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Design Considerations for Space Radiators Based on the Liquid Sheet (LSR) Concept

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DESIGN CONSIDERATIONS FOR SPACE RADIATORS BASED ON THE LIQUID SHEET (LSR) CONCEPT

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ABSTRACT

Concept development work on space heat rejection subsystems tailored to the requirements of various space power conversion systems is proceeding over a broad front of technologies at NASA LeRC. Included are orbital and planetary surface based radiator concepts utilizing pumped loops, a variety of heat pipe radiator concepts, and the innovative liquid sheet radiator (LSR). The basic feasibility of the LSR concept has been investigated in prior work which generated preliminary information indicating the suitability of the LSR concept for space power systems requiring cycle reject heat to be radiated to the space sink at low-to-mid temperatures (300K to 400K), with silicone oils used for the radiator working fluid.

This study is directed at performing a comparative examination of LSR characteristics as they affect the basic design of low earth orbit based solar dynamic power conversion systems. The power systems considered were based on the closed Brayton (CBC) and the Free Piston Stirling (FPS) cycles, each with a power output of 2 kWe and using previously tested silicone oil (Dow-Corning Me^2) as the radiator working fluid. Conclusions indicate that, due to its ability for direct cold end cooling, an LSR based heat rejection subsystem is far more compatible with a Stirling space power system than with a CBC, which requires LSR coupling by means of an intermediate gas/liquid heat exchanger and adjustment of cycle operating conditions.

INTRODUCTION

Ever since the revolutionary "liquid droplet radiator" (LDR) concept, based on radiative heat rejection from unconfined or "external flow" working fluid, i.e. a droplet sheet or cloud, directly to the space sink, was first proposed by Mattick and Hertzberg [1,2], the LDR has been the subject of extensive technology development in the space radiator community. Numerous reports, a selection of which is referenced here [3-7], were written on the performance characteristics of major components and on the relative merits of the concept as compared to other space radiator configurations for space power conversion system (PCS) applications. A schematic of the basic LDR concept as applied to a generic PCS is shown in figure 1. The apparent potential of very low mass for the radiator subsystem along with excellent stowability (i.e. low launch payload volume) and relative immunity to micrometeoroid damage, needs to be weighed against some of the less favorable characteristics of external flow radiators.

Typical among these negative aspects of an LDR are: very low vapor pressure for the working fluid (1.0E-8 torr) in order to keep evaporative losses low over a reasonable service life, possible working fluid reaction with atomic oxygen (AO) in earth orbital applications; the need for accurate aiming of the droplet stream between injector and collector; and the relatively high injector fabrication cost, due to the precise drilling requirement of very large numbers of accurately positioned injector orifices. These precision orifices together with piezo-electric excitation devices are needed to generate the droplet stream for the LDR.

To reduce injector complexity and cost, the liquid sheet radiator (LSR) concept was proposed by Chubb [8,9]. This external fluid radiator concept is similar to the LDR (fig. 1) in every respect but one: the droplet cloud is replaced by a continuous sheet of 100 μm to 200 μm thickness. Consequently fabrication of the injector is greatly simplified by replacing the myriads of injector orifices with a single slit having the proper width and thickness. The need for piezo-electric exciters is also eliminated. An added advantage obtained with the LSR is that due to surface tension forces the thin sheet issuing from the slit will eventually coalesce to a point. As a result the liquid sheet assumes a triangular configuration, as shown both theoretically and experimentally with Dow-Corning 705 silicone oil for slit widths of 3.4 cm and 23.5 cm by Chubb and Calfo [9]. For the larger slit width, representing the test facility limit, the point of coalescence occurred about 3.5 m downstream of the injector thus generating a total radiating sheet surface area of 0.82 square meters. Although sheet emissivity has not yet been measured, theoretical predictions indicate that values of at least 0.7 should be achievable for a nominal sheet thickness of 150 μm or more at temperatures in the 300 K to 400 K range.

Aside from its greatly simplified injector and self focussing characteristic, the LSR should perform like an LDR in all other respects, and some of the equipment originally fabricated for the LDR program, i.e. pumps, fluid ducts, heat exchangers, fluid collectors, and structural components should work well with the LSR. However, further development on larger scale injector hardware will have to be undertaken to verify sheet dynamic stability and also the predicted sheet emissivity performance (fig. 2) based on published absorption data [13]. To ensure that such larger scale component development is focussed toward the proper power system applications, a more detailed study of space power system design and radiator integration issues needs to be performed.

