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HEAT-REJECTION RADIATOR MASS AND ITS INFLUENCE IN SPACE POWER SYSTEMS

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Abstract—The influence of radiators on space nuclear power system mass has been studied by determining this mass as a function of the parameter K_R = radiator mass/area. Four power-conversion schemes are considered: Brayton, Rankine, thermoelectric and thermionic, over the power range 200–1000 kW. The total system includes power processing equipment and the secondary radiator.

The Brayton cycle becomes competitively light (improvements by factors up to 5), and the power range of interest for thermoelectric systems increases significantly with achievable values of K_R. The power processor, secondary radiator and shield render present thermionic systems massive, so that other concepts promise lower mass if K_R can be reduced to less than 0·5 kg/m^2.

NOMENCLATURE

M, mass [kg];
K_R, radiator mass per unit area [kg/m^2];
K_P, power processor specific mass [kg/kW];
ε, power conversion, or power processing efficiency;
T, temperature [°K];
P, electric power [kW].

Subscripts
SYS, total power system;
EGS, electric generating system;
PROC, power processor;
RADE, secondary radiator (to cool the power processor);
MAX, refers to maximum cycle temperature (turbine inlet, hot junction, or emitter);
REJ, refers to heat rejection temperature (compressor inlet, cold junction, or collector);
PCS, power conversion system;
REA, reactor;
SHI, nuclear shield;
RAD1, main radiator;
RAD2, auxiliary radiator (to cool lubricant and coolant);
e, refers to unprocessed electric power output;
out, refers to processed electric power output.

INTRODUCTION

THE SPACE radiator makes it possible to extract useful power continuously from a heat source by joining the power system to the heat sink of space. It also permits operation of equipment at reasonable temperatures by draining dissipated heat to space. Its presence, however, entails serious penalties in mass and reliability of the power system. It is known already that some improvements in radiator mass will benefit certain power systems. What is not known is the extent of gain possible, and the possible shift in relative masses between various systems.

There is no reason a priori why radiators cannot be improved radically. Attempts have

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been made in the past [1–5]. These have damped out because possible benefits were not evaluated quantitatively, for comparing against development efforts. It is therefore of importance to determine the following: (i) what some improvements in radiator mass could mean to space power system mass; (ii) whether the gain is great enough to justify fundamental work aimed at improving radiators. The object of this study is to answer these two questions. It concentrates only on mass versus power output. However, other considerations must enter, e.g. reliability, realizability, mission compatibility, etc.

ANALYSIS

1. *Power system*

The total power system is represented in Fig. 1 and is divided into two parts: (i) the electric-power-generating system; (ii) the power processor and secondary radiator. The total power system mass can be expressed as:

$$M_{SYS} = M_{EGS} + M_{PROC} + M_{RADE}. \quad (1)$$

The EGS mass is given by:

$$M_{EGS} = M_{PCS} + M_{REA} + M_{SHI} + M_{RAD1} + M_{RAD2}. \quad (2)$$

The total system mass is calculated for a given power output as follows:

(a) *Inputs selected*

P_{out}, K_R, EGS converter type, EGS parameters (T_{MAX}, whether manned, whether redundant), K_P.

(b) *Calculations*

Select a value of ε_{PROC}

Calculate M_{PROC} from P_{out}, ε_{PROC} and K_P

Calculate P_e from P_{out} and ε_{PROC}

Calculate M_{RADE}, emitting at 345°K

From P_e and the EGS parameters, minimize M_{EGS} with respect to T_{REJ}

Calculate M_{SYS}

Minimize M_{SYS} with respect to ε_{PROC}

2. *Components*

The PCS characteristics of interest in this study are its mass and its overall efficiency. For the present work, the means of PCS masses given by other workers is used. We assume that PCS mass is a function only of net unprocessed power. The result of a survey of Rankine-cycle PCS masses is presented in Fig. 2. These masses include all PCS elements including the primary loop and structure, but excluding the reactor. Similar mass surveys have been made for other PCS's as well as for nuclear reactors and shields.

