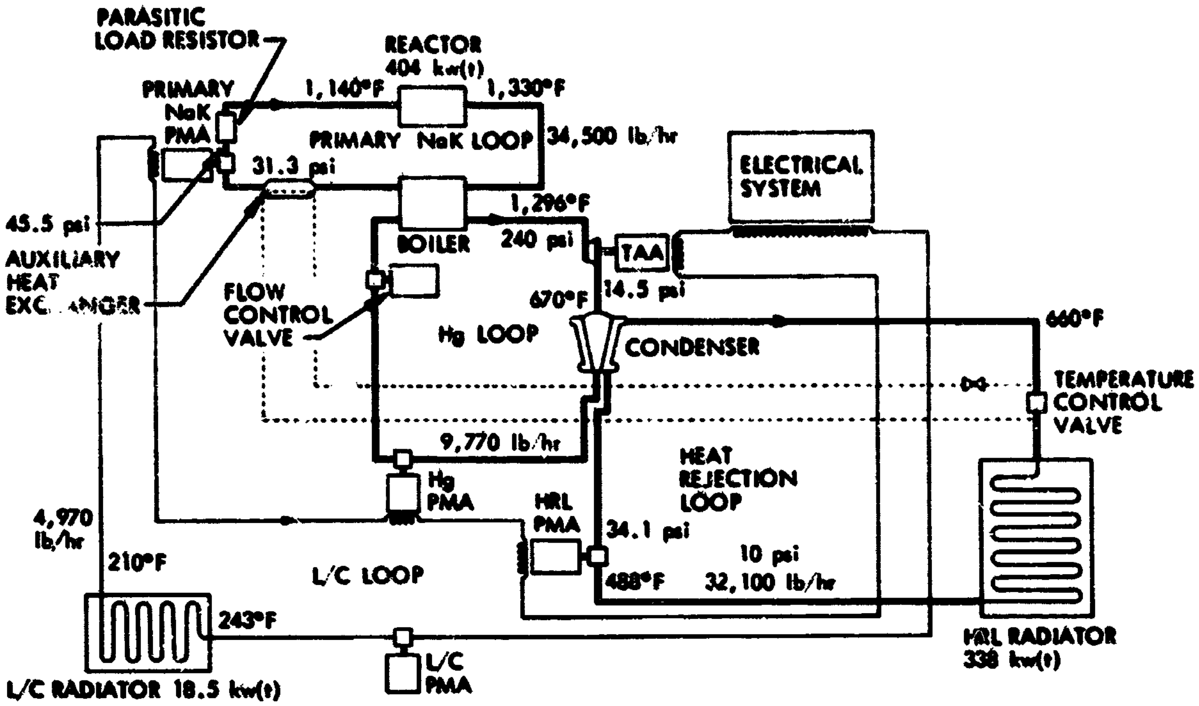

FIGURE 3.—Baseline SNAP-8 power system.

Performance summary	
Net reactor input to PCS, kWt	404
Net electrical output (BOL), kWe	40
Net electrical output (EOL), kWe	35
HRL radiator heat rejected, kWt	338
L/C radiator heat rejected, kWt	18.5

Available pressure drops	
HRL radiator, psi	18
L/C radiator, psi	15

available with the integral mode in accordance with payload envelope dimensions employed. Radiator deployment was studied in view of its potential application to a high-output SNAP-8 and the thermoelectric and Brayton systems. Two techniques were considered: flexible tubing and assembly and welding of radiator panels. Investigation of potential techniques for semiautomatic welding of tubing and pipe joints by astronauts on the lunar surface indicated that highly reliable welding probably could be perfected. There is comparatively little experience with flexible tubing in liquid metal systems; it was felt that the thin-wall nature of flexible-tubing designs would present leak hazards, and therefore the welding approach was selected. This selection was conditional, since integral concepts were chosen as preferred modes for all systems.

The off-loaded SNAP-8 concept allows delivery of two complete systems (two reactors, etc.) on one Saturn V logistics flight, as a result of greatly reduced shielding mass and reduced separation distance. However, the estimated assembly and setup work required three suited astronauts working 6 hours a day for 17 days. Therefore, the off-loaded concept was rejected in spite of its attractive mass characteristics.

The selected SNAP-8 integral configuration is shown in figure 4. To increase the assurance of mission success, redundancy is incorporated by connection of two complete power conversion systems to the primary loop. The boilers are in series in the primary loop, and this loop contains a standby NaK pump. There are two lubrication and coolant loops; each can cool both pumps in the primary loop and can operate with either power conversion system.

