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Electrical Power System for the U.S. Space Station

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ELECTRICAL POWER SYSTEM DESIGN FOR THE U.S. SPACE STATION

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ABSTRACT

The Space Station Electrical Power System presents many interesting challenges. It will be much larger than previous space power systems, and it must be designed for on-orbit maintenance and replacement, along with having a growth capability. The power generation, energy storage, and power management and distribution (PMAD) subsystems comprise the primary elements of the overall system. Each was analyzed by NASA Lewis Research Center and its two contractors -- Rocketdyne and TRW -- in the definition studies of the program to determine the optimum approach to minimize initial costs and life cycle costs. For the PMAD subsystem, a ring bus architecture operating at 440 V, 20 kHz, single phase, was selected. Photovoltaic and solar dynamic power generation subsystems were both studied. Major tradeoffs were made for each subsystem and for the overall system, and a hybrid system (both photovoltaic and solar dynamic) was selected.

KEYWORDS

Space Station; space electrical power system; photovoltaic power generation; solar dynamic; power management and distribution; closed Brayton cycle; organic Rankine cycle; power system design; energy storage.

INTRODUCTION

The definition and preliminary design phase of the Space Station Program was started in 1984. NASA Lewis Research Center (LeRc) has responsibility for the electrical power system (EPS) for both the core station as well as the free-flying platform. Along with its two contractors - Rocketdyne and TRW, Lewis has conducted extensive technical and cost trade studies of overall EPS concepts and their associated components, subassemblies, and assemblies. An aggressive Advanced Development program was also conducted, keyed to providing required technologies in promising areas in a timely manner. The definition trade studies have resulted in the current baseline design, which is now entering the preliminary design phase.

There are a number of technical and programmatic considerations that have been influential in arriving at the current design for the manned core electrical power system. The high initial power level of 75 kWe to the user, coupled with the need for rapid on-orbit growth to 300 kWe or higher, places unique demands upon the power system. The initial 75 kWe is, of course, a space first in terms of size. Indeed, the physical size of the EPS, as shown in Fig. 1, constitutes a major design challenge. It is a significant factor in defining the station's overall mass, stability, and control. In addition, the nature of the Space Station Program imposes a need on the EPS to be user-friendly and adaptable to a changing and evolving set of user requirements. Thus, it must be more like a terrestrial utility power system as opposed to the fixed-purpose, dedicated power systems of current spacecraft.

Another requirement unique to the Space Station manned core is the necessity to assemble the station on-orbit over a period of 1 to 2 yr, using a variety of packages brought up in a series of Space Transportation System launches. Power will be needed for construction of the first launch package assembly, and such power will continue to be needed after the Space Shuttle Orbiter has returned to Earth. And, power requirements will grow for each subsequent launch and assembly. This situation of having to meet unique power growth steps is further complicated by the lack of solar pointing capability on the first few launches. Again, this factor must be considered in the power system design approach selection.

On-orbit maintainability of the power system assemblies and their on-orbit replacement is also necessary, along with need for a modular path for growth. These are requirements that must be designed into the manned core system at the beginning. The frequency of repair and replacement becomes a major factor in life-cycle costs, hence in system selection.

The relatively low orbit of 278 to 500 km (150 to 270 nmi) that is required to provide easy access by the Space Shuttle imposes very significant energy storage requirements. The low Earth orbit yields an in-Sun time of about 59 to 60 min and an eclipse time of 35 to 36 min, with over 5000 orbits/yr. These are more severe design requirements than for previous space applications, such as geosynchronous satellites. Also, at these low orbital altitudes, drag becomes a major issue in the design trades. This led to consideration of power generation systems other than photovoltaic, such as solar dynamic systems.

The platform power system has somewhat different requirements and constraints from the manned core station. As previously mentioned, the manned core components will be designed for replacement on-orbit. This is not possible for the platforms, and they must be designed for much higher system reliability since they have only a 30-month visitation frequency. The platform power levels are also considerably lower than for the station, and the type of peaking is also different between the two systems. For the manned core, utility-type power is required in order to satisfy a wide range of power needs, with the individual loads not normally having a major impact on peaking. Thus, there is a need for maximum system flexibility for user accommodation. For the platforms, there will be only a few power users per flight; hence, each load will have a significant impact on peaking. Also, each mission will have well-defined power requirements. There is also a requirement that the platform solar array be retractable for servicing at the station. Finally, there is a severe mass limitation on platform systems due to various launch considerations. These requirements also indirectly impact the station since the desire for commonality (for minimum overall program initial costs) results in common components between the manned core and the platform.

A number of subsystem options existed which could meet the above requirements. The options considered for power generation were limited to photovoltaic and solar dynamic systems. Nuclear generation was not considered because of concerns related to schedule, cost, and development risk. Energy storage options for photovoltaic systems included regenerative fuel cells and batteries. For the solar dynamic system, thermal energy storage was considered, using either latent heat of fusion or sensible heat. In the power management and distribution (PMAD) system, options were direct current (dc) or alternating current (ac), with voltage levels from 150 to 440 V. Both ring and radial bus architectures were evaluated.