Hence, it is the purpose of this report to present some pertinent results on power system integration studies for a closed cycle Brayton (CBC) and a free piston Stirling (FPS) based power system, both designed for a nominal 2 kWe power output (satellite applications), operating in low earth orbit (LEO) with solar heat input, and both utilizing an LSR based heat rejection subsystem. Comparison to the same power systems equipped with light weight heat pipe radiators (HPR) is also included. Based on the conclusions drawn from this study, some recommendations are made on the scale up of LSR based heat rejection subsystems matched to megawatt level power systems with nuclear heat sources for planetary surface and nuclear electric propulsion (NEP) applications. However, for these highly scaled up designs (3 orders of magnitude), large hardware test facilities will be required.

ANALYSIS

LSR Heat Rejection Subsystem

Before discussing the system integration issues of an LSR with solar dynamic power conversion systems (CBC and FPS), a brief summary of LSR component masses is presented, in order to arrive at an estimate of LSR specific mass. In an effort to limit scaling linear dimensions of components to no more than twice the LSR size already tested for sheet stability [9], a four module series-parallel configuration, as shown in figure 3, was considered for the 2 kWe PCS radiators. At constant Weber Number, a doubling of the injector slit width to 0.5 m will also double the distance to the self focusing point to about 7 m, and each of the four triangular sheet areas will be 1.75 m^2, for a total sheet area of 7.0 m^2. It should be noted that with the sheets being essentially flat and in the same plane they radiate to the space sink from both sides. Hence, the total radiating area will be 14 m^2. In compiling the table of LSR component and subsystem masses, table I, the use of high strength light weight graphite carbon composites for the structure and fluid tanks was assumed. The tank inner surfaces were provided with liners compatible with the working fluid. Furthermore, all critical components, such as fluid pipes and tanks, were considered to be provided with bumper shields for micrometeoroid protection. For consistency with previous analyses, the heat sink exchanger was considered to be part of the power system. This implies that for PCS not requiring such a heat exchanger the mass advantage will appear at the system level.

Table I: LSR Component and Subsystem Mass (kg) for 2 kWe PCS

Liquid in Sheets	0.9 (14 m^2 radiat. area)
Reserve Liquid & Tanks	8.0
Ejectors	4.0
Collectors	3.0
Structure & Pumps	5.0
Total LSR Mass	20.9

Since the total radiating area for the sheet was shown above to be 14 m^2, the specific mass for the system integration studies was assumed to be 20.9/14, or nominally 1.5 kg/m^2. Hence, all LSR mass calculations in this study were based on this value. It is recognized that in scaling to LSRs with order of magnitude greater sheet areas, specific mass should decrease.

CBC Power System

In performing the analyses for LSR and HPR equipped CBC power systems, the power system analysis code used previously [10,11] was used with essentially the same cycle schematic (fig. 4) and input conditions for the solar concentrator, heat receiver (with LiF storage material), but turbomachinery polytropic efficiencies were lowered to values near 0.8, expected for the small scale of the compressor and turbine required for the 2 kWe power level. Solar heat receiver mass was scaled [12] on the basis of thermal power input. A comparison of the operating conditions and performance of the two alternative power system configurations is shown in table II.

For the LSR heat rejection system, the heat pipe radiator (HPR), consisting of the working fluid duct with penetrating heat pipes, was replaced by the LSR heat rejection system shown in figure 3. Note that the gas-to oil heat exchanger is an indispensable component for the Brayton heat rejection subsystem, since the gaseous working fluid, He-Xe mixture, needs to be cooled from recuperator outlet to compressor inlet temperature. The gas temperature drop is near 150 K, whereas the oil will experience a temperature rise of less than 10 K, consistent with the mass flow requirements for the sheet, at velocities of 5 to 10 m/sec. Moreover, in sharp contrast to an HPR with an effective radiating temperature well above compressor inlet temperature of the cycle working fluid, the effective radiating temperature for the liquid sheet will be below compressor inlet temperature. As shown in table II, a CBC using a light weight heat pipe radiator (i.e. 5.0 kg/m^2 being developed under the CSTI program) could operate with a compressor inlet temperature of 286 K (with a space sink temperature of 250 K) and still have an effective radiator temperature of 340 K. For an LSR operating at the same cycle conditions, the effective sheet temperature would have to be at least 10 K below compressor inlet temperature (i.e. 276 K), leading to a total radiating area of about 50 m^2 and an LSR radiator mass of 75 kg.

