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AN OVERVIEW OF SOLAR DYNAMIC SYSTEMS FOR SPACE APPLICATIONS

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Summary

Solar dynamic systems (heat engines) are being considered as alternatives to photovoltaics as the prime power source for the U.S. Space Station The current design power levels are 75 kW and 300 kW for the initial and growth design, respectively. The Brayton and Rankine cycle engines are the most attractive for the metal phase with the Stirling cycle showing promise for the later space application. The advantages and disadvantages of these systems compared with photovoltaics are discussed along with the significant design problems and trade-offs.

Solar dynamic systems are essentially heat engines. Heat is added to a fluid, heat is rejected from the fluid, and the difference is available for producing useful work such as electrical power. The energy source for the conventional heat engine is hydrocarbon fuel. Solar dynamic systems use the sun's energy as the heat source instead of oil combustion.

The current interest in solar dynamics is in its application in the U.S Space Station. Both solar dynamics and photovoltaics are candidates for the initial power system design and for the growth versions. The current design power levels are 75 kW and 300 kW for the initial and growth designs, respectively. Much of the present thinking for solar dynamics is based on work that NASA–Lewis pursued in the late 1960s. That work was to establish the technology that could be used for extended space flight requiring large power loads. When such missions failed to materialize, the technology was shelved. Today, with little change occurring in the intervening years, that technology is being utilized.

The major change in solar dynamic programs during this interim period has been in applications. DOE developed a number of terrestrial systems as part of its charge to conserve energy. Though this effort did advance the solar dynamic state-of-the-art, the difference in environment largely precluded the use of any such advance for space applications.

The major components of a solar dynamic system are the concentrator, heat receiver, energy converter and the heat rejection system. Figure 1 shows the concept packaged for space application. The concentrator can be a re-

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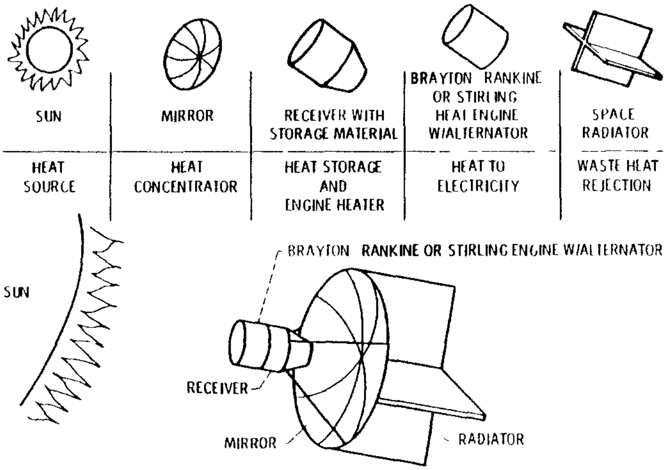

Fig 1 Solar dynamic system concept packaged for space application

fractor but it is, conventionally, a reflector surface that focuses solar energy into the heat receiver The receiver is usually designed integrally with the storage to operate through the shadow part of an orbit The energy converter is the thermodynamic cycle, the output of which provides useful electrical power. For the Space Station, Brayton and Rankine cycles are being considered Stirling shows promise for growth or for later space applications The waste heat is rejected by a radiator.

The advantage of the solar dynamic system over the photovoltaic array in providing power to the Space Station is its higher efficiency in converting solar energy to useful power The factor is about 4. This means that the photovoltaic field must expose 4 times as much area to the sun as the solar dynamic system The contrast can be illustrated in Fig 2. The larger area means greater drag even in the rarified environment of the orbiting station The greater drag means greater expenditure of fuel to keep the solar array in the same orbit as a solar dynamic system

The drawback to solar dynamics is the paucity of relevant data for such systems. None has been flown in space before The advanced development program at NASA/Lewis is aimed at developing the relevant technologies to maturity. Though no solar dynamic system has had space experience, data have been developed for its components and subsystems.