PHOTOVOLTAIC SYSTEM STUDIES

A broad range of options were considered for the solar cells, including both silicon and gallium arsenide materials. Based on a number of tradeoff studies, involving aspects of cost, development status and risk, efficiency, and production considerations, silicon was selected. The cell size was 8 by 8 cm, 203.2 μm (8 mils) thick, with a 152.4 μm (6 mil) ceria-doped microsheet coverglass. Cells of 8 by 8 cm are currently in pilot production. Wrap-through contacts were selected to reduce array and assembly costs, along with a gridded back to achieve a lower operating temperature, hence higher efficiency.

A variety of solar array concepts were evaluated. Two prime candidates were selected for further evaluation after preliminary screening studies. These were (1) erectable or deployable rigid planar and (2) deployable flexible planar. The concept finally selected was the deployable flexible planar. This concept uses accordion-folded flexible blankets supported by a deployable/retractable mast and is similar in design to the OAST-1 experiment flown on the Space Shuttle (Fig. 2).

The selected Space Station solar array wing is shown in Fig. 3, along with its nominal dimensions. Each wing consists of two blankets (instead of one as on OAST-1) made up of mechanically hinged, coated, flexible Kapton panels which carry the solar cells and wiring, supported by the deployable/retractable center mast. Each blanket would be folded into a container/cover assembly when retracted. The Kapton substrate on which the cells are mounted is coated for atomic oxygen protection and is transparent, thus facilitating transmission of infrared radiation, hence increasing overall efficiency. To avoid potential interactions between the arrays and the space plasma environment, an operating voltage of 160 V was selected. The selection of flexible arrays over rigid arrays was driven by the mass sensitivity of the polar platform. The design shown in Fig. 3 is optimized for the polar platform, but was also selected for the core station and the co-orbiting platform to save redesign and development costs, thus achieving minimum program initial cost.

The photovoltaic energy storage candidates considered were regenerative fuel cells, nickel-cadmium batteries, and nickel-hydrogen batteries. Nickel-cadmium batteries have a long, successful history of use in space. To achieve long life, however, operation must be at low depths of discharge, with a corresponding battery mass penalty. The net result was that nickel-cadmium batteries were about twice as heavy as nickel-hydrogen batteries for the same service, with higher overall costs; hence were eliminated.

Regenerative fuel cells, while having important advantages in terms of flexibility in levels of energy storage, were also eliminated. The active nature of the heat rejection system for the regenerative fuel cell, along with its considerably larger volume as compared to batteries, created problems in their use on the platforms. Regenerative fuel cell maintainability was also a problem on the platforms. Replacement could not be accomplished until the platform was returned to the manned core station for servicing. Thus, to achieve the required reliability, redundant regenerative fuel cell modules were required, with a resulting large weight penalty.

This combination of factors led to selection of nickel-hydrogen batteries for the platforms. For the station, nickel-hydrogen batteries were also selected, with commonality with the platform being the primary driver. This resulted in lower overall initial program costs.

SOLAR DYNAMIC SYSTEM STUDIES

Solar dynamic systems are of interest to the station because of their higher overall efficiency, as compared to photovoltaic systems. The heat engine is about 20 to 30 percent efficient with thermal storage being about 90 percent efficient. This can be compared to a solar cell efficiency of 14 percent and battery efficiencies of 70 to 80 percent. This increased efficiency directly translates into reduced area; hence, reduced drag, and has a significant cost impact, particularly for life cycle costs.

Two types of solar dynamic conversion cycles were considered: (1) the Closed Brayton Cycle (CBC) and (2) the Organic Rankine Cycle (ORC). These are shown schematically in Figs. 4 and 5. For either cycle, there is a concentrator that collects and focuses the solar radiation to a small area; a receiver that captures the focused thermal energy, transmits it to a working fluid, and stores excess energy for use during eclipse; the power conversion unit that uses the heated working fluid in a heat engine to drive a turbo-alternator and produce electricity; and a radiator to reject waste heat. In the ORC system, toluene was selected as the working fluid, based on its extensive history. For the CBC system, a helium-xenon gas mixture is used.

A number of different concentrator concepts were examined during the definition studies. Both Newtonian (single reflection) and Cassegrainian (multiple reflection) systems were evaluated, but the Cassegrainian concept was eventually discarded due to its complexity and higher cost. The selected Newtonian concept uses an offset or off-axis reflector design (Fig. 6). This concept consists of a segment of a larger parent parabola and permits placing the receiver and engine close to the truss, thus reducing the system moment of inertia. The concentrator is composed of a number of hexagonal panels constructed from graphite-epoxy trusses. Individual triangular facets with a spherical surface are mounted on the hexagonal panels. The facets, made of aluminum honeycomb with graphite-epoxy facesheets, are coated with silver plus a protective coating to provide the reflective surface.

Energy for eclipse is provided by storing heat. Storage concepts integral to and remote from the receiver were considered. Also, a number of different concepts for the storage material were evaluated; latent heat of fusion of a phase-change material and sensible heat storage in a solid being the two primary candidates. Analyses indicated a phase-change salt integral to the receiver was the most promising approach.

For the Brayton cycle receiver (Fig. 7), the cavity is lined with tubes running the length of the cavity. Thermal energy storage is provided by a melting/freezing salt enclosed in a series of annular shaped metallic containment rings surrounding the working fluid tubes. The ORC receiver uses heat pipes running the length of the cavity, with each heat pipe containing a working fluid tube and a salt storage tube (Fig. 8 shows one concept using this approach). Heat pipes are used to provide heat flux leveling, thus preventing hot spots that could degrade the temperature sensitive working fluid (toluene). In both cases, a cylindrical cavity was selected as being the most cost-effective approach to leveling the unsymmetrical heat fluxes coming from the off-set concentrator. While the current baselined designs from the definition studies are shown in Figs. 7 and 8, design activity is continuing on evaluating other receiver concepts, particularly in the supporting Advanced Development efforts.

