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GOALS OF THERMIONIC PROGRAM FOR SPACE POWER

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INTRODUCTION

Prior to 1973, the thermionic concepts for nuclear space power were predicted to have the lowest specific mass of any of the competitive concepts. In recent studies, this is no longer true. For example, Table I lists estimated characteristics for both the thermionic and Brayton gas-turbine concepts for power generation from references 1-3. References 1 and 2 both considered thermionic-emitter temperature to be 1650 K. Although reference 2 assumes efficiency of the power-generating system to be 0.15, reference 1 considers the values 0.1 and 0.15; the reference-1 weight in Table I is the average of the two weights.

In reference 1, power processing is assumed to be 90 percent efficient. Weight of power processing plus ion thrusters is given as 2000 kg; in Table I, power-processing weight is taken as 3/4 this sum. Reference 2, with its greater detail gives both weight and output power for the power processor. For the Brayton concept, power processing was included in the power generator (ref. 3). Overall, the thermionic concepts have specific weights 35 to 60 percent higher than the Brayton, even if the Brayton concept has 100-percent redundancy in the power-generating system.

Reference 4 considers the thermionic concept at 1650 K emitter temperature and 500 kWe of output power; overall conversion efficiency is given as 0.15. Power processing is not mentioned. Specific mass of the thermionic concept is given 17 kg/kWe.

For the Brayton concept in reference 4 reactor-outlet temperature is 1400 K; turbine-inlet temperature would be about 100 K less (ref. 3), or 1300 K. The resulting 250-kWe Brayton concept is there estimated to weigh only 14 kg/kWe, although several differences in the assumptions for the reactor shields for the thermionic and Brayton concepts are also cited. "Putting the two designs on the same relative basis would result in substantial weight savings in favor of the thermionic system" (ref. 4). Reference 5, on the other hand, scales the 250-kWe Brayton data of reference 4 in a pessimistic manner to 500 kWe and shows that putting the two designs on the same basis produces equal specific mass (17 kg/kWe). Use of turbine-inlet temperature of 1500 K (as in ref. 3) instead of 1300 K would reduce radiation mass for the Brayton concept and thereby give it the superiority of specific mass shown in Table I. The thermionic concept has thus lost its original superiority in specific mass to a power-generating concept less risky to develop.

The purposes of this paper are as follows: (1) to assess the feasibility of operating a Brayton power-generating system at 1500 K and (2) to explore the manner in which changing goals for the thermionic program may have resulted in the rise in specific mass cited above.

BRAYTON TECHNOLOGY

In 1970 a Brayton power-generating system of 10-kWe design power output was assembled from components that had not yet been tested individually. Its design level of turbine-inlet temperature was 1150 K (1600° F). In NASA-Lewis's Space Power Facility (SPF), overall performance of the system was measured in a vacuum. At the 10-kWe level, overall power-generation efficiency was 0.29 (ref. 6). This efficiency was based on the net power output from what was a complete powerplant except for a solar or nuclear heat source, that is, all internally consumed power for controls, pump, generator excitation, voltage regulation, frequency control etc. was deducted. During this test, the generator's hot-spot temperature was found to be below the 200° C limit on the electrical insulation and that actually 15 kWe of net output could be produced within that limitation; accordingly, rated power was raised to 15 kWe.

Following 2561 hours of testing in SPF, endurance testing continued in a conventional, air-filled laboratory. Such testing in air was possible because the engine's superalloys, appropriate to its peak temperature of 1150 K, would tolerate that oxidizing environment. Testing continued to a total of 38 000 hours at which time problems with the electric heat source forced termination. The rotating machinery (a compressor, turbine and alternator on a common shaft supported by gas bearings, and a motor-driven pump) operated for this period without any problems or any performance degradation.

Separate tests of the compressor and turbine revealed modest performance deficiencies for each component. Minor changes in these components boosted their efficiencies measured in additional component tests. Redesign of the speed and frequency control decreased its power consumption as demonstrated by a breadboard test. Had these improved components being retrofitted into the engine, its overall efficiency of power generation would have risen to 0.32 (ref. 6). Overall, these tests demonstrated the achievable performance level and the durability of Brayton power systems at the 1150 K level.