Most of the experience has been accumulated for the Rankine system, more particularly the organic Rankine Figure 3 shows the schematic of such a system The Rankine cycle is characterized by the working fluid undergoing phase changes — liquid boiled to vapor at heat input and returned to liquid in the condenser Toluene has been used extensively in the past and is the Rankine reference fluid for the Space Station Maximum temperature is 672 K (750 °F)

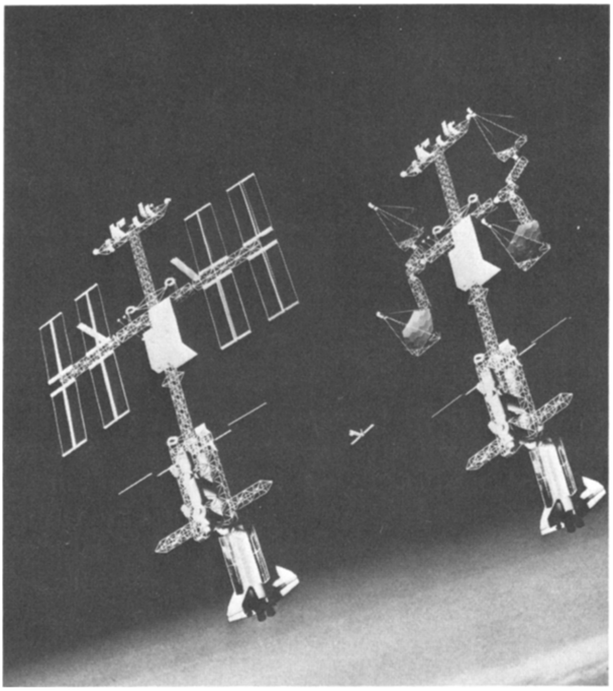

Fig 2 Space station concept Left: photovoltaic array system, right solar dynamic system

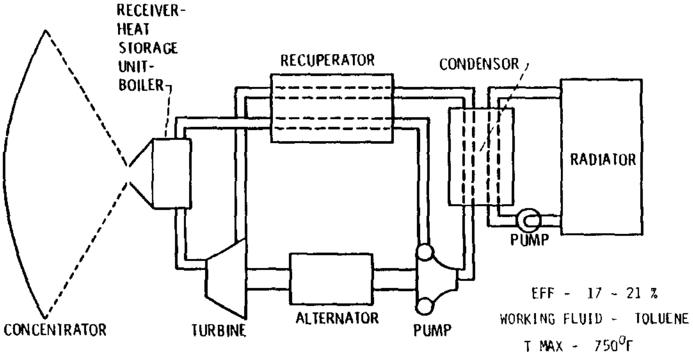

Fig 3 Schematic diagram of the solar organic Rankine cycle

In thermodynamic cycles, the higher the heat source temperature, the more efficient the system (for constant heat sink temperature). Brayton heat engines are designed to operate as high as 1089 K (1500 °F) Brayton systems, however, have not had the experience enjoyed by organic Rankine heat engines. Figure 4 is the schematic of the Brayton cycle Unlike the Rankine, the working fluid of the Brayton cycle does not undergo any phase

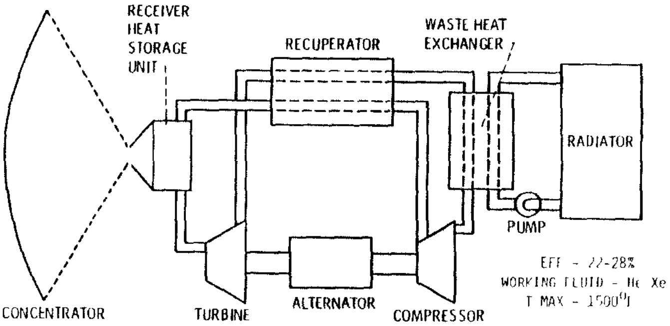

Fig 4 Schematic diagram of the solar Brayton cycle

change. The Brayton system under consideration uses a He–Xe gas mixture as the working fluid. The higher heat source temperature enables the cycle efficiency to be several points higher than the Rankine

The foregoing discussion has referred specifically to the Brayton and Rankine heat engines This is just a part of an overall evaluation when designing solar dynamic systems. Table 1 lists three typical areas for consideration — trade-off analysis, developing critical technologies, and assessing the impact on the overall system (the Space Station in this application)

High turbine inlet temperature, as was mentioned previously, is desirable for higher efficiency The required high operating receiver temperature is also desirable in that a smaller volume, smaller area and smaller mass is required On the other hand, high temperatures can cause localized overheating, aperture area becomes more critical to minimize re-radiation loss, and thermal stress problems are exacerbated