Both CBC and ORC systems have a considerable experience base in terrestrial and aeronautical applications. The closed Brayton system, designed for space application, has achieved over 50 000 hr of test time (38 000 hr on one unit) in the NASA Space Power Program in the 1960's, while the organic Rankine systems using toluene have accumulated over 100 000 hr in terrestrial applications. Engines for the Brayton system which uses helium-xenon working fluid with a turbine inlet temperature of 788 °C (1450 °F) and engines for the Rankine system which uses toluene at 399 °C (750 °F) are considered within current state-of-the-art. Currently, both CBC and ORC systems have been carried into preliminary design.

POWER MANAGEMENT AND DISTRIBUTION STUDIES

The primary parameters evaluated in the Power Management and Distribution (PMAD) studies were frequency, voltage, and architecture. Both alternating current (ac) and direct current (dc) were considered, with ac being selected due to greater flexibility and easier switching. Also, while 28 V dc components do exist, such components at 150 V dc and higher, designed for space, are considered lacking in technology. The primary alternating current distribution frequencies studied were 400 Hz and 20 kHz. 400 Hz ac is commonly used on aircraft, thus systems-level technology exists. However, the technology level is believed low for space-type components. Also, 400 Hz has potential problems with acoustic noise and electromagnetic interference, particularly with regard to plasma coupling which could jeopardize plasma research at the Space Station.

A single phase, 20 kHz frequency was selected. Due to the high frequency, components are small, lightweight, low cost, and highly efficient. There is also an existing technology base for the components, no problems with acoustic noise exist, and there is little if any electromagnetic interference. Because of the high power level (75 kWe initially with growth to 300 kWe), high distribution voltages were attractive. 440 V was selected, resulting in lower cable weights and costs as compared to the much lower voltages currently used.

The PMAD system has the general characteristics of a terrestrial utility power system. It must be user friendly, accommodate changes in load type and size, and be adaptable to growth. Both dual-ring and radial busses were examined, with the dual-ring being selected (Fig. 9). Power from the power generation module is controlled by a main bus switching assembly (MBSA) and distributed through the dual-ring bus to a number of power distribution control assemblies (PDCA's) on the upper keel and boom, lower keel and boom, transverse boom, and inside the manned modules. The PDCA's interface with the loads and have the provision to connect critical loads to multiple outlets for reliability. A dedicated control system will be used for sensing and command. Fault protection within the ring distribution system is provided by remote bus isolators (RBI's) within the MBSA's and PDCA's. Remote power controllers (RPC's) within the PDCA sense faults within the loads and act to protect the power system.

The electrical distribution architecture for the platforms uses the same components as selected for the manned core station. Although a radial bus has been selected rather than a dual-ring bus, the power type is the same (20 kHz, single phase, 440 V). Thus, common components can be used.

POWER SYSTEM SELECTION

A broad spectrum of system trade studies were conducted to satisfy the various requirements. All factors impacting cost were identified and evaluated in terms of initial and life cycle costs for both the core station and the platforms. Included were power system hardware and software development, manufacturing, verification, overhead, and launch costs. Full consideration was given to commonality between manned core and platform components.

The selected electrical power system for the core station is shown in Fig. 1. It is a hybrid system, with both photovoltaic and solar dynamic power generation. The photovoltaic system provides 25 kWe to the users from four wings, while the solar dynamic system provides 50 kWe to the users (from two units). Growth would be provided by adding pairs of the 25 kWe solar dynamic systems. Design selections for the power generation and PMAD system are as previously described. In this configuration, there would be a photovoltaic power module and a solar dynamic power module on each side of the keel, extending outward from the alpha-joint (Fig. 10). The exact arrangement of radiators for the solar dynamic system will be examined further in the preliminary design phase.

The primary reason for selecting the hybrid system is the large life cycle cost saving as compared to an all photovoltaic system. For a 30-yr life, analyses indicate that a hybrid system, growing to 300 kWe through solar dynamics, would save about one and a half to two billion dollars over an all photovoltaic system. These savings result primarily from reduced cost of replacement components, increased life of components, and reduced drag makeup requirements. Also, there will be reduced logistics costs because the hybrid station allows operation at lower altitudes than the all-photovoltaic system. By providing for the availability of the solar dynamic system on the initial station, these advantages will accrue from the beginning of operation.

In addition to life cycle cost savings, there are other benefits to the hybrid power system. The photovoltaic system provides the required power during the early launches when pointing capability is not available. Having two parallel approaches lowers developmental risk. Also, once in orbit, the non-similar nature of the two systems reduces the possibility of a generic failure in one system causing either a catastrophic power loss or having a major cost or operations impact. The initial cost of the photovoltaic system, in the hybrid case, is reduced by using the same identical arrays and nickel-hydrogen battery cells used on the platforms. These are very close to optimum for a system providing only 25 kWe to the user, and provide a significant savings in development costs and total costs through commonality.

