MATERIALS FOR ENERGY CONVERSION

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MATERIALS PROBLEMS IN DYNAMIC ENERGY CONVERSION SYSTEMS

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Introduction

To present a brief review of some of the fundamental design and material problems involved in the successful development of a dynamic space power system is the purpose of this paper. This brief review should assist in stimulating discussions on the nature of the problems, methods of solution, and the degree of emphasis required in the solution of particular problems.

In an effort to cover such a broad subject, a quantitative approach is used and two specific examples, namely collectors and radiators, are selected to further illustrate some fundamental design and material problems.

Dynamic Energy System

Figure 1 illustrates schematically a typical dynamic energy conversion system. Heat is added to the working fluid in the boiler or heat exchanger by either a nuclear or solar heat source. The high thermal energy in the high pressure fluid is transformed into kinetic energy, through nozzles, and partially transformed in the turbine to mechanical shaft power. The remaining energy is rejected from the system by cooling the lower pressure and temperature working fluid in the radiator-condenser. The working fluid is brought back to initial pressure by either a pump or compressor. Basically, either a two phase fluid in a Rankine cycle or a single phase fluid in a Brayton cycle is used in a dynamic energy conversion cycle.

Specific drawbacks of the Rankine cycle include corrosion and mass transport characteristics with the use of liquid metal as a working fluid, turbine blade erosion due to a partial two-phase fluid, phase changes occurring under the absence of gravitational force, and the pressure drops occurring during the phase changes. These severely penalize proper cycle operations.

Solar Dynamic System

From a series of design studies of dynamic energy conversion systems with various power levels, akin to the rubber engine concept in propulsion, the relative contribution of individual components to the overall design problem may be studied. Thus, the relative contribution to the weight of a range of solar dynamic power systems is shown in figure 2, for major components.

Three components, collector, energy storage, and radiator, increase in percentage weight with power output. Two components, the boiler and turbine-pump, decrease in percentage weight, with power output. Great care should be exercised in reading this plot. A maximum cycle temperature of 1200°F was assumed. This allowed the use of lithium hydride as an energy storage material (approximately 1100 btu/lb are available as latent heat).

An increase in cycle efficiency is most readily achieved by an increase in temperature differential and/or temperature level (i.e. increase in maximum cycle temperature). The increase in cycle efficiency will greatly benefit the collector. If an increase in cycle efficiency is achieved by an increase in maximum cycle temperature, the new energy storage material will now be either sodium fluoride (350 btu/lb latent heat), beryllium (450 btu/lb), or silicon (550 btu/lb). The decrease in latent heat capability coupled with the increase in material density may result in a system design where the percentage weight of the energy storage device equals or even exceeds the percentage weight of the collector.

Let us select the collector component and review some of the design considerations which have a bearing upon materials requirements.

Collector Design Considerations

The parameters encountered in designing a solar collector are primarily mechanical. Surface finishing, geometric accuracy, concentration ratio, reflectivity, boiler absorpttivity and emissivity, solar constant, and overall system efficiency play a predominant part in arriving at the collector area required for a solar powered space system.

In order to achieve a usable temperature at the boiler surface, the low space solar density is amplified by means of concentration. Figure 3 illustrates the effect of concentration ratio, defined as the ratio of projected collector area to target-boiler area, on design considerations of solar collectors. Plotted on this slide we have the collection efficiency, versus boiler temperature, with the concentration ratio as parameter. To obtain reasonably high operating temperatures for improved overall efficiency, a high concentration ratio is necessary.

Material conditions have a pronounced effect on the concentration capability of large collectors. Imperfections introduced in the manufacturing of collectors may be classified as either geometrical errors or surface finishing errors. The possibility of producing geometrical errors is rather high, especially for collectors of 30 to 60 feet in diameter. Any large surface may deviate from an ideal geometry in a number of ways. Errors such as surface ripples, overdished or flattened profiles, will result in a reduction of collector performance. The existence of ripples will generally cause a spread of the focal region. The over-dished or flattened profiles will result in a variation of the focal length. The factors directly involved in th control of geometrical errors are the type of construction and the method of manufacturing. Commonly considered types of construction are the rigid deployable with very light weight metal or honeycomb petals and the inflatable plastic type (e.g. mylar) rigidized with a foamed plastic. The materials and type of construction have a great bearing upon how extensively temperature gradients effect geometrical accuracy. An analytical assessment of geometrical errors is rather difficult and must be substituted by a cumbersome and costly experimental checkout. Surface finishing errors include the roughness of the base material and the surface roughness errors introduced by coating the base material. The majority of these errors will tend to create a beam spread or a dispersion effect which will seriously reduce the overall collection efficiency.