A better alternative is to raise compressor inlet temperature by lowering cycle temperature ratio, and thermal efficiency, even though the resulting heat rejection requirement will increase from 3.6 to 5.6 kWt. This new optimum temperature ratio will result in a radiator area of 13.9 m^2 as shown. Further reduction of temperature ratio would be counterproductive since the increased heat rejection requirement would offset the higher radiating temperature.

Free Piston Stirling Power System

A similar analysis procedure was followed for the free piston Stirling based power system described by the schematic shown in figure 5. In considering the LSR based heat rejection scheme, it was found, however, that a separate heat sink heat exchanger, as shown in figure 3, is not needed since the FPS cold end can be cooled directly by the silicone oil used for the LSR. This feature represents a significant advantage over the CBC as indicated by the entries in table III. However, the Stirling FPS is also quite compatible with light weight heat pipe radiators, especially in a flat plate configuration where radiator specific mass can be cut in half due to radiation from both sides.

Comparison of specific power values given in tables II and III shows that, for the power level considered in this study, the Stirling FPS using an LSR based heat rejection subsystem has a 30 percent higher system specific power, or approximately 30 percent lower system mass than the CBC. Integration of the FPS heater head with the solar heat receiver would eliminate the need for the heat source heat exchanger and thereby increase the FPS advantage to over 50 percent. For HPR based heat rejection, the FPS advantage would range from 3 to 25 percent. However, all masses are expected to scale favorably as power level is increased by an order of magnitude or higher (20 to 35 kWe) as shown in previous work using HPR [10,11].

Note that in calculating sheet emissivity, a higher sheet thickness (180 μm) was used for the FPS than for the CBC (130 μm). The higher sheet thickness and emissivity results from the lower injector slit width required for the smaller FPS radiator at near constant sheet mass flow.

Table II. 2 kWe CBC Performance With Two Heat Rejection Subsystem Alternatives (Sink Temp. = 250 K)

	LSR	HPR
Turbine Inlet Temp - K	1086.	1086.
Cycle Temperature Ratio	3.1	3.8
Compressor Inlet Temp. - K	350.	286.
Compressor Press. Ratio	1.8	2.1
Thermal Efficiency %	25.1	34.2
Cycle Heat Rejected - kWt	5.6	3.6
Effective Rad. Temp.- K	340.	340.
Emissivity (130 μm sheet)	0.75	0.85
Total Radiating Area - m^2	13.9	8.3
Rad. Specific Mass - kg/m^2	1.5	2.5
System Specific Power - W/kg	8.6	10.5
Component Masses- kg		
Concentrator	37.	28.
Heat Receiver	77.	61.
Recuperator	17.	17.
Turbomachinery & Controls	28.	28.
Heat Sink Heat Exchanger	21.	6.
Main Radiator	21.	21.
Power Cond. Radiator	10.	10.
Structure	22.	18.
Total PCS Mass	233.	190.

Table III. 2 kWe Stirling Performance With Two Heat Rejection Subsystem Alternatives (Sink Temp. = 250 K)

	LSR	HPR
Heater Head Temp. - K	1086.	1086.
Cycle Temp. Ratio	3.0	2.8
Thermal Efficiency %	42.7	40.9
Cycle Reject Heat - kWt	2.7	2.9
Emissivity (180 μm sheet)	0.8	0.85
Effective Rad. Temp. - K	352.	378.
Total Radiating Area - m^2	5.7	4.1
Rad. Specific Mass - kg/m^2	1.5	2.5
System Specific Power - W/kg	11.1	10.7
Component Masses - kg		
Concentrator	22.	23.
Heat Receiver	55.	56.
Heat Source Loop Heat Exchanger	34.	34.
Engine and Controls	30.	30.
Heat Sink Heat Exchanger	0.	6.
Main Radiator	9.	10.
Power Cond. Radiator	10.	10.
Structure	18.	18.
Total PCS Mass	181.	187.