Heat rejection temperature should be low so that, in combination with a high heat source temperature, the potential for useful work output is

TABLE 1

Considerations in solar dynamic system design

Cycle trade-offs
- Turbine inlet temperature *vs* heat receiver
- Heat rejection temperature *vs* radiator
- Brayton *vs* Rankine

Critical solar dynamic technologies
- Concentrator
- Heat receiver and thermal energy storage
- Fluid stability
- Radiator

Space station factors
- Shuttle stowability
- EVA
- Deployability

increased. Any decrease in the heat rejection temperature, however, means that the radiator area must be increased to dissipate the required heat

The Brayton *versus* Rankine issue is one comparing a higher efficiency, less data base heat engine with one that has more experience but a lower cycle efficiency. These are a few of the principal parameters that are involved in arriving at an optimized system.

Four solar dynamic technologies have been identified as ones that need development to demonstrate operation in orbit. Though this list arises from the Space Station application, these technologies require similar effort in any mission requiring solar dynamics.

The critical technology issues of concentrators include. (a) those that affect reflector surface characteristics (contamination, accuracy, sun/shade thermal distortion, coating performance and durability, and pointing accuracy), (b) concentrator designs (Cassegrainian (double reflecting surfaces) *versus* single reflectors, fabrication, and space assembly *versus* deployable approach).

Critical issues concerning the heat receiver and thermal energy storage include: (a) the design affecting integral *versus* separate storage; (b) volume change of thermal storage material with phase change, (c) matching the solar flux input with the heat transfer to the working fluid, (d) structural material to withstand corrosion, to operate under vacuum, and to operate at high temperature.

The fluid stability issue refers to the organic fluid in the Rankine heat engine. A closed loop where the maximum temperature approaches the decomposition point of the organic needs intensive scrutiny. The other main consideration is operation under zero gravity when the cycle calls for the fluid to constantly change from liquid to vapor and back again.

The radiator will operate between 200 °F and 350 °F depending on whether the heat engine operates as a Rankine cycle or Brayton cycle. Virtually all experience has been gained by operations at 100 °F or less. The higher temperature range calls for different heat rejection fluids and an investigation of the best method for the subsystem — as a heat pipe or as a pumped loop.

Aside from the narrow, solar dynamic considerations, there are space station concerns. Stowability is a factor in that a more compacted package may require fewer shuttle launches — an increasingly important item because of the cost concerns of the Space Station. The items of extra-vehicular activity and deployability are concerned with making the most effective use of the shuttle and crew to minimize the time and the effort prior to power start-up An important consideration here also is the safety of astronaut operators. Reliability of deployable mechanisms must be high to avoid a situation where a spring-loaded mechanism can jeopardize the operator.

One of the most critical technologies, as mentioned before, and which is most appropriate to this audience, is the thermal energy storage, Table 2. The purpose of storage here is to convert the varying heat source associated with the sun–shade cycle of a low earth orbit to a constant energy output required of the power system

TABLE 2

Solar dynamic thermal energy storage

Function	Level power throughout orbit
Types	Sensible, latent
Design	Integral, separate
Desirable characteristics	
	● High heat of fusion
	● High density
	● Low volume change
	● Non-corrosive to container material

Of the several heat storage mechanisms available, two that have received consideration for the space station are those using sensible heat and latent heat. In sensible heat, energy is stored by an increase in temperature of the maerial and returned by temperature decrease. In latent heat, the energy is stored by changing the phase of the storage material, the storage and release of energy occurs at a fixed temperature, meaning that the transfer of heat to the working fluid would be under constant conditions over the entire sun–shade cycle. Using heat storage to provide constant energy into the cycle meets the requirement for a constant power output of the heat engine

The issue of whether heat storage should be integral to, or separate from, the heat receiver was mentioned previously An integral design is more complex It involves combining two separate functions into a single component — storage and heat transfer to the flowing fluid A separate storage component is simpler since it can be designed only for storage There will be a greater fluid temperature fluctuation and therefore power fluctuation associated with a separate component, however An integral design also contributes to lessening the temperature fluctuations of the heat receiver itself