Nuclear Dynamic System

Figure 4 represents the variation in weight of the components of a nuclear dynamic power system as a function of power output. A two loop system using lithium in the primary loop and potassium in the secondary loop with a turbine inlet temperature of 1900°F and a condenser temperature of 1340°F is assumed in figure 4. The system does not include the penalty involved with subcooling for lubricating both the alternator and bearings.

As you can observe, the weight of the radiator and alternator increase with power output. The weight of reactor and shield decrease with power output. The weight of the turbo-heat exchanger is approximately constant with power output.

Let us now select the radiator component and review some of the design considerations.

Radiator Design Considerations

Both internal and external parameters dictate the design of a space radiator. Factors involved in the design of a radiator include: system configuration, whether direct or indirect condensation is selected; the internal heat transfer coefficients; allowable pressure drops; fluid velocity; corrosion; zero gravity operations; tube diameter; wettability of fluids; flow stability; tube-fin combination; fluid and material temperature drops; properties of materials; coatings; allowable configuration (flat plate, cylinder, etc.); and external environmental factors.

The necessity of operating at elevated temperatures necessitates the use of liquid metals as either working fluids or cooling fluids. Liquid metals are very corrosive, and their corrosion rate is very sensitive to the operating temperatures, and temperature differential. High-strength materials, such as the stainless steel series and Haynes 25 will find limited use in nuclear dynamic systems. Refractory materials, for example columbium, will also be required.

The importance of internal design considerations is illustrated in figure 5. Allowable pressure drops have to be kept to a minimum since at the operating temperatures, the pressure level of liquid metals is rather low. This restriction, combined with the absence of gravity, may severely restrict the actual value of the film coefficient. The variation in radiator area required as a function of radiator temperature with the film coefficient as parameter is illustrated in figure 5.

Operational and External Environmental Considerations

In addition to the internal environmental and design considerations for evolving the components of an integrated energy conversion system, there are external environmental and operational considerations which will have a strong influence. (figure 6).

Meteoroids

Possible harmful effects of meteoroids are as follows:

a. May penetrate radiator tube wall resulting in either a puncture with a loss of working fluid or, at a minimum, a structural weakening of that particular component.

b. May erode surface finishings, therefore changing radiator surface emissivity and collector optical characteristics. In order to design properly the components affected by meteoroids, it is imperative that the design engineer has some knowledge of the properties of meteoroids, their frequency of occurrence, mass, and size distribution, their velocity distribution, an analytical and/or empirical description of impact phenomena at the hypervelocities encountered.

Radiation

The low thermal efficiencies of dynamic space power systems requires the removal of approximately 80 to 90 percent of all the heat generated in the power plant. The vacuum in space necessitates the use of radiation mechanism as the sole heat removal possibility for long duration systems. To reduce exposure of critical areas such as radiator tubes to meteor penetration, fins will be employed dividing the heat load between the tubes and the fins.

The radiator area varies inversely with the emissivity of the surface. In view of the low emissive capability of bare metals, coatings are employed; however, every care must be taken that the right coating is selected for each component. For example, for radiators high emissivity is desired in the infrared region, but low absorptivity at the solar wavelengths.

High Vacuum

Perhaps the most critical question is that of stability. Will the selected materials and coatings last (1 to 2 years), the duration of the powerplant?

Reliability

A maximum reliability is obviously desired. Replacement of minor parts, although not impossible, should be kept to an absolute minimum. The major problem here is how to achieve maximum reliability with minimum penalty from both an operational and weight standpoint.

Weight and Volume

A minimum of both is desirable and will generally be achieved with an increase in cycle operating temperatures requiring a maximum of new material development. The working fluids will be of the liquid metal class where problems of corrosion, erosion and mass transport are very severe.