SUMMARY

The selected photovoltaic/solar dynamic hybrid power generation system for the manned core station meets all the current programmatic and technical requirements. Extensive definition studies show that it provides minimum life cycle costs with affordable initial costs, and that it provides a user-friendly power system capable of growth to 300 kWe or higher. Subsystem and component selections were made based on a combination of minimum initial cost with low life cycle costs, along with low development risk. Efforts have started under the NASA Advanced Development Program to assure technology data will be in hand for the critical areas by the end of the preliminary design period in the station development phase.

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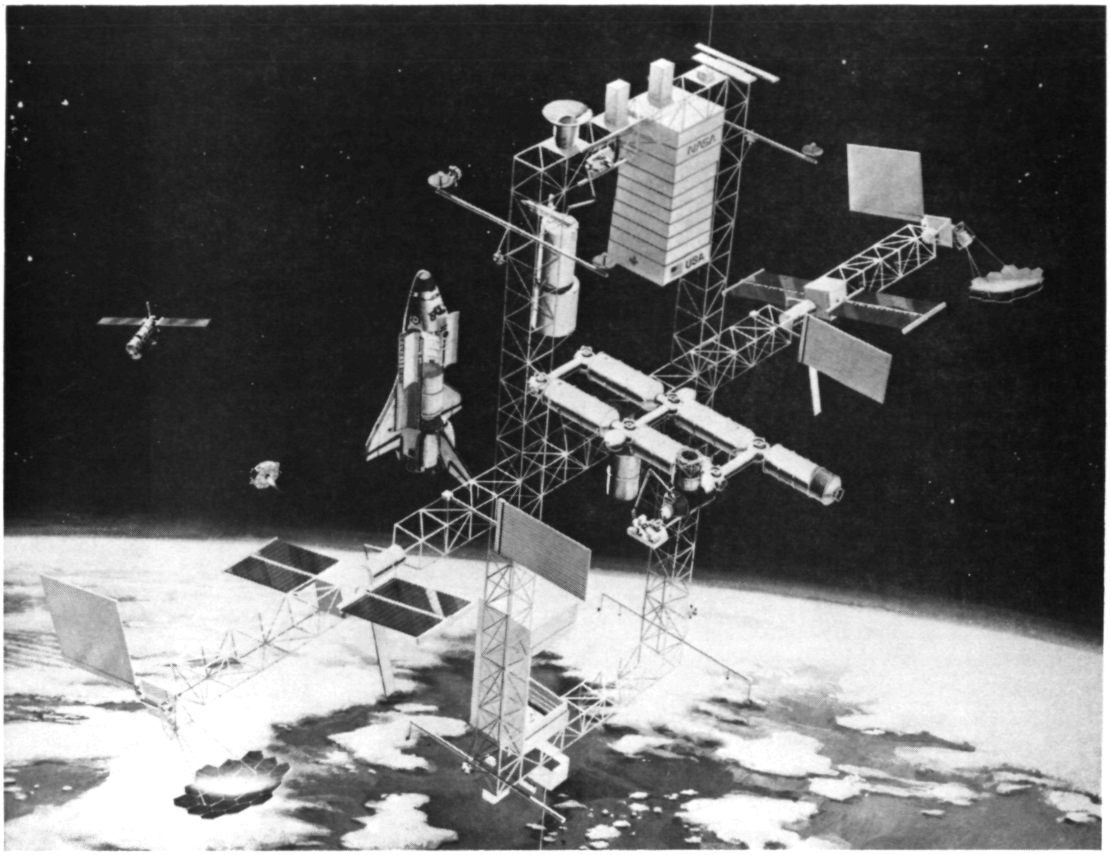

FIG. 1. - DUAL-KEEL SPACE STATION CONCEPT.

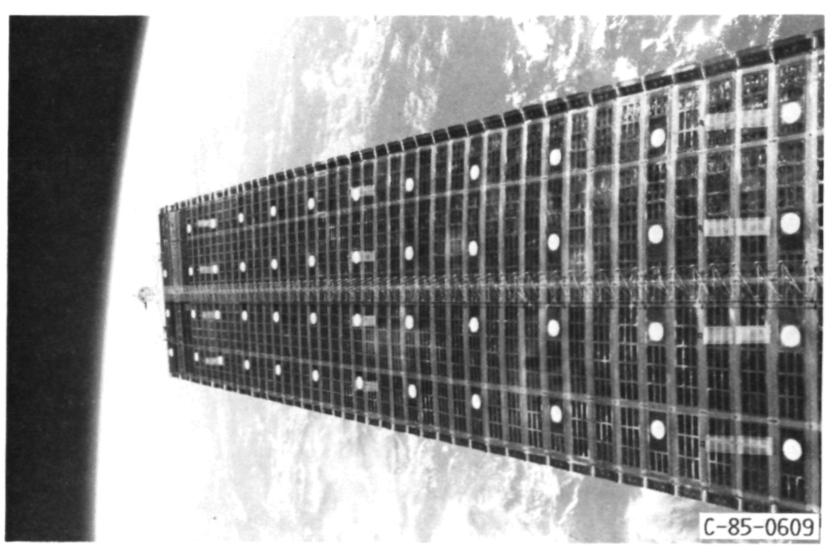

FIG. 2. - OAST-1 ARRAY.