The function of thermal energy storage will be enhanced if the storage material has the desirable characteristics of high heat of fusion and high density (for compactness), low volume change with phase change, and no corrosive attack on the container material

The range of latent storage materials and their properties are listed in Table 3 For Space Station applications, three are being considered — LiF for the high temperature Brayton system, $46\ LiF + 44\ NaF + 10\ MgF_2$ for the lower temperature Brayton, and $LiOH$ for Rankine These were chosen for the temperatures required for the cycle points of the systems and for their physical characteristics

Actual fabrication of a heat receiver with integral thermal storage, shown in Fig 5, was done in the early 1970s for space applications, though never flown. The design features allow for many of the concerns expressed thus far. Solar flux reflected from the concentrator enters the heat receiver through the aperture and impinges upon the bank of tubes along the inside surface of the receiver The gas working fluid flows through 48 parallel tubes from the inlet to exit manifolds. The receiver was fabricated of a

TABLE 3

High temperature heat of fusion materials

No	Material	Melt temp (K)	Heat of fusion (kJ kg^{-1})	Density (kg m^{-3})
1	KF	1125	454	2480
2	Na_2CO_3	1125	279	2530
3	Ca	1123	221	1540
4	LiF	1121	1044	2640
5	$LiBO_2$	1108	698	1400
6	75 NaF + 25 MgF_2	1105	649	2680
7	62 5 NaF + 22 5 MgF_2 + 15 KF	1082	607	2630
8	NaCl	1074	484	2180
9	CaI_2	1057	142	3490
10	$CaCl_2$	1046	256	2280
11	KCl	1043	372	1990
12	67 LiF + 33 MgF_2	1019	947	2630
13	65 NaF + 23 CaF_2 + 23 MgF_2	1018	574	2760
14	$Na_2B_4O_7$	1013	523	2370
15	Li_2CO_3	998	605	2200
16	$MgCl_2$	988	454	2240
17	60 KF + 40 NaF	983	479	2510
18	LiH	956	2582	790
19	Al	933	388	2710
20	60 LiF + 40 NaF	925	816	2480
21	Mg	923	372	1740
22	46 LiF + 44 NaF + 10 MgF_2	905	858	2610
23	52 LiF + 35 NaF + 13 CaF_2	888	640	2630
24	LiCl	883	470	2070
25	52 NaCl + 48 $NiCl_2$	843	558	2840
26	$Ca(NO_3)_2$	834	130	2500
27	73 LiCl + 27 NaCl	825	430	2090
28	48 NaCl + 52 $CaCl_2$	773	328	2160
29	49 KF + 51 LiF	765	461	2560
30	80 Li_2CO_3 + 20 K_2CO_3	763	377	2170
31	LiOH	743	930	1460
32	11 5 NaF + 42 KF + 45 LiF	727	442	2560
33	NaCl + $MgCl_2$	713	326	2240
34	80 LiOH + 20 LiF	700	1163	1550
35	KOH	673	140	2040
36	LiCl + KCl	623	255	2030
37	KNO_3	613	128	2110
38	NaOH	593	160	2070
39	$Na_2N_2O_2$	588	244	1730
40	93 6 $NaNO_3$ + 6 4 NaCl	568	191	2260
41	95 3 NaOH + 4 7 Na_2SO_4	566	326	—
42	7 8 NaCl + 6 4 Na_2CO_3 + 85 8 NaOH	555	316	2100
43	37 LiCl + 63 LiOH	535	437	1640
44	NaCl + $ZnCl_2$	533	198	2480
45	23 LiOH + 77 NaOH	528	233	1890
46	$LiNO_3$	527	379	2400
47	$AlCl_3$	468	290	2440
48	NaOH + KOH	463	233	2060
49	Li	453	442	530