Perhaps the most critical design consideration for both radiator and collector is the question of space meteoroids, critical in the sense that this design criteria may very well dictate whether a large area component is possible. Three major design considerations need to be explored. First, what is the distribution of space meteorids? Second, what is their frequency? Third, what is the damage caused by a meteoroid? Factors of importance in the distribution of meteoroids include size, velocity, and density. Upon the establishment of velocity, density, and mass distribution, the meteoroid flux will establish the number of hits per unit area per unit time. Damages caused by meteoroids cover possible loss of working fluids from penetration and spalling of tubes. Design possibilities to overcome meteoroid damages include the use of fins, bumpers, segmentation, all of which increase the temperature drop throughout the radiator. An increase in survival probability will cause a tremendous increase in weight. For example, an increase in probability of 0.9 to 0.999 will cause a five-fold increase in weight.

In order to reduce vulnerable area, non-fluid radiators have been proposed. A schematic is illustrated in figure 7. The fluid to be condensed is maintained in either a stationary or rotating fluid manifold. A moving belt is forced to contact the manifold; the heat is transferred by conduction. As the belt rotates through free space, the temperature decreases by radiation. Therefore, a continuous heat transfer process through contact with the fluid manifold is insured. Only the manifold in this case must be protected from meteoroid damage. The belt could be made very thin, thus realizing the lower weight system. Crucial material problems involved here are emissive coatings that will operate not only in a high vacuum, but under a variable temperature; seizure problems in high vacuum accompanied with extreme temperature differential and high contact pressure, internal heat transfer; and possible seal problems.

Summary and Conclusions

The problems outlined herein do not constitute all of those present in dynamic power systems. This discussion has included detailed materials problems for two of the major components, namely: solar collector and thermal radiator. Similar discussions can be put forth for the remaining critical components, including heat exchanger-radiators, thermal energy storage, liquid metal turbines, bearings, and pumps. Although the design characteristics of dynamic space power systems are fairly well established, there are many materials problems whose answers will have great influence on the resultant system. Some of the questions are:

1. What are the temperature and velocity limitations with respect to corrosion, erosion, and mass transfer?

2. What are the thermodynamic properties of the fluids?

3. How serious is the sublimation rate of materials in a high vacuum?

4. Can foam materials be used in the construction of light weight and small volume collectors for required duration?

5. What are the contact resistances of materials? What roughness of the surface is required and what are the limits of contact pressure?

6. In bi-metallic systems (tube-fin, turbine-blade), what are the effects of differential expansion?

7. What are the best joining techniques in components of different mechanical and thermal properties?

8. How can a measurement standardization of surface coating be realized?

9. What are the temperature drop and bond strength of surface coatings?

10. What thickness of coating is required?

11. What are the mechanisms involved in meteoroid penetration?

12. What are the effects of various modes and frequencies on vibration characteristics of large exposed space areas?

13. How can we duplicate experimentally the effect of meteoroid penetration?

Thus we see that there is a continuing requirement for extensive materials experimental and applied research effort to make effective dynamic energy conversion systems possible.

BIBLIOGRAPHY

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2. Analysis and Development of a Space Heat Rejection System and its Optimum Integration into a Space Vehicle, Electro-Optical Systems, Inc., ABMA Contract DA-04-495-ORD-1473, December 1959.