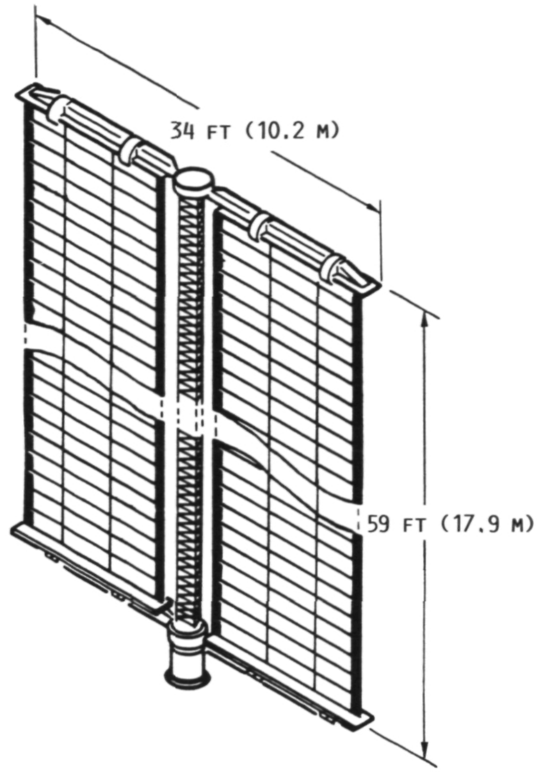

FIGURE 3.- TWO-BLANKET FLEXIBLE SOLAR ARRAY (6.25 KWE TO USER).

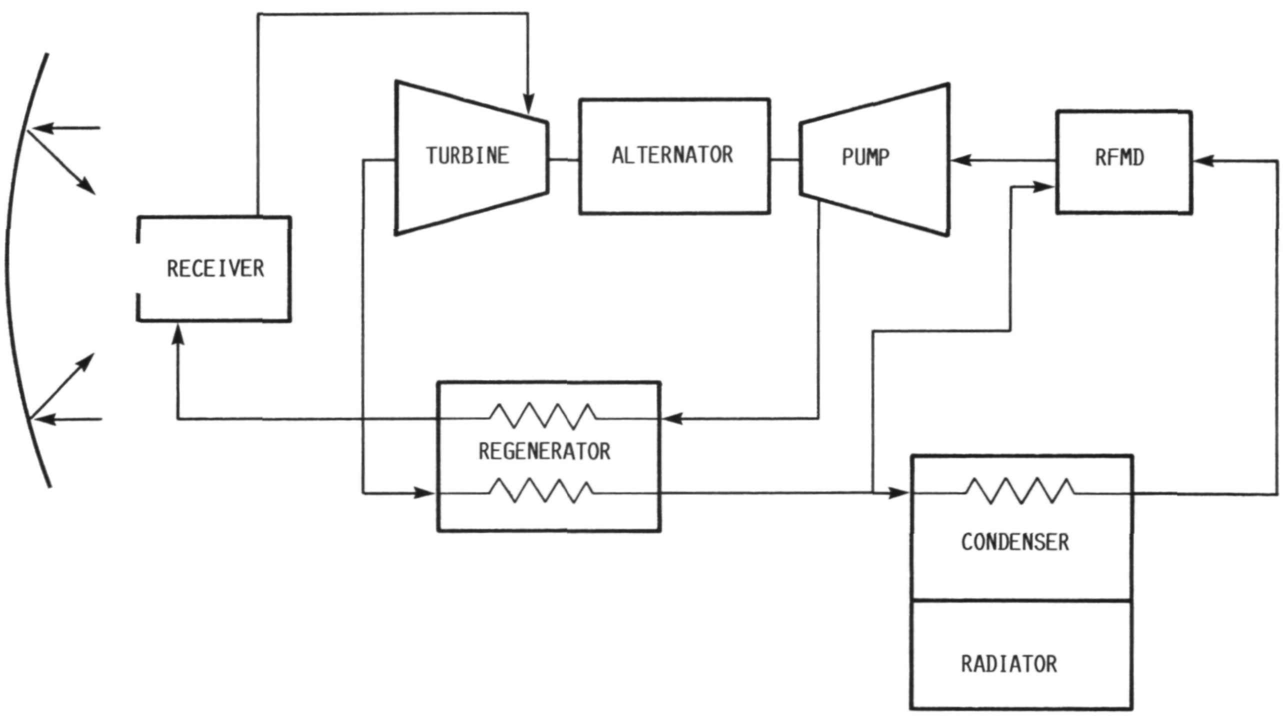

FIGURE 4.- CLOSED BRAYTON CYCLE SYSTEM SCHEMATIC.