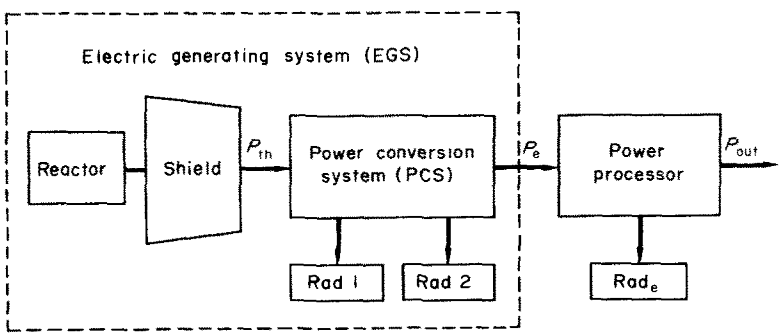

FIG. 1. Schematic of the power system.

PCS overall efficiency depends on ideal or Carnot efficiency, and on device efficiency (which depends on design details). In this study pub-

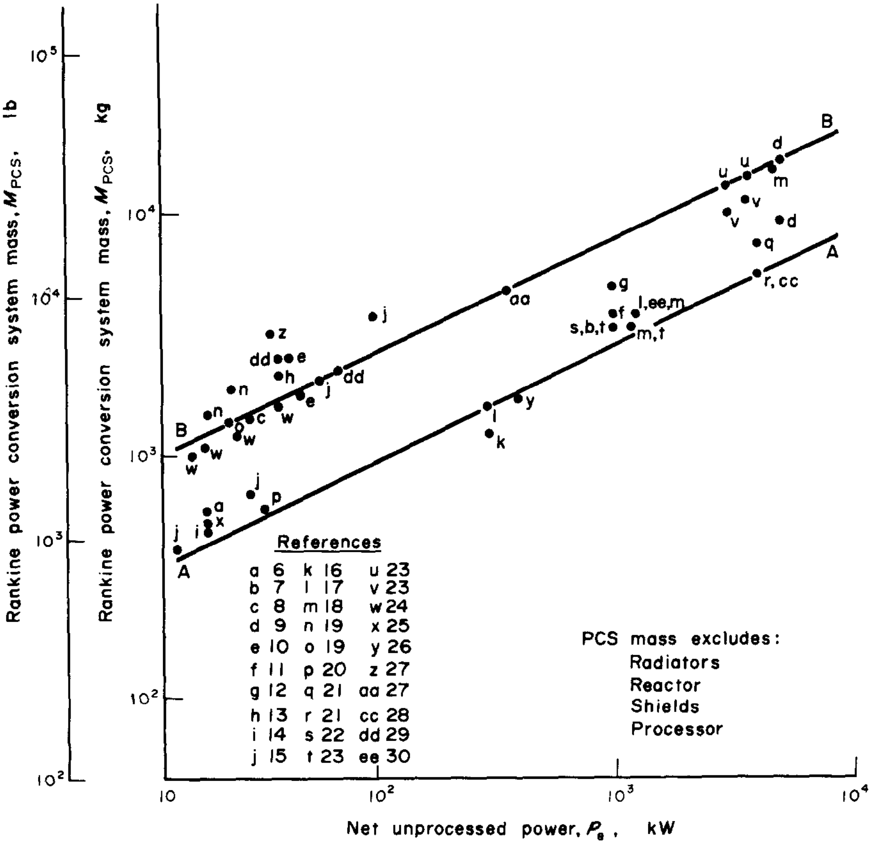

FIG. 2. Rankine-cycle PCS mass survey.

lished values of PCS efficiency have been obtained for each concept, as a function only of T_{REJ}/T_{MAX} and P_e, assuming that these values represent design practice today. Real values somewhat different from those estimated could be found, but this approach is useful for a survey over a broad range of parameters.

Two PCS radiators are considered: the main radiator, and an auxiliary radiator to cool lubricant and coolant in dynamic systems. The heat load of the latter is assumed to be 0·02 that of the former, and is rejected at 330°K. In addition, the secondary radiator (to cool the power processor) is included in the total processed power system.

A uniform value of K_R is used for all radiators in any one system. K_R is varied in the range 0–15 kg/m^2. Present state-of-the-art can give about 6 kg/m^2, using beryllium vapor-chamber fins. Improved choice of materials may reduce this value to about 1·5. New concepts could be hoped to reduce this further by a factor of ten. The higher value of 15 is included as representing solid stainless steel bumper-conducting fins.

The mass penalty due to power processing (not including transmission) is related to the efficiency of the processor. A good approximation for the relationship is:

$$M_{PROC} = \frac{K_P}{1 - \varepsilon_{COND}} P_{out}.$$

We consider power that is processed for use in an ion thrustor. Table 1 indicates the values of K_P used. [31–34].