DYNAMIC ENERGY CONVERSION SCHEMATIC

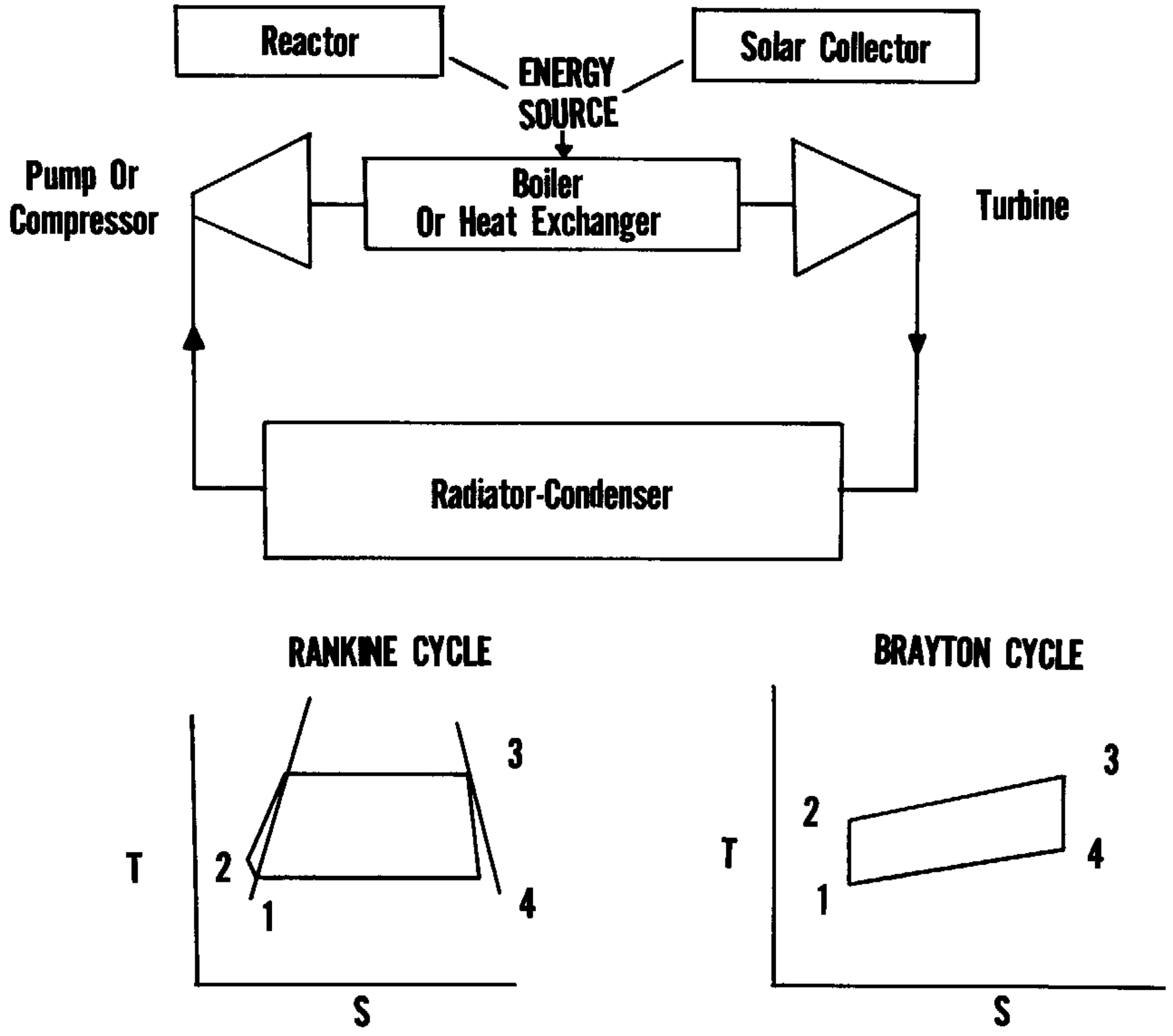

Figure 1.