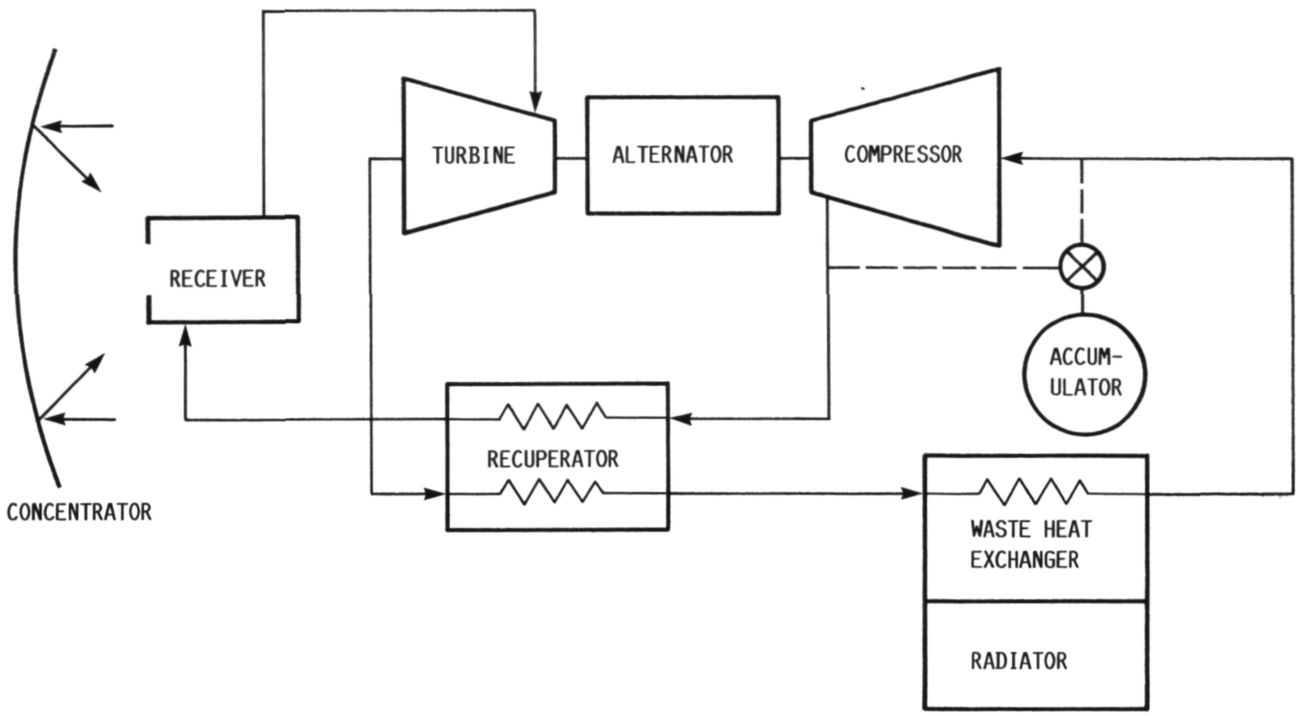

FIGURE 5.- SOLAR ORGANIC RANKINE CYCLE SYSTEM SCHEMATIC.

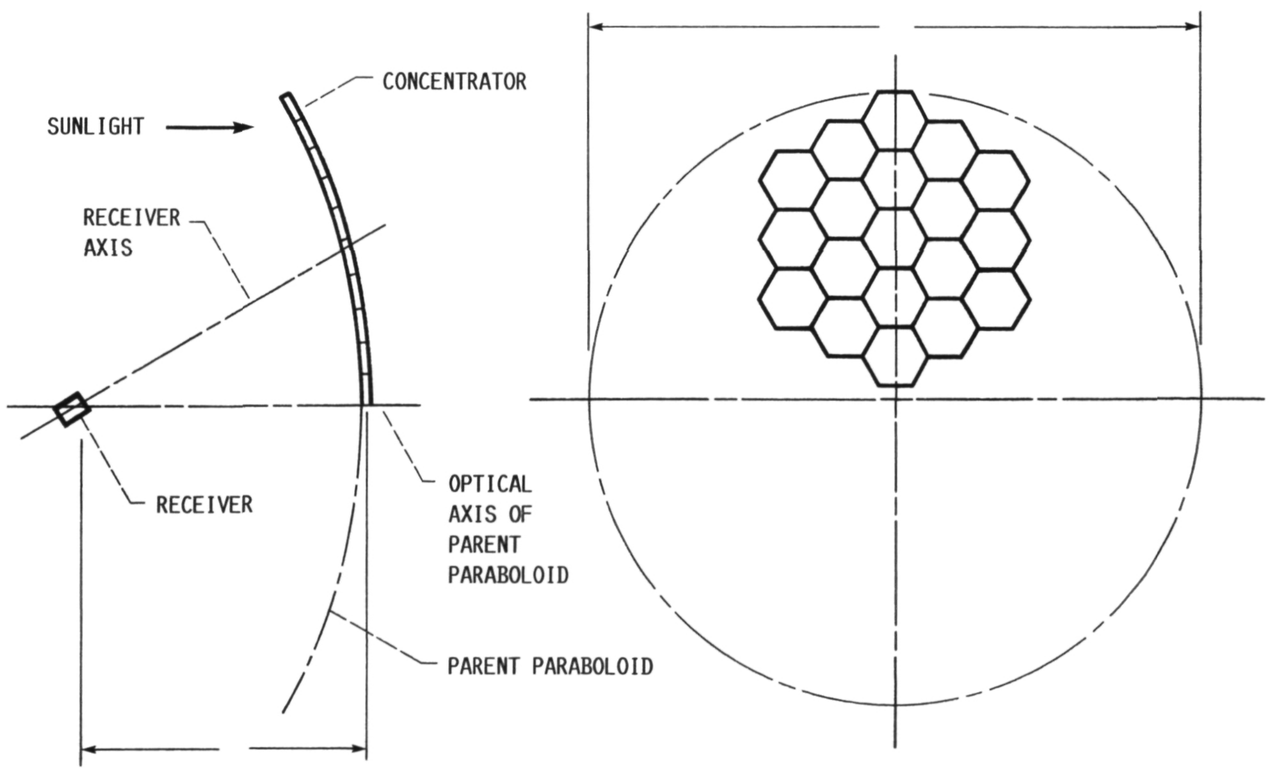

FIGURE 6.- OFF-SET CONCENTRATOR CONCEPT.