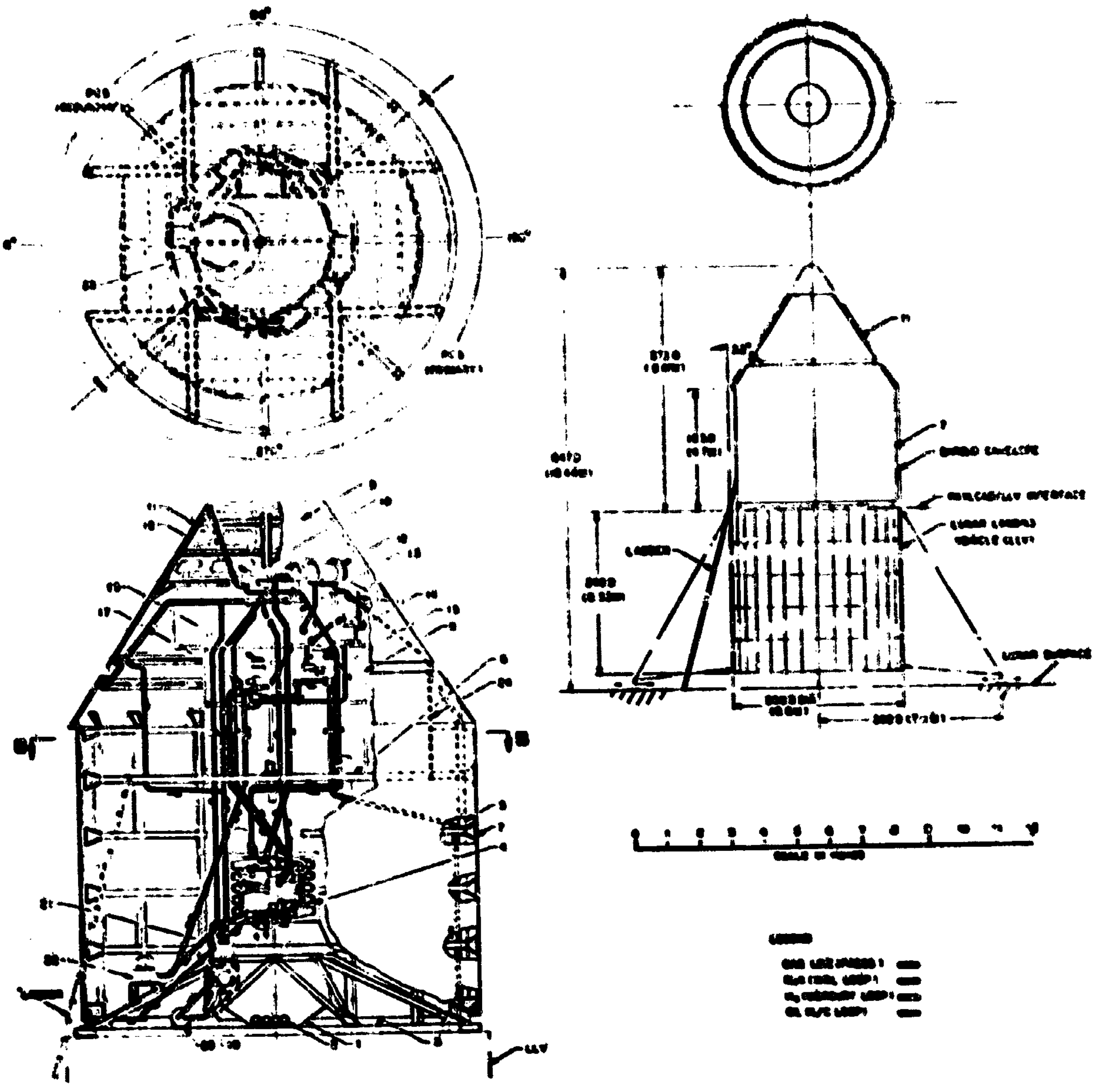

FIGURE 4.—Detailed configuration of SNAP-8 concept selected.

1. Reactor and shielding
2. Reactor control motors
3. Lower walkway
4. Primary loop and shielding
5. Tubular structure integral with HRL radiator
6. Upper floor
7. HRL radiator
8. Tubular truss structure
9. Sheet metal structure
10. Pole for basket
11. L/C radiator integral with structure
12. Turbine alternator assembly
13. Condenser
14. Electrical equipment
15. NaK-pump motor assembly
16. Mercury pump
17. Flow control valve
18. Pump, oil (L/C loop)
19. Pressure sphere (L/C and HRL loop)
20. Reservoir assembly (NaK)
21. Reservoir assembly (oil)
22. Injection system (mercury)
23. Basket
24. Insulation
25. Thermal blanket
26. Aluminum sheet
27. AL extrusion with STL tube insert
28. Weld

The two independent heat-rejection loops share the same radiator fins. Crew access and a movable basket are provided in order to facilitate manned maintenance and repair during down periods.

The electrical control subsystem would be transported to the lunar surface in one of the crew shelters. Since the shelter must be environmentally controlled during storage, this arrangement avoids providing environmental control for this equipment in the powerplant during a storage period. During setup operations, the electrical package is placed on the lunar surface about 75 feet from the powerplant. This distance satisfies thermal control requirements and locates the package conveniently for maintenance access.