Extension of Results to Large Power Levels

In scaling to higher power levels, it is reasonable to expect radiating sheet area to increase much faster than LSR component mass. As a result, radiator specific mass should decrease up to an order of magnitude, an estimate that is in agreement with the projections of Bruckner et al. [3,4] for large lunar power system (3.4 MWe) LDR radiators. An extension of Bruckner's lunar heat rejection concept to LSR is shown in figure 6, with the sheet flow being in the direction of the lunar gravity field. Providing each of these sheets with an individual gas to LSR fluid heat exchanger should also be investigated.

Once developed, the use of direct contact gas/liquid heat exchangers [3] may alleviate the problem of integrating the LSR with a CBC power system. For lunar based systems with a nuclear reactor heat source organic working fluids such as silicone oil may not be suitable due to potential polymerization to heavier hydrocarbons in the expected radiation environment. Obviously this problem may be solved by additional shielding or by positioning the reactor in a cavity with lunar regolith as shielding. But the use of liquid metals, such as NaK, Li, Sn, and Al, would cover a temperature range of 300 K to 1100 K, which should meet the heat rejection requirements for the spectrum of power conversion systems under consideration. Working fluids capable of higher operating temperatures than feasible with silicone oil will also be needed because of the high (350 K) lunar midday radiator sink temperatures.

CONCLUDING REMARKS

The importance of carrying out space power system integration studies before selecting a major subsystem, such as the radiator, was demonstrated in this study of the suitability of the liquid sheet radiator for Brayton and Stirling space power systems.

For the low power systems considered, the Stirling FPS was found to be ideally suited to integration with an LSR heat rejection subsystem, since the LSR fluid can be used to cool the engine cold space directly. Also, the near constant temperature cycle heat rejection process was found to be compatible with the low temperature rise in the LSR working fluid.

Brayton cycle power systems benefit more from light weight heat pipe radiators which can more effectively take advantage of the high gas temperature entering the radiator. Similar studies will need to be conducted for higher power systems for lunar base and NEP applications.

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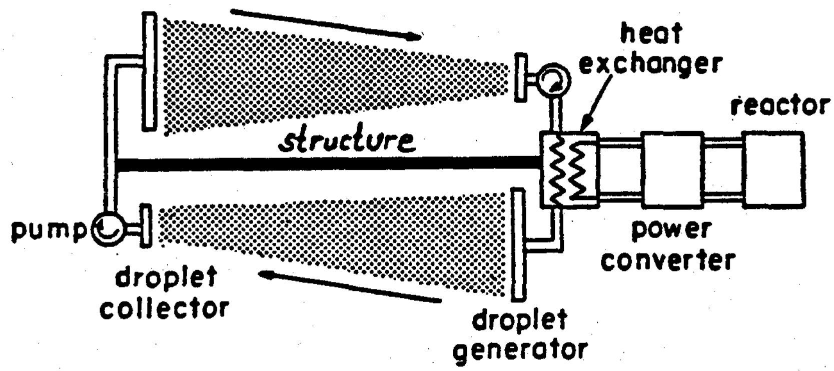

Figure 1.—LDR concept with generic space power system.

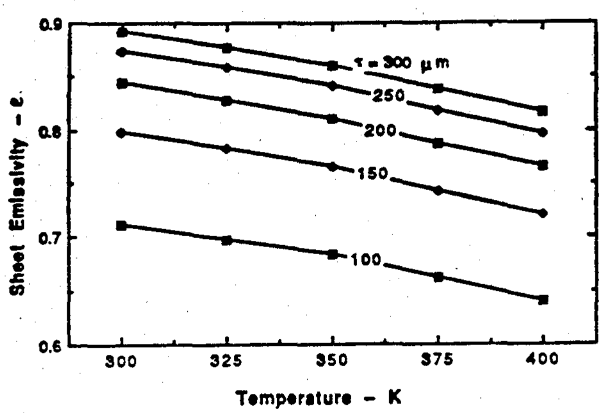

Figure 2.—Sheet emissivity for Dow-Corning Me_2 silicone oil (τ is sheet thickness).