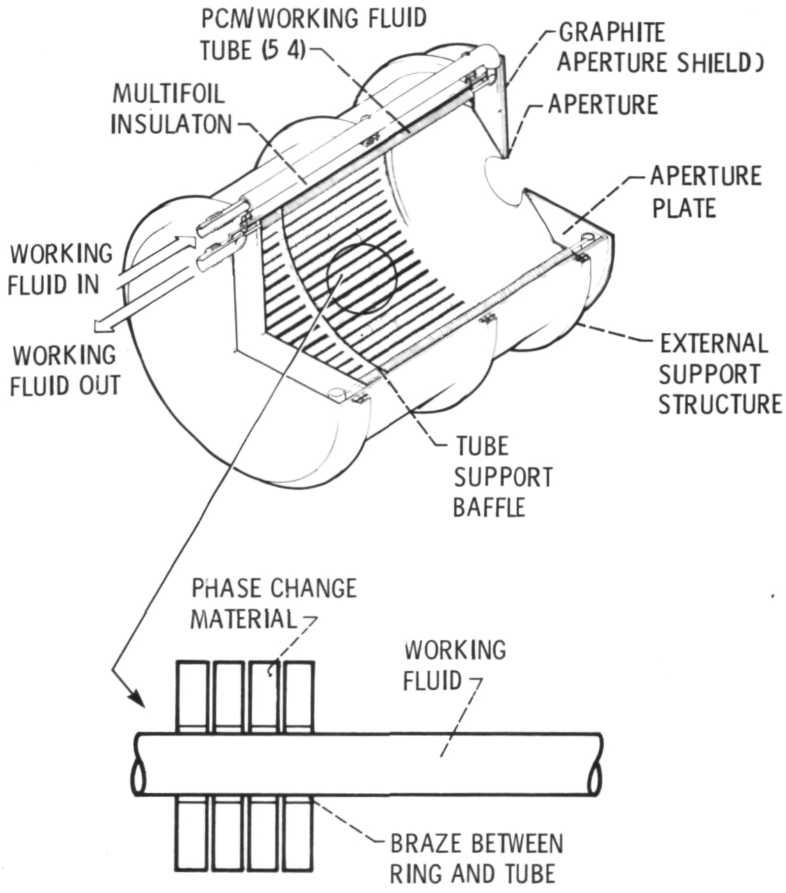

FIGURE 7.- BRAYTON RECEIVER CONCEPT.

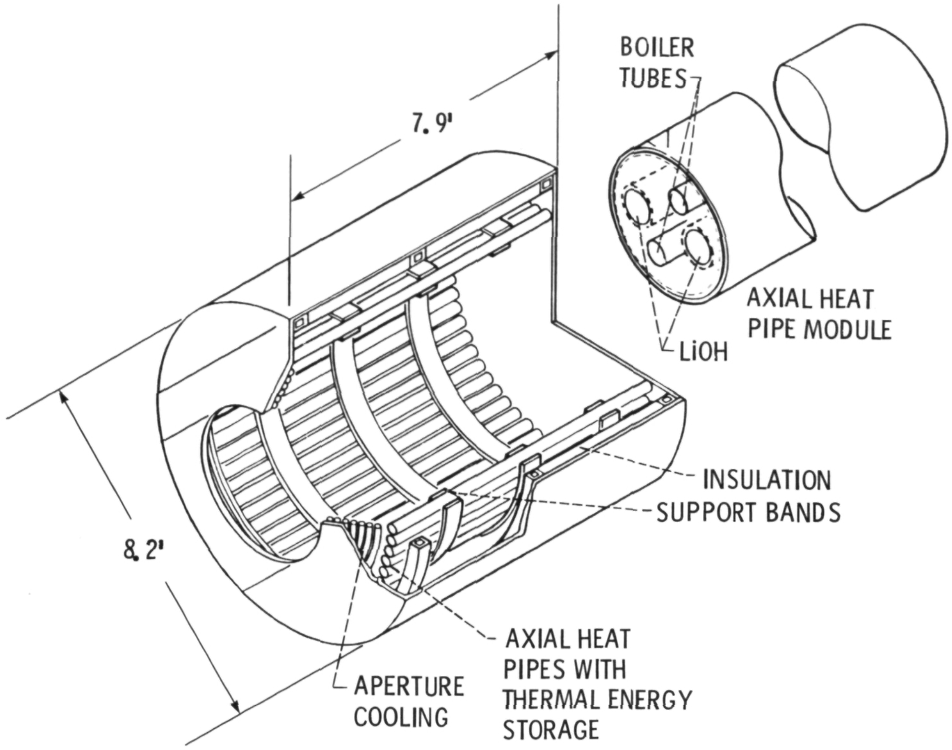

Figure 8.- Organic Rankine receiver concept.