The compact converter thermoelectric reactor power system is schematically shown in figure 5. Before the configuration of this powerplant was determined, parametric studies were made of weight and radiator area required versus power delivered for a compact converter (lead-telluride) version and a direct-radiating (silicon-germanium) version. Both systems were limited by available radiator area (integral design) to about 20 kWe delivered to the base. Deployed radiators would increase the power capability by about 5 kWe, but the added power was believed not justified because of the reduction in mission success assurance which would be incurred by the use of deployed radiators; therefore, an early choice of integral design was made. The compact converter system was selected by the AEC in preference to the direct radiating system largely because its greater materials efficiency required 40 percent less reactor power than did the latter at a slightly reduced temperature; this former system thereby provided much greater reactor lifetime potential. The thermoelectric system design is shown in figure 6. A high degree of inherent redundancy is provided by eight independent converter and heat-rejection loops; therefore, manned access is provided only to reactor control devices and control electronics located around the periphery of the base of the system (fig. 7).

The Brayton system schematic is shown in figure 8 and the integrated design in figure 9. Again, an integral design was chosen, although deployed radiators could have provided additional power capability. Two power conversion loops are provided for redundancy. The working fluid is a helium-xenon mixture and

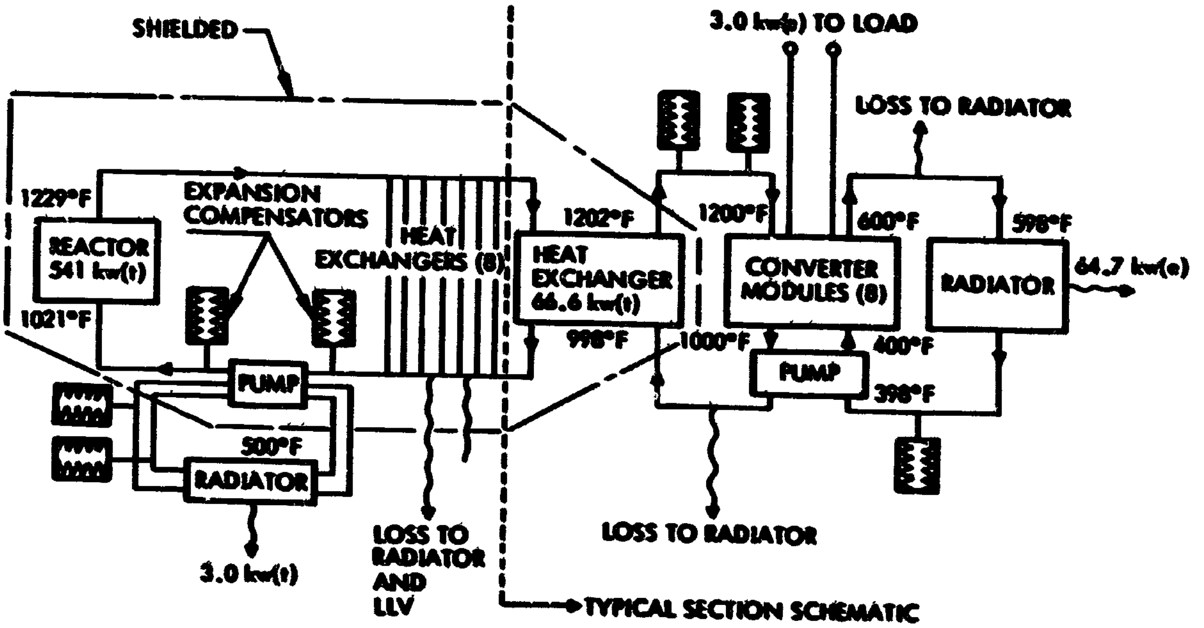

FIGURE 5.—Flow diagram of SNAP-8 compact converter thermoelectric power system.