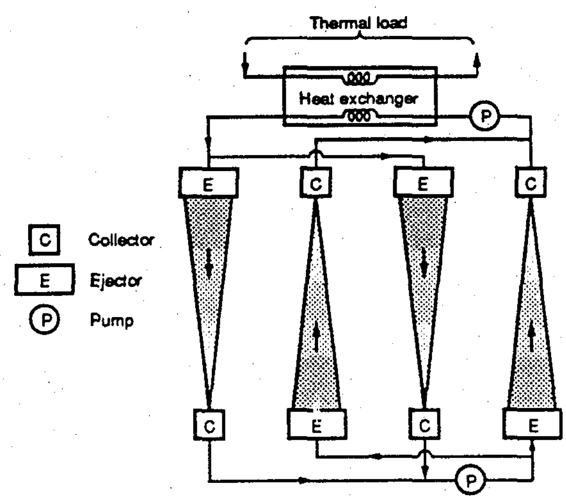

Figure 3.—Modular liquid sheet radiator subsystem.

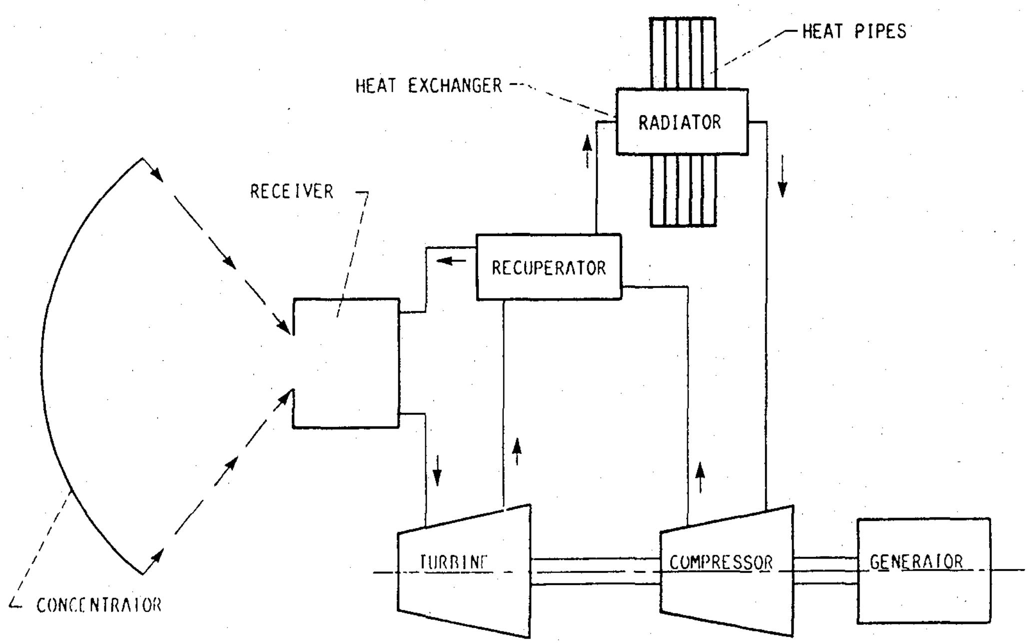

Figure 4.—Brayton cycle space power system.

