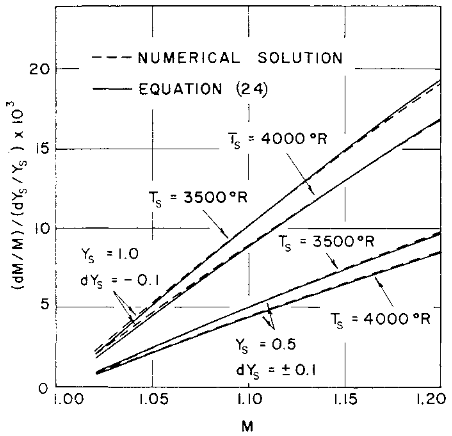

Fig. 1 Comparison of Eq. (24) with corresponding numerical solutions for the condition p_s = 500 psia, R = 67.7 ft-lb/lbm-°R, γ = 1.24, ϵ = 45,320 °R, $a = 5 \times 10^{10}$ sec^{-1}, U_c/c_p = 1500°R, $\dot{w}$ = 2.0 lb/sec-ft^2, $U_c dY = c_p dT$, and $d\rho_s/\rho_s = -dT_s/T_s$.

Results

Equation (24) gives the reduced change in shock Mach number dM/M as a function of dT_s/T_s, dY_s/Y_s, $d\rho_s/\rho_s$, shock Mach number M, and H that is always positive in an exothermic chemical reaction. When a weak shock-fronted pulse passes through a combustion region in one direction, reflects from a boundary, and passes back through the combustion region in the opposite direction, the change in dM/M produced by the temperature, density, and concentration gradients in the two directions may compensate (because the gradient will reverse signs), but the heat released by the chemical reaction will tend to amplify the pulse. The result is a net amplifying effect on a shock-fronted pulse propagating back and forth in the combustion chamber.

Figure 1 presents $(dM/M)/(dY_s/Y_s)$ vs M with different constant values of the parameters dY_s, Y_s, and T_s for the purpose of comparing Eq. (24) with the numerical solution. The numerical solution was obtained by the simultaneous numerical integration of Eqs. (6–9), employing an IBM 7094 computer; Eqs. (16–19), in conjunction with the steady-state temperature profile, were employed as a boundary condition, and it was assumed that the relaxation time for the chemical process was long compared to the time required for the passage of the shock. The conditions under which the two solutions were compared are listed under the figure. The two solutions are in satisfactory agreement; the difference diminishes from ~10% at M = 1.02 to <2% at M = 1.2. The curves are nearly straight lines which indicates that, for a given set of parameters, $dM \propto M^2$.

For the particular example chosen the value of H was small. Therefore, for the case of Y_s = 0.5, the difference between the curves for plus and minus dY is not apparent in Fig. 1. The numerical values from which the curves in Fig. 1 were plotted did show, however, that the curves for plus dY lie slightly above the corresponding curves for minus dY.

Equation (24) can also be employed to treat the less complex problem of a normal shock propagating through a gas having a gradient in temperature, but without chemical reaction. In that case, H is zero; and if the further restriction is made that $d\rho_s/\rho_s \approx -dT_s/T_s$, Eq. (24) reduces to the following relation:

$$\frac{dM/M}{dT_s/T_s} = \frac{-(\frac{1}{2})\,K(M^2 - 1)}{2(\gamma M^4 + 1) + K(M^2 + 1) - 2(M^2 - 1)^2} \quad (25)$$

A plot of the right-hand side of Eq. (25) vs M is very nearly a straight line up through M = 1.2, indicating that, for a given dT_s/T_s and γ, $dM \propto M^2$. Equation (25) is rather insensitive to the specific-heat ratio over the range of values normally encountered; changing γ from 1.24 to 1.4 alters the results by <0.2%.

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Electric Propulsion Possibilities Using Steam Space Power

Henry R. Kroeger* and J. Frank Coneybear†
Astra, Inc., Raleigh, N. C.

Studies by Toms et al.[1] and others suggest that space power for electric propulsion may cost from 1 to 2 billion dollars. Considering costs and possible scheduling problems, it would seem that power for electric propulsion may be available late, if ever, if the present approach is continued, and that other approaches should be considered. This note presents a preliminary examination of systems consisting of electric thrusters and advanced steam space powerplants. The results indicate an advantageous matching of intrinsic characteristics.

Three power ranges are of interest for electric propulsion. Two of these are suitable for applications; one is suitable only for tests. Toms et al.[1] conclude that "the power requirements for electric rockets in the 1980's can be met by (a) a nuclear system in the 300–600-kw range having an initial 10,000 hour life and developing later to 14,000 hours with a shutdown capability for coasting periods, and (b) a larger system in the 2–6 Mw range an initial 10,000 hour life."