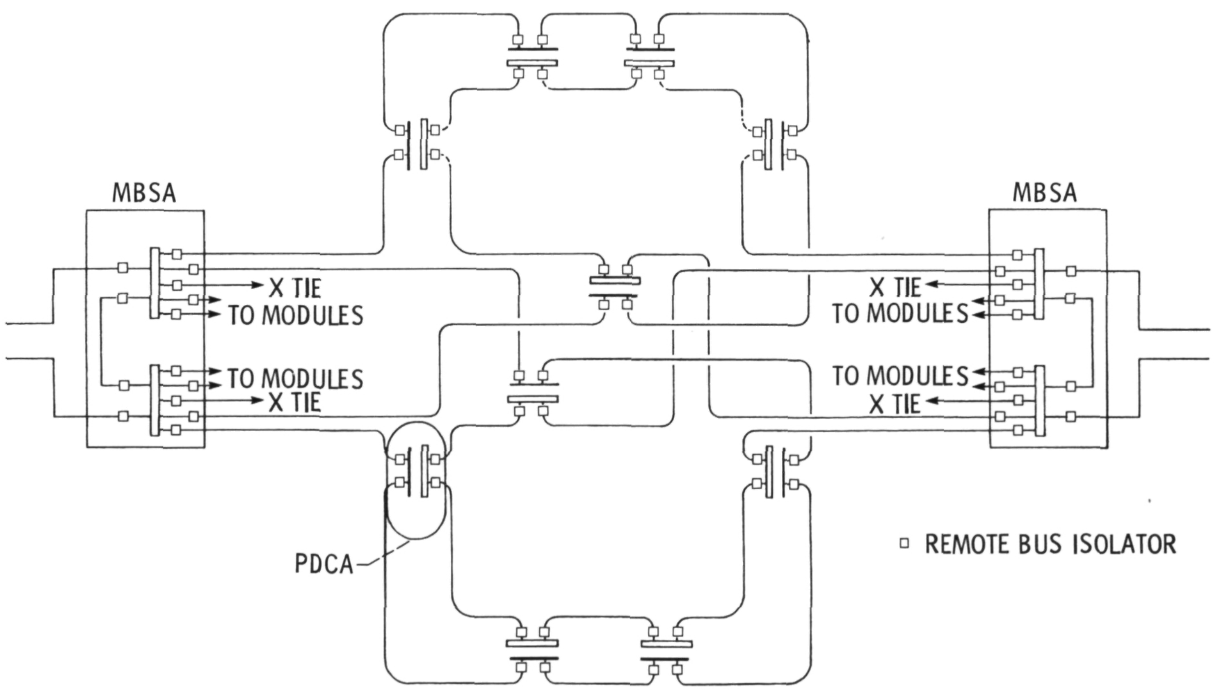

Figure 9.- Ring distribution architecture.

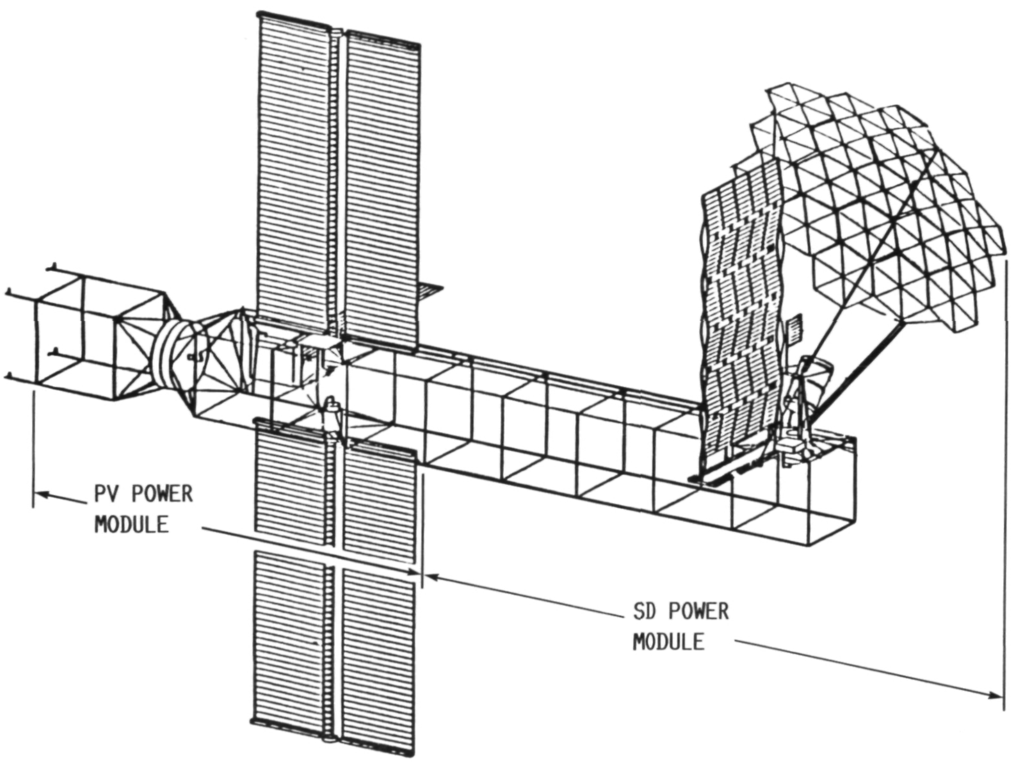

FIGURE 10.- PHOTOVOLTAIC AND SOLAR DYNAMIC POWER MODULES.

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15. Supplementary Notes

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16. Abstract

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