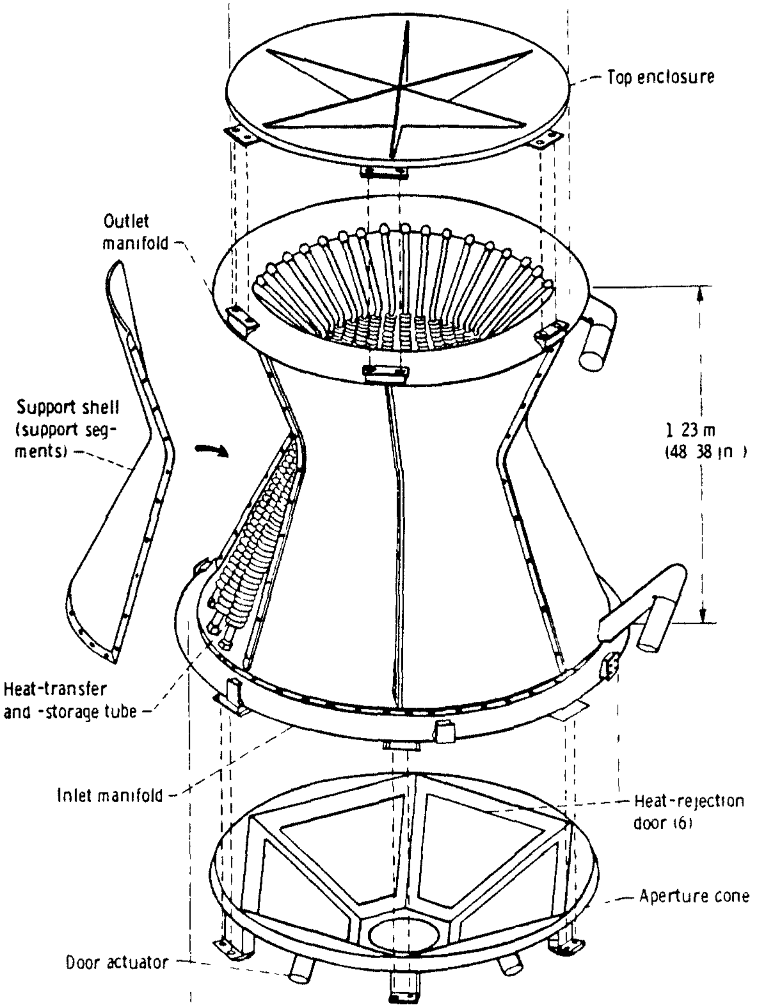

Fig 5 Brayton heat receiver with internal thermal storage

columbium (niobium)–zirconium alloy. Because the metal is a refractory alloy, the receiver was not tested in the atmosphere Instead, three tubes were tested in a vacuum chamber under simulated solar conditions. Test results indicated that the tube design would operate satisfactorily in the application

Figure 6 shows the detail of the tube design. The diagram indicates that there are really two tubes — an inner one through which the working gas flows and an outer, convoluted tube. The volume between the tubes is filled with the thermal energy storage material — LiF salt This design, then, is an example of an integrated heat receiver–thermal storage component The convolutions are designed primarily to maintain the salt distri-

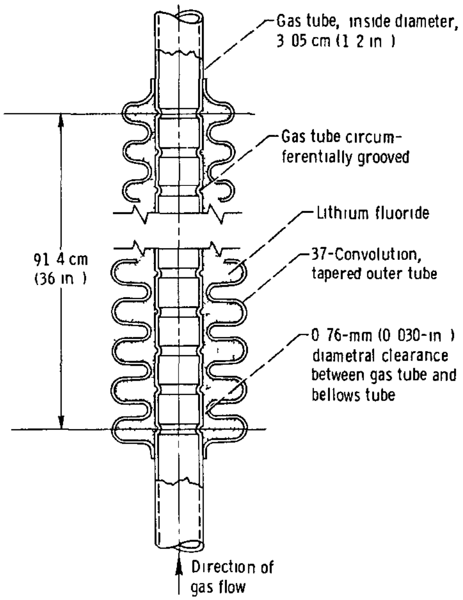

Fig 6 Brayton heat receiver tube design detail

bution along the tube length. Though the tube is initially filled with liquid, the salt shrinks in volume as it solidifies. The convolution is intended to minimize any migration of the salt by initial freezing of the material at the neck. The salt then remains distributed along the tube even though the liquid can shrink approximately 30% while freezing. Heat transfer to the gas is, effectively, the same whether in the sun or in the shade

This is but one design approach to one solar dynamic concept. Within the next few months we expect a decision to be reached on which option, the Rankine or Brayton, shall be carried on, and which power system — solar dynamic or photovoltaic — will be the system of choice.