The necessity for proof-of-principle flight tests has been postulated, and it has been estimated that initial meaningful tests could be carried out with powers in the 10–30-kwe range.[2] Now, however, the close similarity of results obtained from ground tests and from the recent, successful space electric rocket tests (SERT) would seem to indicate a decreased need for further low-power tests.[3] Electric power in the range between 300 kwe and 6 Mwe can only be supplied by nuclear systems.[4] Powers in the 10–30-kwe range are low enough to be supplied by solar dynamic systems.[5,6]

Combined System Performance Characteristics

Lifetimes for steam-cycle systems will be longer than other approaches, because, as noted by the Atomic Energy Commission (AEC),[7] lower temperatures result in greater reliability, and because steam systems have higher over-all efficiencies. Figure 1 (derived from the Fig. 1 in Ref. 7) shows that pertinent steam components essentially can achieve the necessary 10,000- and 15,000-hr lifetimes, now. Note that liquid metal components must displace the temperature vs lifetime curve, in lifetime, by four orders of magnitude. The use of steam cancels the need for auxiliary cooling loops for the powerplant, the thruster, and the power con-

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* Vice-President.

† President. Member AIAA.

ditioning equipment, as well as diminishes the need for heat shielding. Over-all weights, therefore, will be less with steam.

Near the earth unheated water will not freeze in the radiator. (This is not true for the alkali metals except NaK.) At greater distances, advantage can be taken of the very small amount of water involved. (Typical total requirements are 230 lb of water, as compared with 3600 lb of liquid metals.) Since very little water is in the radiator, shutdown techniques can be simple, even including jettisoning. In sum, water systems give superior shutdown and coasting capabilities.

For low-power tests (10–30 kwe), the off-vehicle disposal of waste heat from the propulsion system will not be a major problem; direct radiation should be possible. There are, however, situations in which the high temperatures needed for thermal radiation cause deterioration of propulsion efficiency. Such systems require an auxiliary coolant. With some approaches, such as arc jets, there must be structure near gases or plasma at very high temperatures. The problem may then be one of preventing high local temperatures; off-vehicle heat disposal may or may not be a major problem.

Characteristics of the Steam Power Subsystem

For several years Astra has been demonstrating that a Rankine cycle, using water, would provide the lowest development risk for space power and would give surprisingly good performance. Recently, the Air Force, under the advanced solar turbo-electric conversion system (ASTEC) program, came to identical conclusions for solar heat space power.[5] In Astra's systems concept[6,8–10] the working fluid flow is as shown in Fig. 2; Fig. 3 is the corresponding temperature-entropy chart. The steam enters and leaves the turbine superheated. Between the turbine and the condenser, heat is transferred via a regenerator-recuperator to water flowing from the pump to the heat source.

For the easily developed lower-power systems, peak pressures and temperatures would probably be ~1200 psi and ~1200°F. A high-power, steam-only nuclear plant would involve slightly higher temperatures and a peak pressure of ~2400 psi. A more advanced, very low specific weight possibility, examined with others, is a "binary" thermionic-plus-steam system with the thermionic elements rejecting heat to steam within the reactor. This would give very high efficiencies. (The extrapolations for this concept are at least as conservative as those made for concepts using other working fluids.)

Radiator and powerplant weights are competitive despite lower radiator temperatures because tube weight, rather than the radiator area, dominates the radiator weight.[11] Headers and tubes have smaller diameters, which derive from the thermodynamic characteristics of water and higher over-all efficiencies. Lower-temperature systems can use lighter weight metals. Although radiator areas are greater, and developing a suitable radiator for any high-power system will be a major problem, the design flexibility achieved by the use of smaller diameter headers and tubes more than offsets the disadvantage of greater areas. Finally, the temperature regimes are such that cycle working fluid can be used directly for cooling purposes.

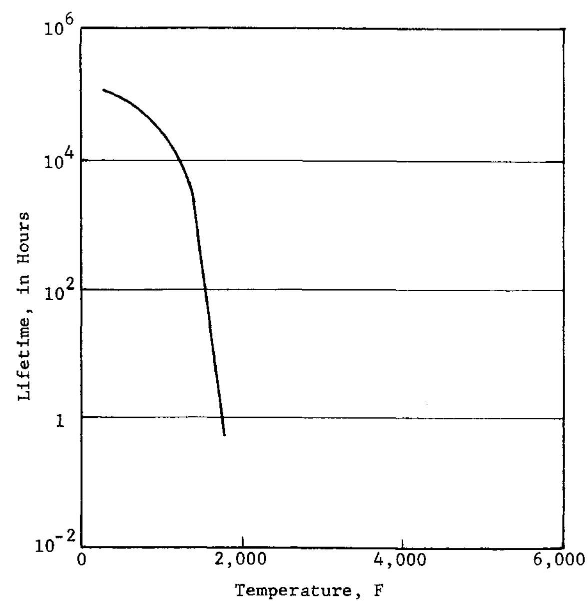

Fig. 1 Lifetime for powerplant rotating machinery vs operating temperatures (derived from Ref. 7).