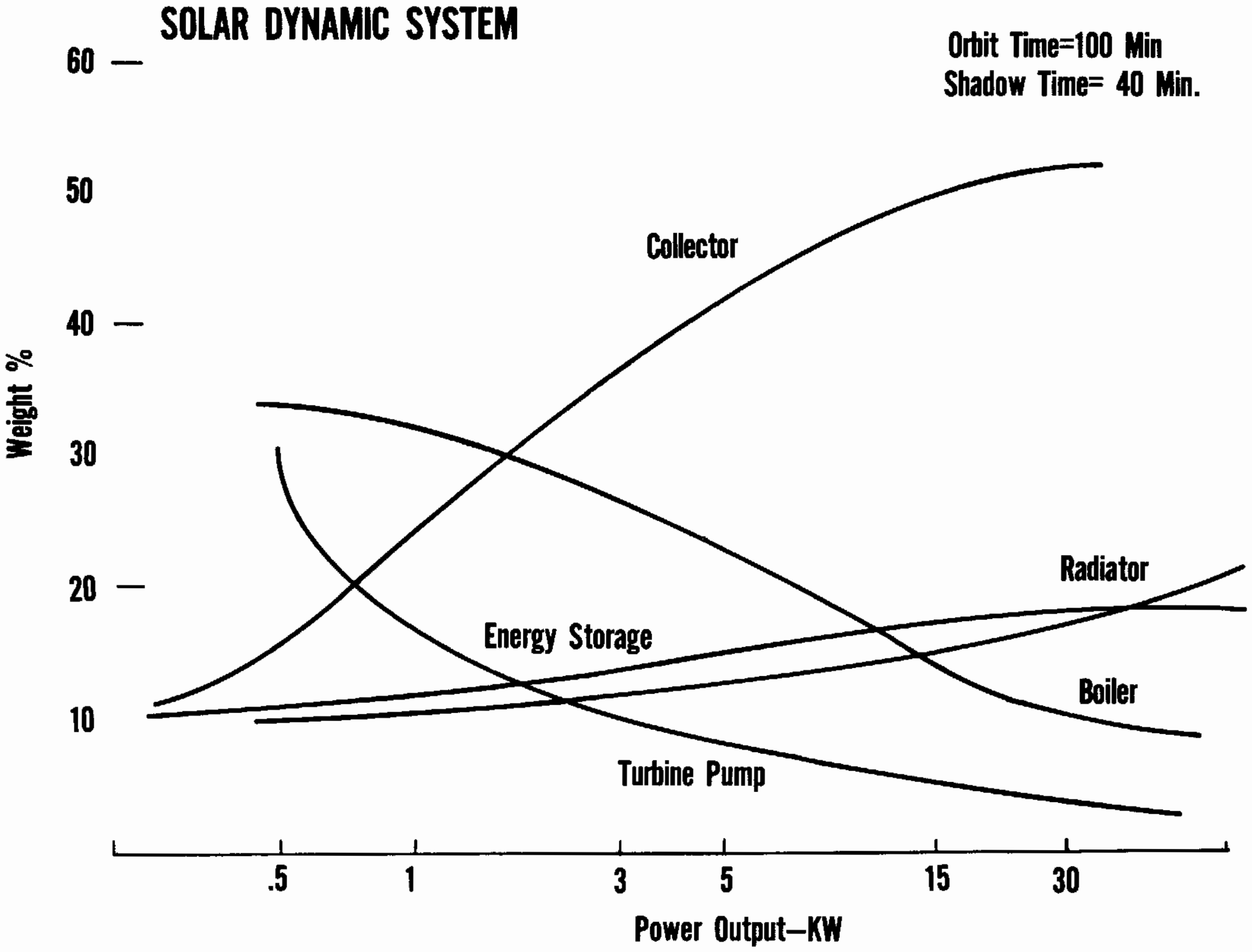
SOLAR DYNAMIC SYSTEM
Orbit Time=100 Min
Shadow Time= 40 Min.
Weight %
60
50
40
30
20
10
Collector
Radiator
Energy Storage
Boiler
Turbine Pump
.5
1
3
5
15
30
Power Output—KW

Figure 2.

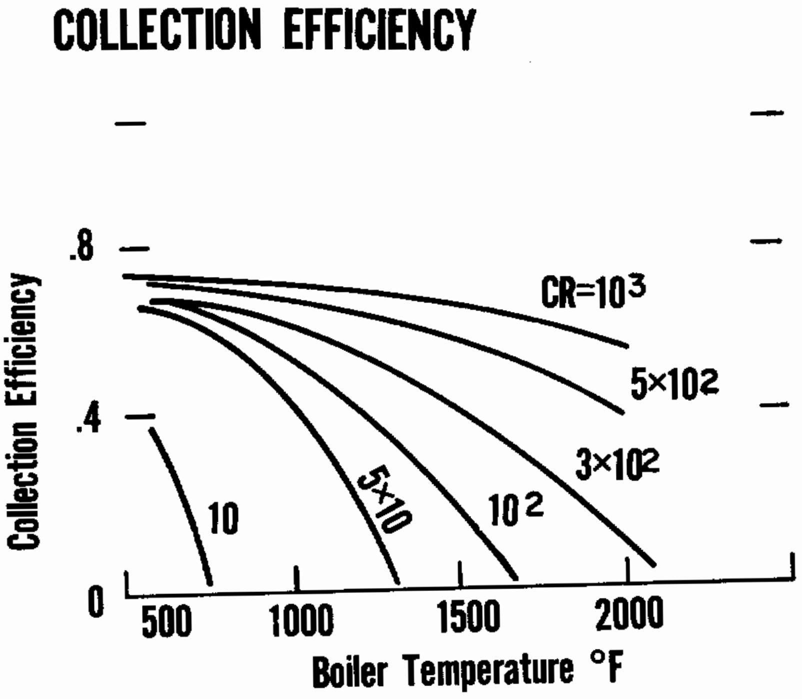
COLLECTION EFFICIENCY
Collection Efficiency
.8
.4
0
Boiler Temperature °F
500
1000
1500
2000
CR=10³
5×10²
3×10²
10²
5×10
10