For operation at the 1300 K temperature of reference 4 or the 1500 K of reference 3, refractory alloys are required. Although no Brayton space-power system has been built for operation at these temperatures, the long-time creep tests in reference 7 indicate what temperatures might be practical. The tantalum alloy ASTAR-811C (Ta-8 W-1 Re-1 Hf-0.025 C) is readily weldable and has been shown to be still ductile post-welding at temperatures well below room temperature; this readily fabricable alloy is thus suitable for building reactors, pressure vessels, heat pipes, pumps, heat exchangers, ducts and turbine casings. In addition, its 70 separate long-time creep tests (Table II-11, ref. 7) totalling 250, 246 test hours and spanning the temperature range of 1150-1925 K (1600-3000° F) display its tolerance of stress at high temperature.

For good correlation, the data in this table for 1 percent creep were divided into high- and low-stress regimes. For the high-stress regime, the test conditions were narrowed to those imposing stresses of at least 34.5 MPa (5000 psi) and test times of at least 3000 hours; on a plot of stress vs. Larson-Miller parameter, a straight line was fitted to the data by the method of least-squares. (Test hours total 140 084.) For the low-stress regime, stresses no greater than 69 MPa (10 000 psi) were chosen, some overlap with the high-stress regime being deliberately included; in this case, a straight line was fitted to the data by the method of least-squares for a plot of log-stress vs. Larson-Miller parameter. (Test hours total 116 441.) In each case, the standard deviation of the data from the correlating line was also computed.

The results are presented in figures 1 and 2 for the high- and low-stress regimes, respectively. In addition to the lines through the data, second lines have been shifted to lower stress by two standard deviations (2σ). For any given datum, the probability is 97.7 percent that the measured Larson-Miller parameter exceeds the value given by the 2σ-line. This 2σ-line thus provides a more reliable basis for design than does the mean line through the data.

If one chooses 1-percent creep in 40 000 service hours (4.6 years) as his stress criterion, then the 2σ-lines in figures 1 and 2 produce the allowable stresses given in Table II. The allowable stress is seen to provide comfortable margin for design of ducts, turbine casings and heat exchangers at temperatures of 1500 K and below. At 1600 K, less margin is available, and some weight penalty would likely result from use of that high a temperature. On the other hand, one must keep in mind that the selected stress criterion is 1-percent creep rather than rupture. One-percent creep in 40 000 mission hours would produce of the order of 3-percent creep in 120 000 hours (13.7 years), this in an alloy deforming perhaps 25 percent before rupture. Thus, even this conservative stress criterion shows that turbine-inlet temperature of 1500 K and reactor-outlet temperature of 1600 K constitute a reasonable basis for design of the stationary portions of a Brayton space-power system.

Before exploring the stresses tolerable in design of the turbine rotor, we must establish the temperatures to which the rotor will be exposed. For the thermodynamic cycle specified in figure 18 of reference 3 (turbine inlet, 1500 K and turbine outlet, 1169 K), the stagnation temperatures along a radial-flow turbine rotor were computed for a turbine-inlet temperature of 1500 K (fig. 3). In the low-stress region at the rotor tip, stagnation temperature is 1330 K, 170 K below turbine-inlet temperature. Stagnation temperature falls to 1250 K at 70 percent of the tip radius and is roughly 1200 K for the central half of the radius, the highly stressed portion of the turbine rotor. In this central region, heat conduction along the turbine shaft will also lower temperatures slightly below the adiabatic values considered here. Thus, the high-stress, central portion of the turbine rotor will encounter temperatures in the 1200 to 1250 K range.

The molybdenum alloy TZM (Mo-0.5 Ti-0.08 Zr-0.03 C), a candidate for the turbine rotor, has had 11 creep tests totalling 94 140 hours and spanning the temperature range 1150 to 1440 K (1600 to 2130° F) (Table II-7, ref. 7). In figure 4, a straight line through the data and the 2σ-line shown were both determined by the method of least-squares for 1-percent creep. For 1-percent creep in 40 000 hours, the 2σ-line yields the following allowable stresses:

Temperature, K	Allowable stress	
	MPa	KSI
1200	240	35
1250	150	22
1300	70	10

These combinations of stress and temperature are adequate values for design of turbine rotors. No welding of the turbine rotor would be used in order that embrittlement could be avoided, which is characteristic of many molybdenum alloys.