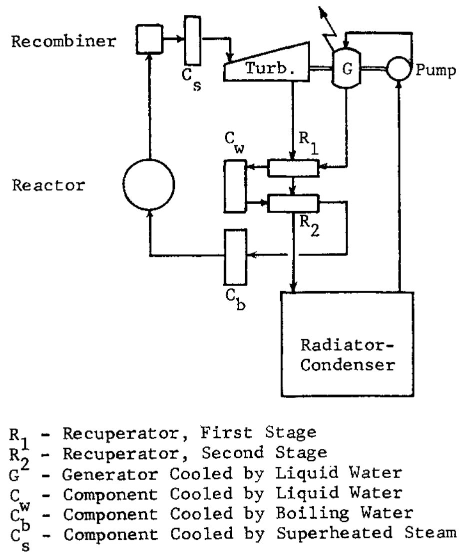

Fig. 2 Possible regenerative component cooling regimes available with steam space power systems.

Component Cooling Regimes

There are a number of possible arrangements for cooling thruster components and power conditioning components; the choice depends upon the heat-load and temperature requirements. As indicated by Figs. 2 and 3, liquid water, boiling water, and superheated steam are all available for cooling (in different parts of the cycle). Cooling by boiling can easily remove heat in amounts equivalent to all of the electric power generated. Thus, with boiling, any over-all

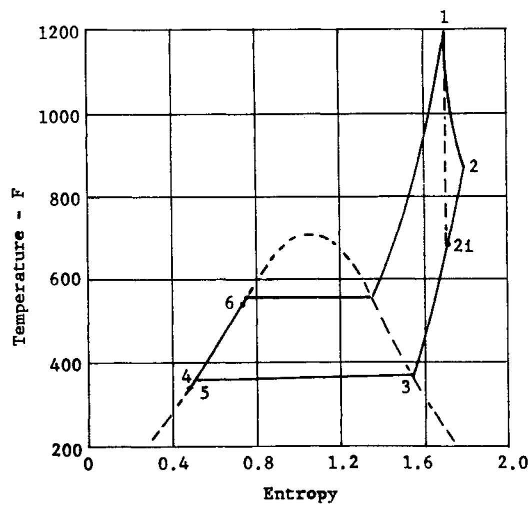

Fig. 3 Temperature, entropy diagram for a typical steam space power cycle.

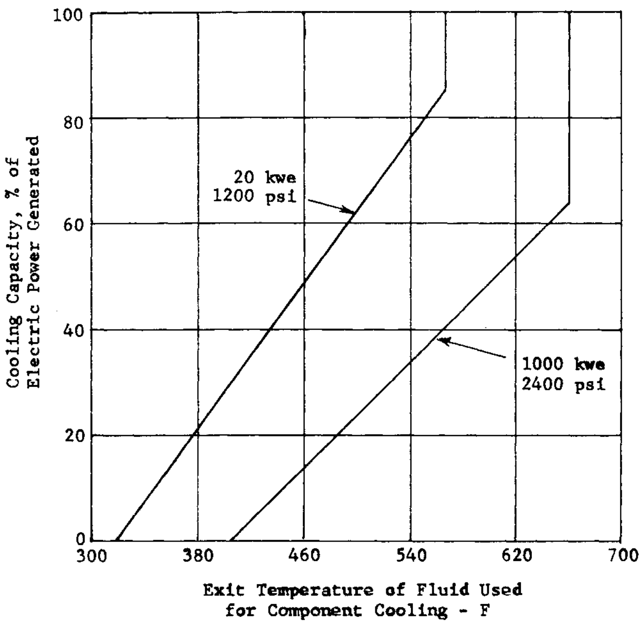

Fig. 4 Regenerative component cooling capacities of steam space power systems.

system heat-load requirement can be met, always assuming that the temperatures are compatible. Cooling by superheated steam as a coolant seems least likely. If a moderate amount of high-temperature waste heat were available, however, it could relax the requirements on the reactor.

With high-power systems, using peak pressures as high as 2400 psi, the saturation temperature is 662°F; thus, any thruster component cooling load could be handled easily as long as the component temperature is slightly greater than 662°F. Liquid water cooling is available in the temperature range of 405°–662°F, for heat loads up to 64% of the total electrical power generated. The amount of cooling varies with the temperature (Fig. 4).

With the easily achieved 1200-psi steam powerplant, the saturation temperature is 567°F. Any thruster (or power conditioning) cooling load could be handled easily, if the component temperature is slightly greater than 567°F. Liquid water, available in the temperature range of 320°–567°F, could handle heat loads up to 85% of the total electrical power generated. The amount of cooling varies with the temperature (Fig. 4).

Concluding Remarks

Steam power systems have characteristic temperatures low enough to make use of "waste heat" from thruster and power conditioning equipment without operating such components at excessively high temperatures. Therefore, when steam powerplants are combined with electric thrusters, over-all system weight savings are obtainable which are not possible with the higher temperatures characteristic of most other coolants. The use of waste heat in the steam cycle gives a small, say 1 to 5%, increase in over-all efficiency. This increase, however, can mean a decrease of 7 to 18% in radiator weight.

Removing the necessity for separate cooling loops, in changing from liquid metals to steam, causes a decrease in weight, an increase in reliability, and less power for auxiliaries.

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