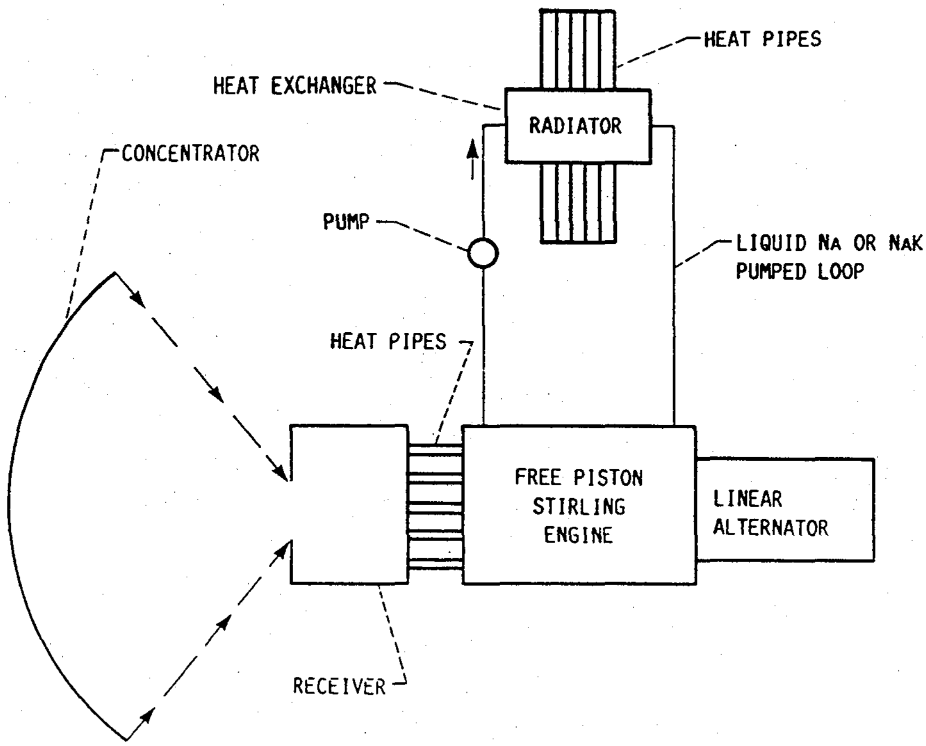

Figure 5.—Stirling cycle space power system.

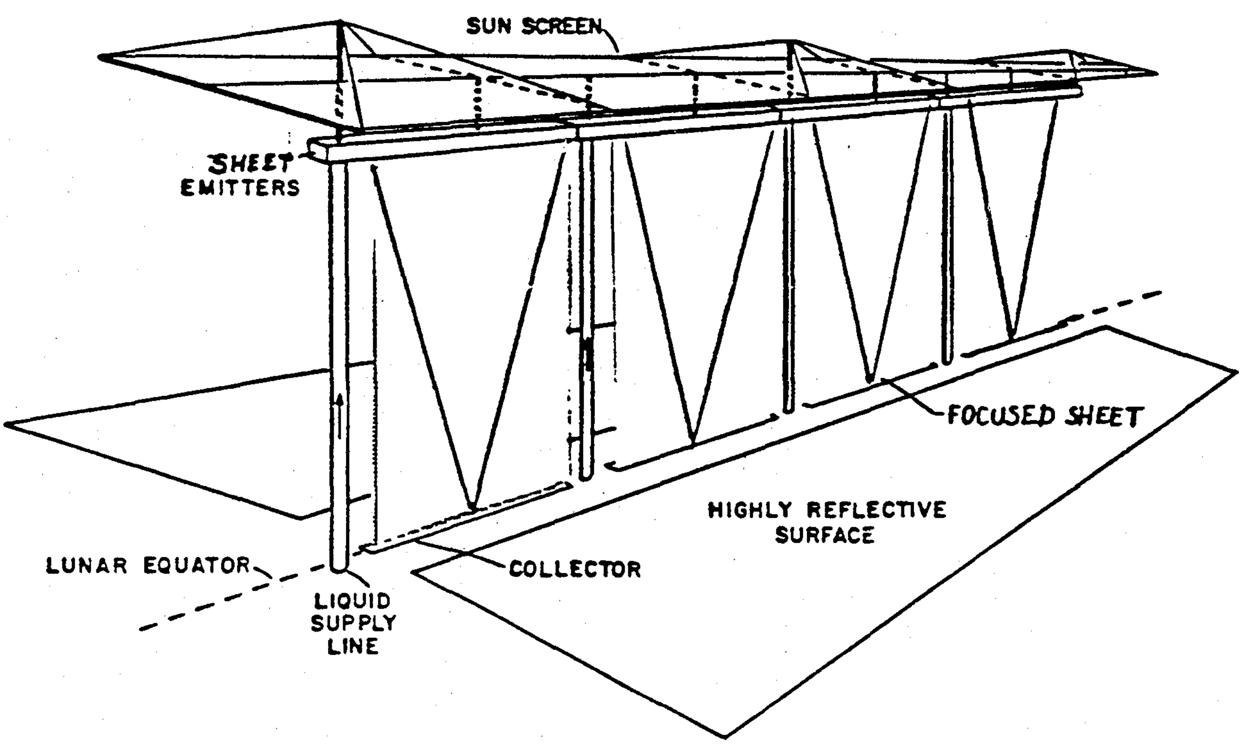

Figure 6.—Conceptual LSR configuration for megawatt level lunar power system.

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