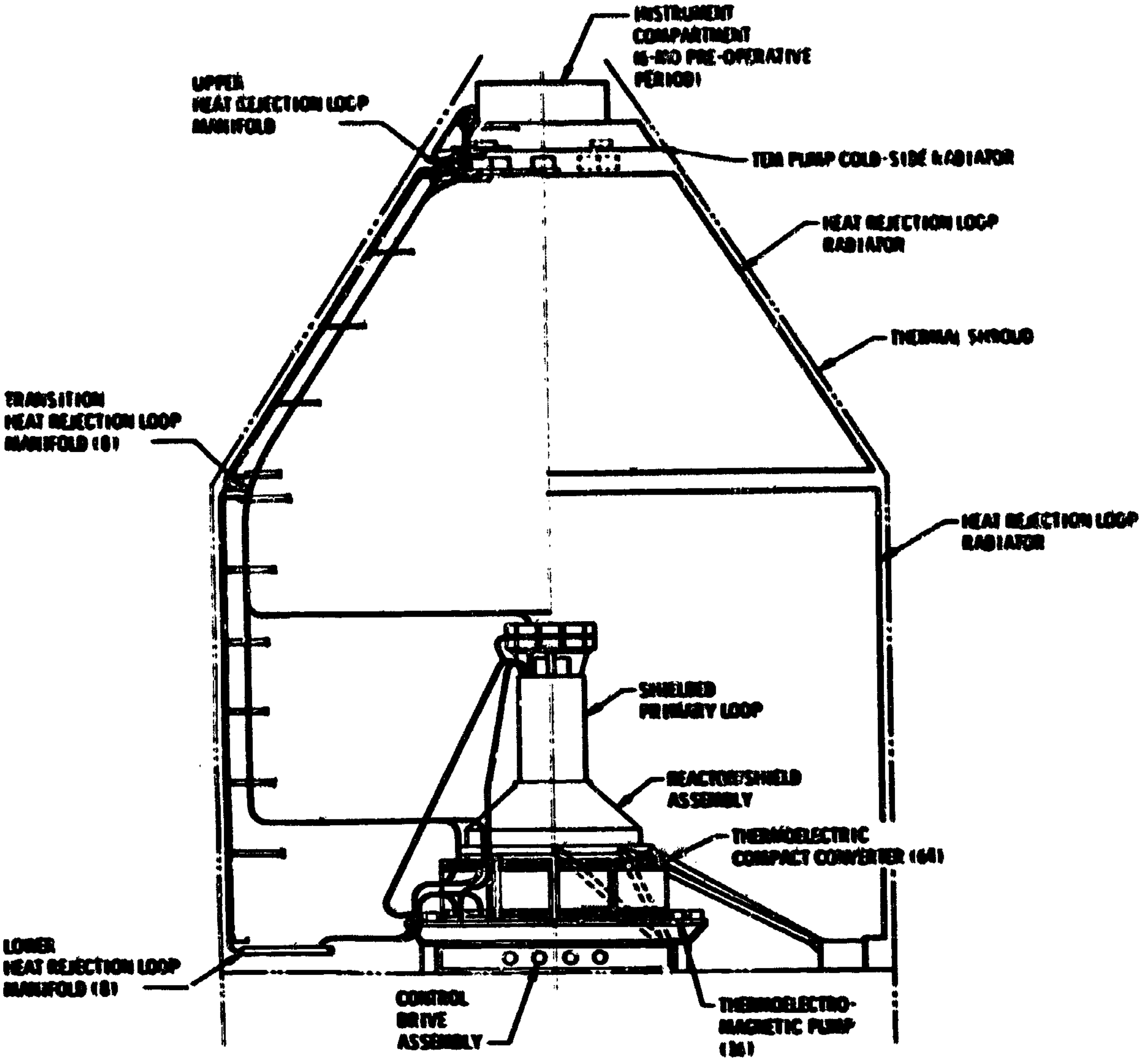

FIGURE 6.—Integral compact converter configuration.

the system employs a gas flow radiator and thus avoids the thermal control problems of a liquid metal radiator. A radiator bypass control valve is used for regulating power. The Brayton cycle runs with comparatively low radiator temperatures and the result is high sensitivity to the lunar thermal environment; power output would increase about 100 percent during the lunar night without this control.

WEIGHT AND PERFORMANCE

Performance parameters and weights of the powerplants are summarized in table 4. Performance parameters for the deployed-radiator and off-loaded version of the mercury Rankine system were the same as those for the integral design, except for masses, which were 31 600 pounds and 29 030 pounds, respectively, and separation distance for the off-loaded system,

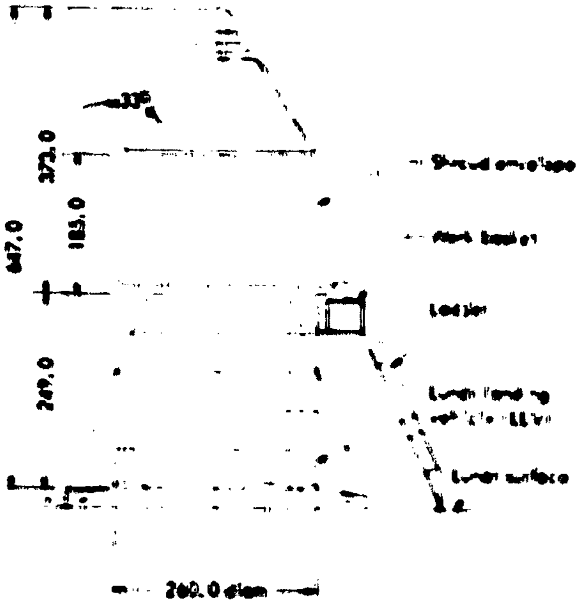

FIGURE 7. Maintenance and repair access to thermoelectric system.

which is 900 feet. Note that the mass of the off-loaded system includes two complete powerplants; each powerplant includes only one power conversion system.

REDUNDANCY AND MAINTENANCE AND REPAIR

The technology with which this study dealt is not sufficiently mature to allow meaningful reliability analyses of the conventional nature. Nonetheless, reliability considerations were necessary in order to attain appropriate concepts for system redundancy. The technique applied was a combination of engineering judgment and comparative analysis. For example, it was decided to provide two power conversion systems connected to a single primary loop for the mercury Rankine system. The interface between the primary (reactor heat removal) loop and the secondary (power) loop is the boiler. Hot NaK from the reactor transfers heat to boiling mercury in a shell-and-tube boiler. One potential failure mode is a boiler leak, wherein the primary loop could become contaminated with mercury and cause permanent reactor shutdown (mercury is a strong neutron absorber). A potential solution would be placement of the boilers in parallel in the primary loop, with shutoff valves. However, this would require a sensor in order to detect very low levels of mercury contamination and zero-leak NaK valves, neither of which is considered to be within the near-term state of the art. Therefore, this solution was rejected and the boilers were placed in series; the result is a simpler system but one requiring a high-integrity boiler, such as a double-containment design.