Figure 3.

NUCLEAR DYNAMIC SYSTEM

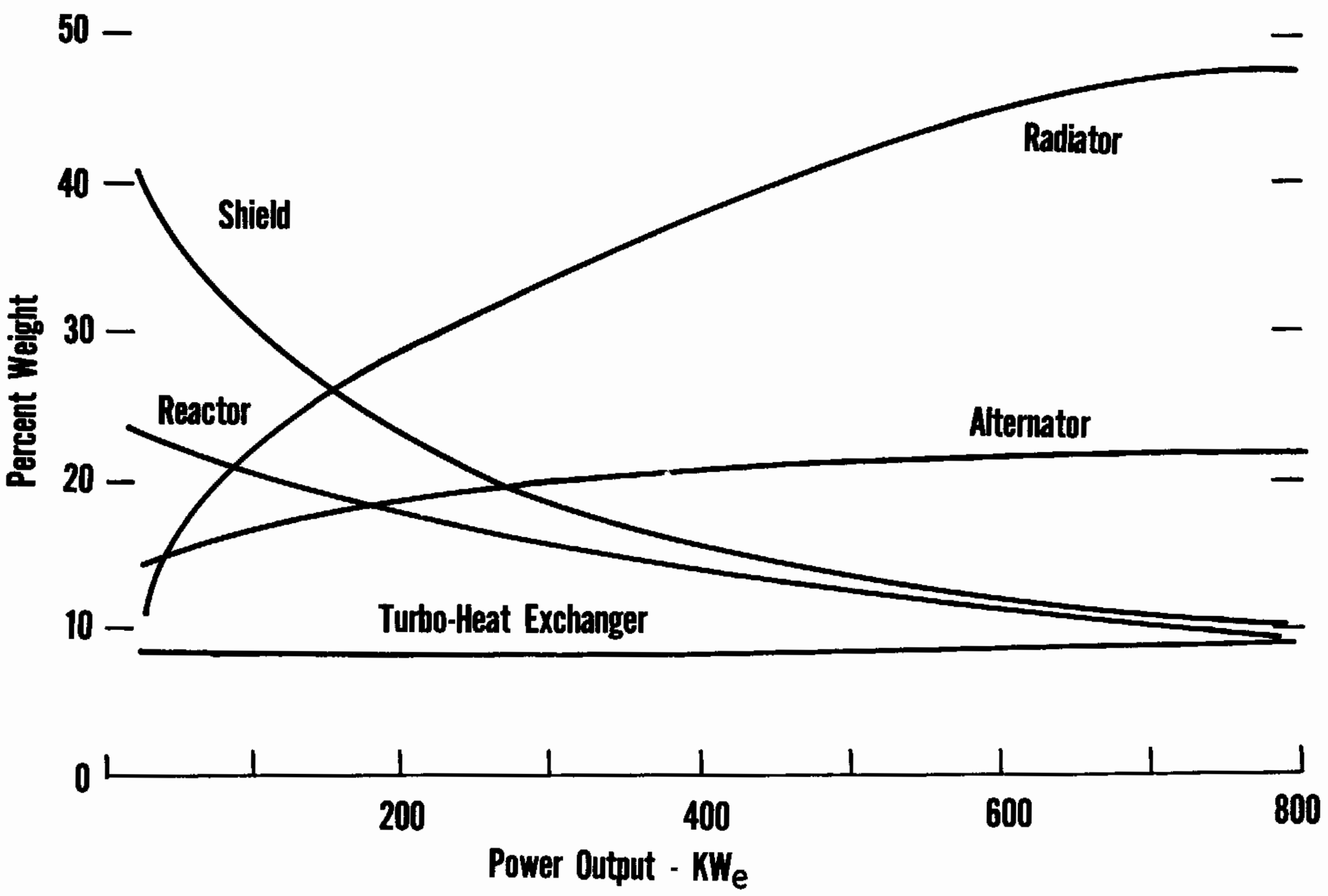

Figure 4.

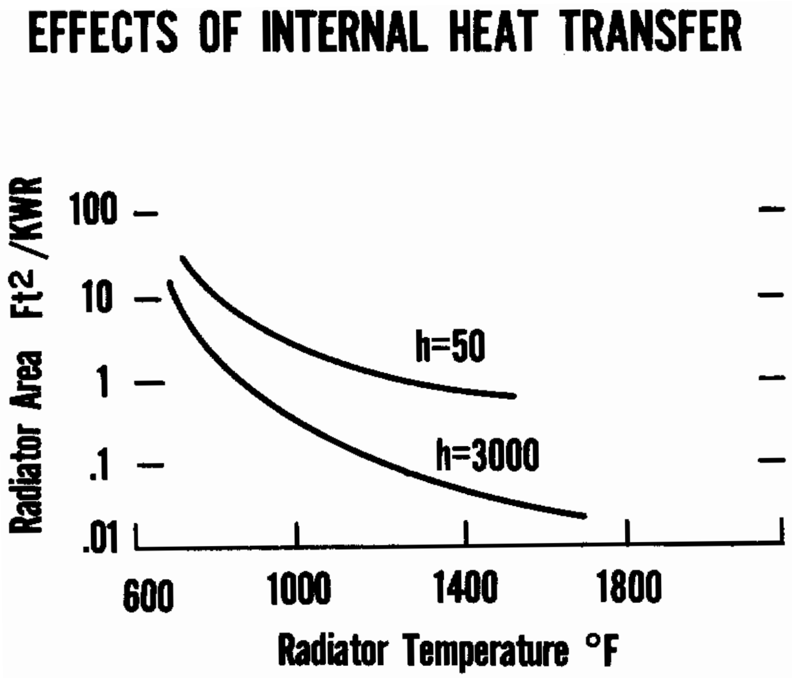
EFFECTS OF INTERNAL HEAT TRANSFER
Radiator Area Ft2 /KWR
100
10
1
.1
.01
h=50
h=3000
600
1000
1400
1800