Table 2. Mass of equipment for processing power for electric propulsion

PCS	K (kg/kW)	Input (V)
Dynamic	0·2	400
Thermoelectric	0·75	150
Thermionic	3·5	15

RESULTS

For unmanned systems (Fig. 3) the masses of Brayton systems at the two temperatures chosen ($T_{MAX} = 890, 1330$°K) tend to merge at $K_R < 0·5$. At $K_R < 1·5$ this system (both temperatures) is relatively cool dynamic cycle over the power range considered.

Thermionic systems tend to be massive, because of the processor, secondary radiator and nuclear shield. In Fig. 4 a dashed line shows the effect, at 1000 kW, of a ten-fold reduction in power processor specific mass.

CONCLUSIONS

Improvements in K_R promise to reduce Brayton system mass by factors up to five or greater. Thermoelectric system mass can also be reduced considerably. Rankine system improvements can occur at powers in the mega W range. Thermionic systems will not experience significant improvements.

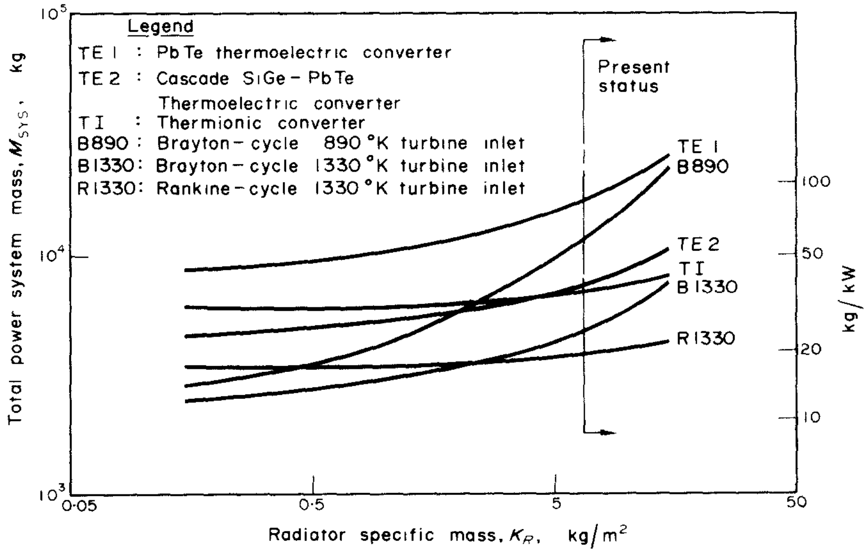

FIG. 3. Comparative variations in total power system mass $P_{out} = 200$ kW; unmanned; no redundancy.

definitely competitive with the Rankine system and is the lightest at $K_R < 0·5$. At $K_R > 5·0$ the Rankine system is clearly the lightest at 200 kW, and will be more so at higher power levels. The 890°K Brayton system changes from nearly the heaviest (at $K_R > 10$) to nearly the lightest (at $K_R < 0·5$). This means that sufficient improvement in K_R would justify using a

Radiators also influence system mass through power processing. For ion propulsion power, the processor and its radiator must be included in (i) optimizations and (ii) comparisons between various energy-conversion concepts.

This study clearly shows that first-order advantages can be expected if radiators are improved. It shows also what radiator improve-