This approach also led to selection of two power conversion systems connected to a single primary loop for the Brayton system and to eight power conversion modules and heat-rejection loops for the thermoelectric system. For the mercury Rankine system, substantial effort was also invested in analysis of the switchover problem which arises in the event of an unexpected failure of one of the power conversion systems. The normal startup procedure for the mercury Rankine system is fairly complex and occupies several hours. The principal tradeoff was between a "quick restart" in which an immediate startup of the standby system would be employed, with no change in reactor power level, and a shutdown and subsequent restart of the standby system. This is a very complex problem which would require a transient thermal and dynamic analysis for proper resolution. No definitive final conclusions were drawn. However, the following factors were considered important:

(1) Certain kinds of failure can cause a rapid loss of capability of removing heat from the reactor. Probably the worst case is a failure of the operating primary loop NaK pump or of the turboalternator which provides its drive power. Somewhat less severe would be loss of the mercury pump.

(2) In the event of such failures, the reactor must be protected from overheating. Some combination of auxiliary heat removal, quick response startup of the standby primary loop NaK pump (if required) on auxiliary power and reactor power reduction, will be necessary to provide adequate protection.

(3) It may be necessary to provide a reactor

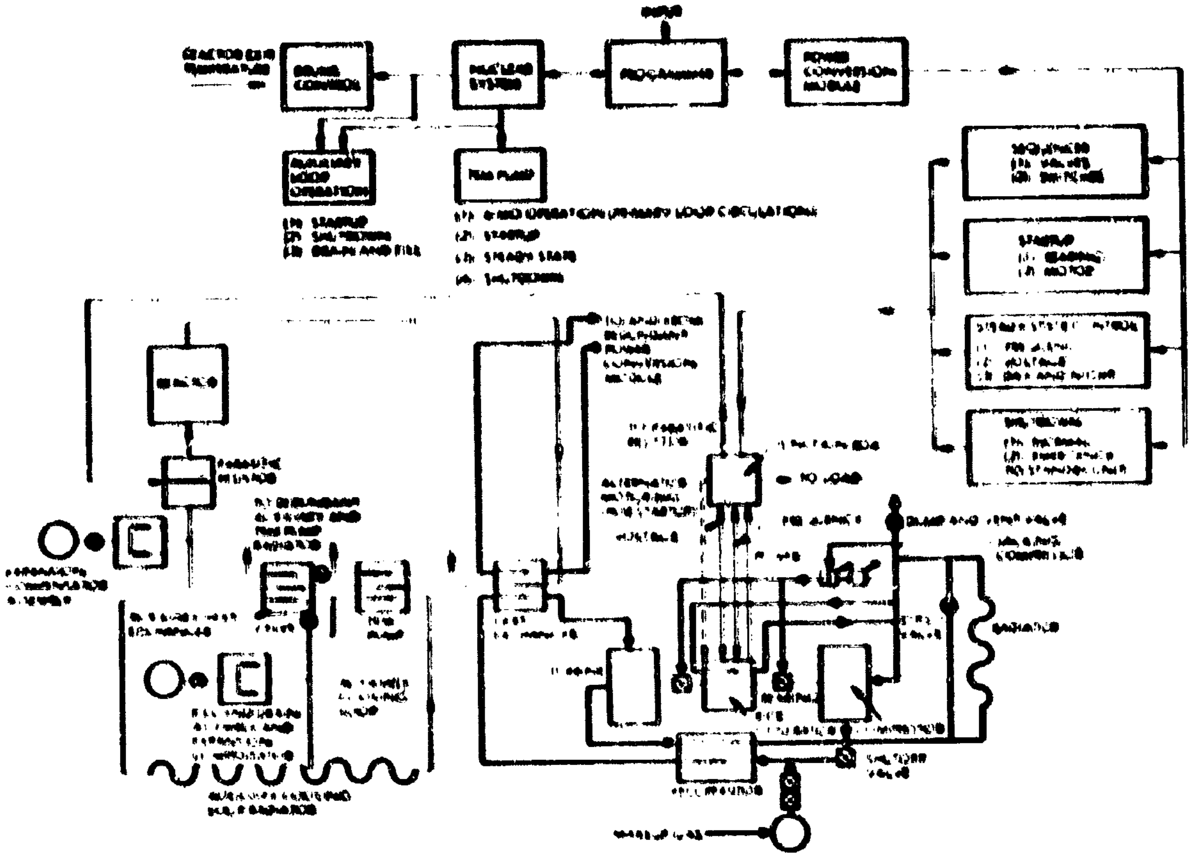

FIGURE 8.—SNAP-8 Brayton system flow diagram

scram capability. However this should be avoided (in favor of use of the normal control drum drive), if possible, since scram circuits and controls are responsible for a large proportion of inadvertent shutdowns of operating reactor systems.