To date, no components have been built and evaluated for use in a Brayton space-power system to operate at 1500 K. On the other hand, the principles in design were successfully demonstrated at 1150 K with materials appropriate to that temperature. Long-time creep data for both the tantalum alloy ASTAR-811 C and the molybdenum alloy TZM support the performance predictions of reference 3, which employs the design methods successful at 1150 K to appraise performance at 1500 K.

EVOLUTION OF THE THERMIONICS PROGRAM

The year 1973 was a watershed in thermionics, when all the nuclear programs on space power and propulsion were sharply cut back. The 1972 international conference on thermionics gives the status of technology and the program thrust at that time (ref. 8). Breitwieser (ref. 8a) describes research for emitter temperature of 1800 K, Holland (ref. 8e) at 1800 to 2000 K and Yates et alia (ref. 8d) at 1670 to

1950 K. Highest performance (both conversion efficiency and W/cm^2) was obtained the highest temperatures. Beard (ref. 8b), in summarizing the U.S. thermionic program specified the following objectives: 12 A/cm^2 at 2000 K, converter life of 2 years at 2000 K and 5-year life at 1800 K. Beard also reported on the durability the electrically-heated converter LC-9 (as did Morris later, ref. 9); this converter performance was stable over a 5.3-year test period at 1975 K, producing 8 W/cm^2 at 0.76 V (ref. 9).

With the program cutback in 1973, testing of thermionic fuel elements ceased befor a sufficient basis for design at 1800 to 2000 K had been created. In the small prograr that continued, attention focussed on achieving a viable thermionic powerplant at 1650 K emitter temperature (refs. 1, 2, and 4, for example), in spite of the successful operation of the LC-9 converter at 1975 K. Reduction in converter output to 6 W/cm^2 also added to system weight. The overall result was degradation in performance of the thermionic concept so that it was no longer weight-competitive with a concept less risky to develop (Table I).

CONCLUDING REMARKS

For the thermionics program, the keys to surpassing Brayton performance are as follows: The original goals of high emitter temperature (1800-2000 K) and high power density should be investigated in a program on enabling technology. The out-of-core concept not only separates the thermionic converters from their reactor but also segregates the risks in their investigation and development. Technical risk would also thereby be diminished by (1) moving the electrical insulators out of the reactor, by (2) permitting a higher thermal flux for the thermionic converters than is required of the reactor fuel and by (3) eliminating fuel swelling's threat against lifetime of the thermionic converters. At present, the power processor adds about 7 kg/kWe to system specific mass and requires low-temperature cooling of its solid-state components. Overall system performance might be improved by including power processing in system optimization during design as well as by a technology program on more efficient, higher temperature power processors.

Some problems basic to thermionic power systems will continue for a long time. The data on swelling of reactor fuel are presently insufficient for design at thermionic temperature of 1800-2000 K. Not only would acquiring such data require considerable time and money but almost no effort has been invested in fuel swelling at these temperatures since 1973. And thermionic reactors (even for the out-of-core concepts) will be larger than for competitive systems having higher conversion efficiency and lower reactor operating temperatures. Although the effect of reactor size on shield weight will be modest for unmanned spacecraft, the penalty in shield weight would be large for manned or man-tended spacecraft.

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TABLE I. - COMPARISON OF THERMIONIC AND BRAYTON CONCEPTS

JPL data for 400 kWe (refs. 1-3)

	Thermionic, 1650 K		Brayton, 1500 K
	Reference 1	Reference 2	Reference 3[a]
Power generation:			
kg	10 600	8426	8270
kWe	400	400	400
Power processing:			
kg	1500	1200	0
kWe	360	343	400
Specific mass, kg/kWe	34	28	21

[a]100 percent redundancy for power generation.

TABLE II. - CREEP STRENGTH OF ASTAR-811C

Criteria: (1) 1 percent creep in 40 000 hours.
(2) Allowance of 2 standard deviations.