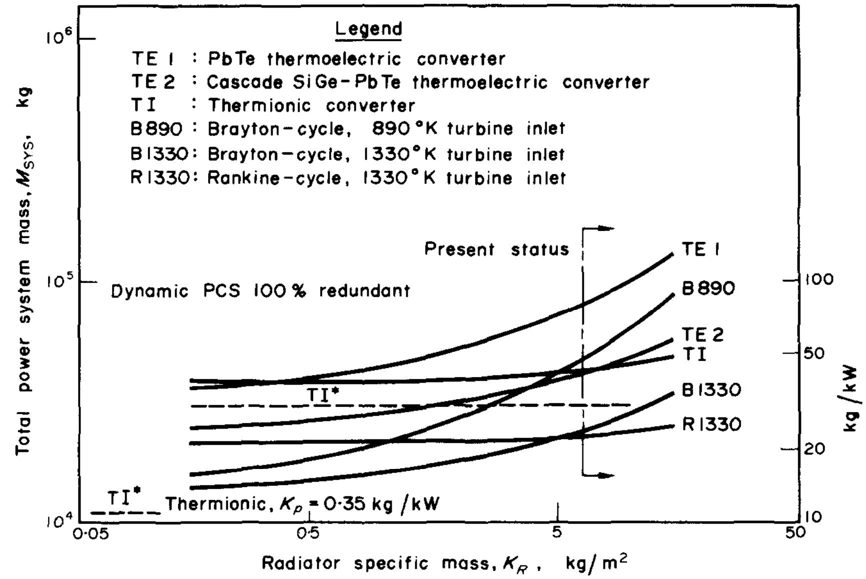

FIG. 4. Comparative variations in total power system mass P_{out} = 1000 kW; manned.

ments are required, and the point of no return in radiator improvements. The definite recommendations is made that further work be undertaken to develop concepts for lighter radiators, with the aim of reducing the effective K_R to values as low as 0·5 kg/m².

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ETUDE COMPARÉE DES SYSTÈMES ÉNERGÉTIQUES SPACIAUX DU POINT DE VUE DE LA MASSE DU RADIATEUR

Résumé—L'influence des radiateurs sur la masse des systèmes spaciaux à énergie nucléaire a été étudiée en déterminant cette masse comme une fonction du paramètre K_R = masse du radiateur/surface. On considère quatre cas de conversion de puissance. Brayton, Rankine, thermoélectrique et thermoionique, pour le domaine de puissance compris entre 200 et 1000 kW. Le système total comprend l'élément générateur de puissance et le radiateur secondaire. Le cycle de Brayton devient compétitivement léger (améliorations par des facteurs supérieurs à 5), et la gamme de puissance intéressante pour des systèmes thermoélectriques croît de façon significative avec des valeurs réalisables de K_R. Le générateur de puissance, le radiateur secondaire, et la protection présentent des systèmes thermoioniques massifs si bien que d'autres concepts assurent une masse plus faible si K_R peut être à moins de 0,5 kg/m^2.

DIE MASSE EINES WÄRMEABGEBENDEN STRAHLERS UND IHR EINFLUSS AUF ENERGIESYSTEME DER RAUMFAHRT

Zusammenfassung—Verschiedene Kernenergiesysteme für die Raumfahrt wurden untersucht durch Bestimmung der Strahlermasse als Funktion des Parameters K_R = Masse des Strahlers/Fläche. Verschiedene Kreisprozesse und Formen der Energieumwandlung werden betrachtet: Brayton, Rankine, thermoelektrisch und thermionisch, in einem Leistungsbereich von 200–1000 kW. Das ganze System schliesst eine Arbeitsmaschine und den Nebenstrahler ein.

Mit erreichbaren Werten von K_R wird das Brayton-System konkurrenzfähig leicht (Verbesserungen bis um den Faktor 5), und der Leistungsbereich für thermoelektrische Systeme nimmt beträchtlich zu.

Arbeitsmaschine, Nebenstrahler und Schutzschild machen die gegenwärtigen thermionischen Systeme schwer, so dass andere Anlagen eine geringere Masse versprechen, wenn K_R auf weniger als 0,5 kg/m^2 reduziert werden kann.

МАССА ТЕПЛОВОГО РАДИАТОРА И ЕЁ ВЛИЯНИЕ НА КОСМИЧЕСКИЕ ЭНЕРГЕТИЧЕСКИЕ СИСТЕМЫ

Аннотация—Влияние радиаторов на массу космической ядерной энергетической системы изучалось путем определения этой массы как функции параметра K_R = масса радиатора/площадь. Рассмотрены четыре схемы преобразования энергии: схема Брейтона, схема Ранкина, термоэлектрическая и термоионная схемы, все в диапазоне 200–1000 киловатт. Вся система включает устройство по переработке энергии и вторичный излучатель.

В сравнении с остальными цикл Брейтона становится более приемлемым (выигрыш почти в 5 раз), а интересующий нас диапазон энергий для термоэлектрических систем значительно возрастает со значениями K_R. Используемые в настоящее время термоионные системы получаются массивными из-за наличия в них генератора энергии, вторичного радиатора и экрана, так что другие понятия обещают меньшую массу, если значение K_R можно будет довести до значений, меньших чем 0,5 Kg/m^2.