(4) If restart is to be delayed, thermal protection for the heat-rejection and lube-coolant loops must be provided in the event that shutdown occurs during the lunar night.

The conclusion was reached early in the study that manned maintenance and repair of minor maintenance items would be mandatory for maximum mission success assurance. This requires provision of manned access to the system (after a 2-day cooldown period). Once manned access has been provided, the additional provisions required for major maintenance and repair are relatively minor. Major maintenance of repair implies replacement of a component, which would require opening a liquid or gas flow loop. Although assurance of success of such an operation is somewhat doubtful, it serves as a backup to a backup (redundancy of design) and is therefore justifiable. Some specific points are:

(1) Maintenance or repair involving opening the primary loop or removing any reactor shielding is considered unfeasible.

(2) Investigation of potential welding techniques indicated that semiautomatic techniques employing either TIG or EB welding attachments, which would be set up in position by the astronaut, could be developed with a high assurance of producing good welds.

(3) Maintenance and repair operations would be restricted to the lunar day. In the event of a shutdown during the lunar night, an attempt would be made to start the backup system and program a repair activity later.

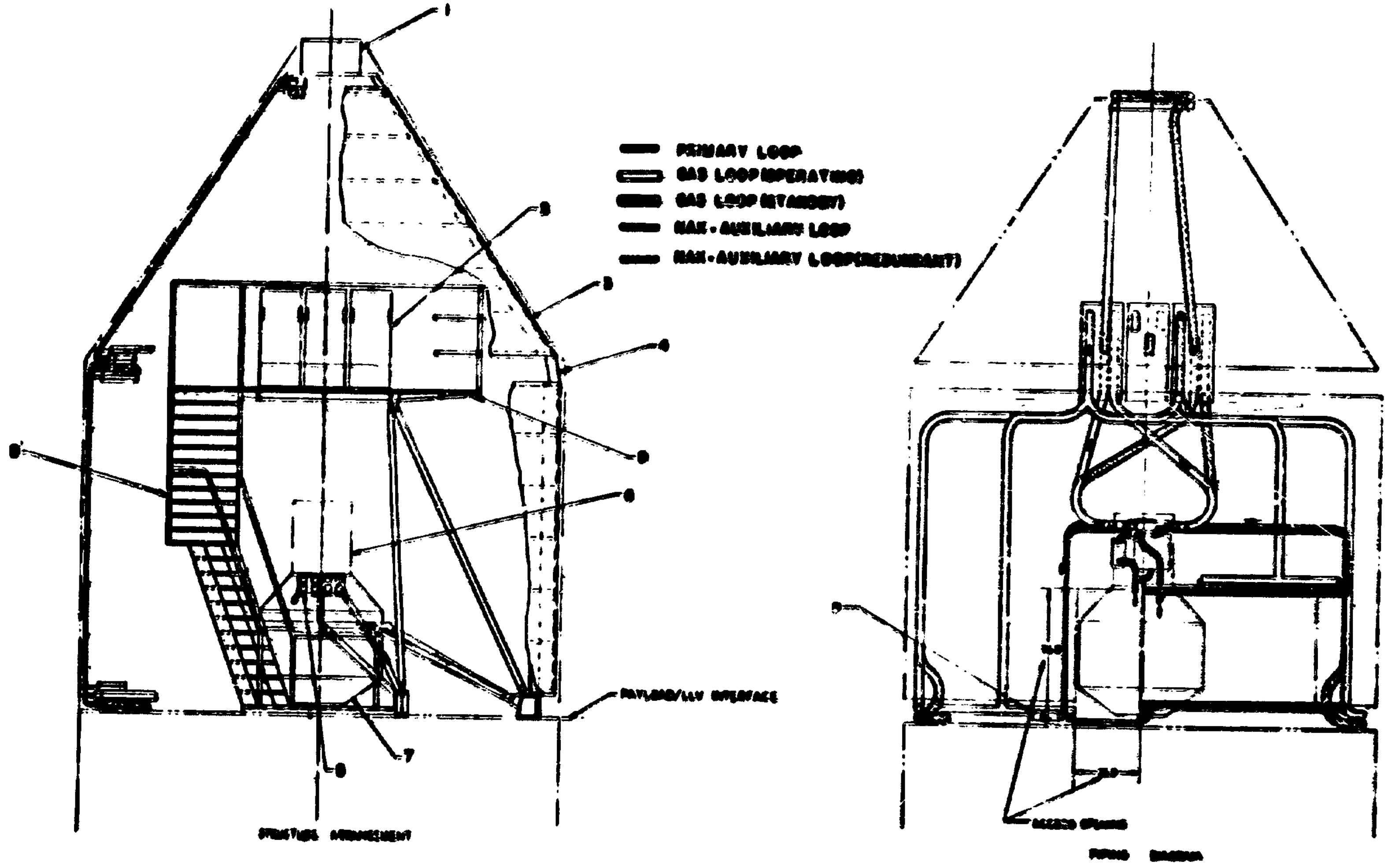

FIGURE 9.—Brayton cycle design.