Radiator Temperature °F

Figure 5.

OPERATIONAL AND EXTERNAL ENVIRONMENTAL CONSIDERATIONS

- Meteoroids
- Radiation
- High Vacuum
- Reliability
- Weight And Volume

Figure 6.

BELT RADIATOR

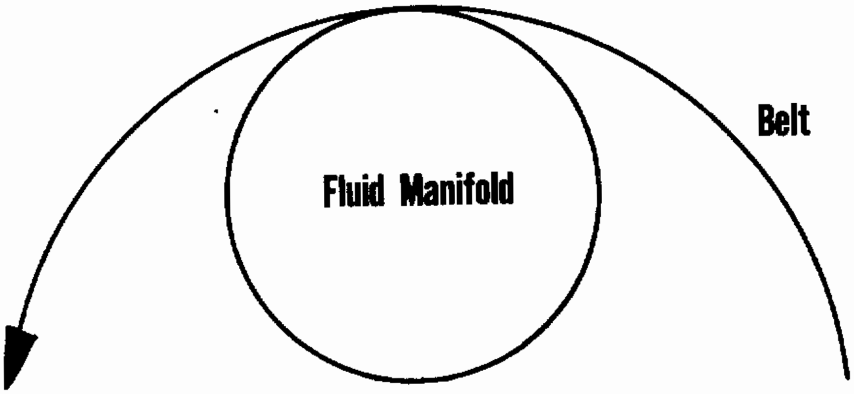

Figure 7.