Temperature, K	Allowable stress	
	MPa	ksi
1300	156	23
1400	96	14
1500	36	5
1600	7	1

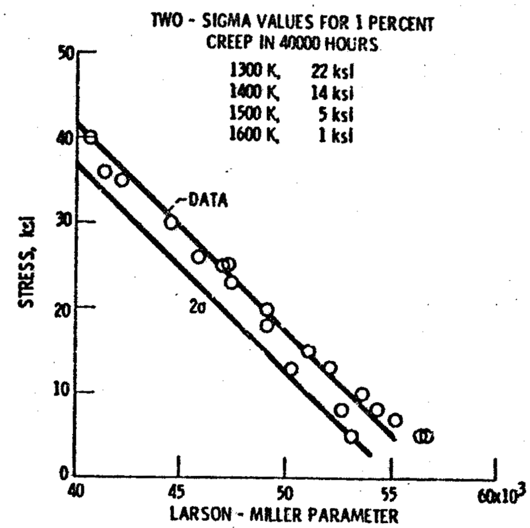

Figure 1. - One-percent creep of ASTAR-811C. 21 tests, 149 084 hours. (Total: 70 tests, 250 246 hours, 1150-1925 K)

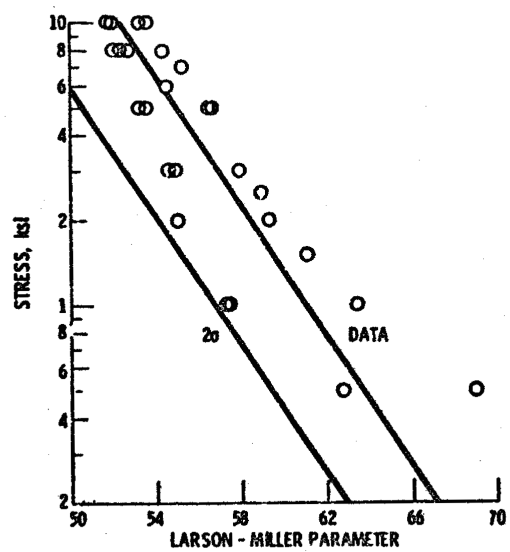

Figure 2. - One-percent creep of ASTAR-811C. 26 tests, 116 441 hours.

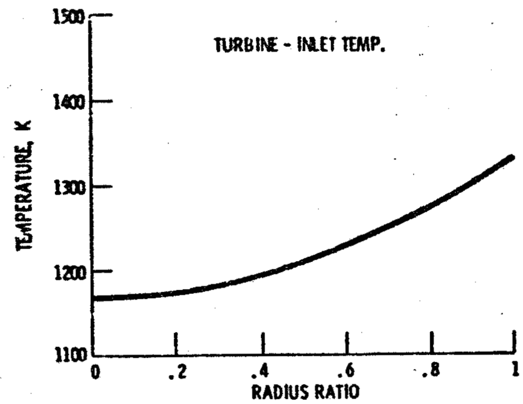

Figure 3. - Brayton - rotor stagnation temperature.

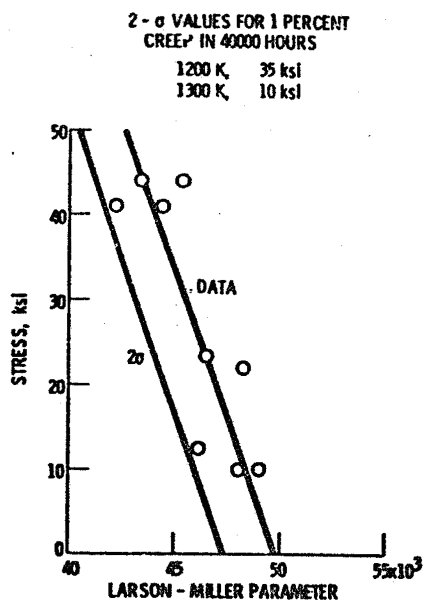

Figure 4. - Moly-alloy TZM creep data (1%). 11 tests, 94140 hours, 1140-1440 K (1600-2130° F).