1. T/M package (used during preoperational storage)
2. Power conversion module
3. Heat exchanger
4. Structure
5. Work platform
6. Primary loop
7. Reactor and shielding
8. Reactor control motor assembly
9. Stairway

TABLE 4.—*Powerplant Performance Summary*

Parameter	SNAP-8 Rankine	Compact converter T/E	Direct-radiating T/E	Brayton
Electric power at base, EOL[a], kW	33	20.4	20.0	25.6
Reactor thermal power, kW	404	541	907	182
Total system mass, lb	[b] 32 880	[c] 27 135	25 836	[d] 21 440
Shield mass, lb	14 000	13 900	13 900	12 500
Total radiator area, ft²	1390	1500	1527	1400
Reactor outlet temperature, °F	1330	1227	1300	1300
Mean radiator temperature (high-temperature radiator), °F	574	498	470	345
Overall thermal efficiency, EOL[a], percent	8.17	3.77	2.2	14.1
Power-to-mass ratio W/lb	1.0	0.75	0.775	1.10
Total radiator area, ft² per electrical kW	43.5	73.5	76.5	54.7
Separation distance, ft[e]	2500	3000	3750	2500

[a] EOL, end of life.
[b] Includes 3723 lb transported with lunar shelter.
[c] Includes 1820 lb transported with shelter.
[d] Includes 1240 lb transported with shelter.
[e] For buried reactor concepts the separation distance is about 900 ft.

(4) Because of the high degree of redundancy provided in the thermoelectric system, provisions were made only for manned access to electrical subsystems and reactor control drum drives; these would not require opening flow loops.

(5) In most cases repair of failed components would be impractical; these components would be discarded and replaced by spares. In no case would a liquid-metal component be taken into a lunar crew shelter.

(6) Time-line estimates indicate that two astronauts could replace a typical failed component, the task including opening the loop and welding in place the spare, in a 6-hour work shift. These time lines are, however, rather uncertain at present, since they have not been confirmed by task simulations.

Potential Modifications to SNAP-8

A number of modifications to the SNAP-8 Rankine cycle system, which are potentially desirable for the manned lunar surface application, were studied. Replacing both NaK pumps in the primary loop with thermoelectric-magnetic pumps or cooling all NaK pumps with NaK rather than with lube oil are desirable modifications. Further study is required in order to determine which of these two modifications is preferred.

OPERATIONAL INTERFACES

One of the most significant operational interfaces is that between the reactor power system and the lunar environment. The principal problem arises during the lunar night when the ambient temperature drops to roughly −250° F. If the powerplant is operating, the waste thermal energy produced suppresses this problem. For the Rankine and thermoelectric systems the heat-rejection temperature is sufficiently high so that changes in the ambient temperature have only a minor effect. As noted, the environmental day-night cycle poses a control problem for the Brayton system.

During storage or downtime periods the night environment (which lasts about 14 days) is cold enough to cause freezing of liquid metal heat transfer agents. Ordinary NaK freezes at 10° F; mercury at, −39° F; and a special NaK-cesium eutectic recently investigated for low-temperature service freezes at about −100° F. It is anticipated, on the basis of laboratory experience, that freezing and subsequent thawing of liquid metals in fluid systems could result in damage, leaks, or burst lines, and therefore such occurrences must be prevented. Several methods were studied; these are listed as follows:

(1) During storage or extended downtime for the Rankine system, liquid metal in the power and heat-rejection loops must be drained into thermally insulated storage vessels, where a few watts of radioisotope heat will prevent freezing.

(2) For all systems, the primary loop can be thermally insulated and maintained liquid by a small radioisotope heater (or by reactor afterheat following a power period). Thermal insulation around the reactor shield must be removed prior to initial startup by an astronaut since the shield is radiatively cooled.

(3) An articulated thermal shroud, remotely actuated, can protect the radiator for short night-down periods of a few hours to a day or so.

(4) The Brayton system concept employed a gas-cooled radiator so that only the primary loop contains liquid metals.

(5) The thermoelectric system could be operated at very low power with the radiator shroud in place during the storage period. This is possible because the liquid metals are circulated by thermoelectric pumps rather than by dynamic pumps (which require electric power) as in the Rankine system.

Crew participation during startup and operation of these systems would be minimal. Some initial installation tasks, such as laying the power cable from the plant to the base and emplacing the power conditioning and control electronics package, is required. These reactor systems have been designed for remote automatic startup and operation and there is no compelling reason for changing this method. Monitoring of key red-line parameters by the crew would be desirable, with override capability provided. Most system measurements would be telemetered directly to Earth.

Crew activities for maintenance and repair were previously discussed in terms of system design and reliability philosophy. Some familiarity with the system by the crew would be necessary. It is likely that most skills required for maintenance and repair would be of a general utility nature applicable to much of the mission equipment for lunar exploration. In the event of a failure, it seems likely that the best approach would be to rely heavily on consultation with appropriate specialists in mission control on Earth. Attempting to give crew members special training in coping with failures, the nature of which is not accurately predictable and the time of which would probably occur many months after the training period, is of dubious value at best.

A variety of methods of simplifying power system operations during preoperational storage, startup, shutdown, and switching to a redundant power conversion system were studied. Within the relatively small effort allotted, the results showed few methods that were significant. More detailed study will be required in order to determine whether the degree of simplification obtainable from potentially desirable modifications is significant.

The only modification considered absolutely essential is the use of a 4π shield around the reactor.

Growth

The SNAP-8 mercury Rankine system appears capable of substantial uprating, should requirements materialize for more power for lunar operations (e.g., processing of lunar resources). Radiator area increases slightly, from 1390 to 1450 ft^2, a size still within the nominal payload envelope. System mass is increased by about 4000 pounds. The power increase comes primarily from increased component efficiency and reductions of parasitic loads.

The other systems are limited with respect to radiator area. The payload envelope employed for this study is not a rigid limit, and more radiator area could be provided for integral system designs. The penalty for doing so is increased sensitivity of the launch vehicle to ascent wind loads and corresponding reductions in launch probability (probably not significant for this mission). The largest payload envelope which has been studied in detail for the standard Saturn V is the Voyager shroud, which was analyzed in connection with Voyager-Saturn V studies. This envelope would increase available radiator area by roughly 1000 ft^2. For the compact converter thermoelectric system, net power could be increased to about 30 kWe, with reactor power of 870 kilowatts and total system mass of 36 000 pounds. For the Brayton system, increased radiator area could be used in order to improve cycle efficiency at constant reactor power and thus provide about 34 kWe; or the system could be scaled up in proportion to the increased radiator area, thereby providing about 45 kWe at a reactor power of 300 kilowatts. System mass does not appear to be a problem, but detailed estimates were not made.

CONCLUDING REMARKS

A related type of nuclear power, radioisotopes, has not been discussed in the present paper. Isotope power (about 70 watts electric) will be used on the Moon to power the Apollo lunar science experiment package which will be emplaced on the Moon by astronauts during Apollo missions. However, isotope power is not likely to be used at the 20-to-30-kWe level because of limitations in the available supply. At this power level, reactor power has another significant advantage over isotope power; the nuclear fuel in a reactor is essentially nonradioactive prior to startup. Isotope heat sources, although much easier to shield than is a reactor, are highly radioactive and present launch hazards. These hazards are quite manageable at power levels in use today but become more difficult at high power.

There seems little doubt that reactor power systems based on technology under development today could be developed for practical operation as the electric generating plant of a lunar outpost. Packaged reactor power is used today in remote regions such as the Antarctic. The expense of conducting lunar operations will place a great premium on powerplant reliability and lifetime. A year of operational life is about the minimum usable, and 3 to 5 years would be desirable. The lunar crew can contribute to this goal by maintenance and repair activities, but a mature technology base is required.

The following conclusions can be derived from this study:

(1) Reactor power is the preferred energy source for lunar exploration missions wherein extended (more than 6-month) operations on the lunar surface will require power levels of 15 kWe or greater.

(2) Missions can be designed so that failure of the power system will not cause loss of crews, but termination of the missions after such failure is implied. The cost of such missions will place a great premium on assurance of power system operation for its design life. This assurance can best be provided by combination of technology maturity, redundancy, and provision for manned maintenance and repair.

(3) Technology presently under development—the SNAP-8 reactor and any of the three power conversion systems analyzed—is capable of meeting presently visualized mission requirements for lunar surface operations.

(4) It would be premature to make a choice now or in the near future as to the preferred power conversion concept. The thermoelectric concept at present appears to offer the greatest assurance of success, but this is partly due to its comparatively greater technological maturity. The thermoelectric system's greatest weakness is its relative inability to provide growth to higher power levels. In this regard, the Rankine system excels. Although it is not anticipated at present that power levels much in excess of 25 kWe will be demanded by lunar surface operations, some missions analysts (but not the authors of the present paper) are enthusiastic about the eventual potential of lunar resource utilization. If they are proven correct, power demands in the neighborhood of 100 kWe will occur.

(5) In the case of the SNAP-8 mercury Rankine system, several modifications were identified (some only tentatively) which would improve mission success assurance. Notable among these was a double-containment boiler. The use of thermoelectric-magnetic TEM pumps in the primary loop also appears promising.

(6) Design concepts employing deployed radiators, or off loading of the system with attendant manned surface operations burdens, do not provide performance gains commensurate with their operational problems and degradation of mission success assurance. Integral designs are therefore strongly favored.

This last conclusion is somewhat dependent upon a ground rule of this study, that shielding advantage of local lunar terrain was not to be available. In the writers' opinion this is a valid ground rule; however, it is a disputable point. If the powerplant were to be located in a local depression (i.e., small crater), radiation dose to the base crew and perhaps shield mass could be reduced. Off loading of an integral system (this does not imply construction and assembly as did the buried-reactor off-loaded system) would make possible the use of a smaller depression than otherwise and might be advantageous. Note, however, that: (*a*) this implies an off-loading system capable of handling the entire powerplant mass and (*b*) use of a depression will worsen the daytime thermal environment experienced by the radiators.

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