JET PROPULSION LABORATORY
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MEMORANDUM #3

PERFORMANCE AND WEIGHT DEPENDENCE OF A SILICON-GERMANIUM RTG ON FUEL CAPSULE TEMPERATURE AND HEAT FLUX

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INTRODUCTION

Although the performance of a thermoelectric generator depends on a great variety of factors, such as thermocouple configuration, thermal insulation characteristics, and electrical load resistance, it is probably the operating temperatures of the generator that have as great an effect on its performance as any of the other factors. In general, within the range of operating temperatures of any given thermoelectric material, the greater the temperature differential across the material, the better the performance from standpoints of power output and conversion efficiency. It would seem desirable therefore to operate a thermoelectric device at hot and cold side temperatures as high and low, respectively, as possible. Although generally true, the degree to which the operation of an actual thermoelectric device under extreme temperature conditions is practicable is usually determined by additional factors that relate to device economics, reliability and safety.

In space applications, the waste heat from a thermoelectric generator is rejected at the cold side of the generator by means of radiation into space. The lower the temperature at which it is desired to operate the cold side of the generator, the larger must be the radiator. In fact, because of the dependence of radiative heat transfer on the fourth power of temperature, radiator size and consequently also its weight, rapidly increases with decreasing temperature. In space applications, therefore, it is weight that usually limits the size and thereby also the lowest attainable temperatures of the radiator and of the cold side of a thermoelectric generator. In practical space power systems the radiator of a thermoelectric generator commonly operates in the range 200 to 600°F, the precise value depending on whether it is desired to emphasize the maximizing of conversion efficiency or the minimizing of generator weight. The former of these goals leads to temperatures at the low end of the range, whereas the latter results in radiator temperatures at the high end of the range. In either case, the final selected radiator temperature is really the result of a compromise between the usual power system design goals of high efficiency and low weight.

The hot side operating temperatures of a thermoelectric generator are determined and limited by the high temperature capabilities of the heat source and of the thermoelectric converter, including the thermoelectric material and associated technology. Specifically, it is device reliability, as concerns performance and mechanical strength characteristics, and questions of heat source safety in the case of nuclear systems that are the determining factors in the selection of maximum generator hot side operating temperatures. Historically speaking, the earliest thermoelectric materials that exhibited attractive performance characteristics in thermoelectric power conversion were limited in their high temperature operating capabilities to about 1100°F. It sufficed therefore to develop heat sources that were capable of being used at temperatures only slightly (a few hundred degrees Fahrenheit) higher than 1100°F to fully utilize the then available thermoelectric materials. In the meantime, new and, in many respects, more attractive thermoelectric materials with substantially improved high temperature operating capabilities have been developed, viz. the silicon-germanium alloys. As regards space applications with nuclear heat sources, however, unfortunately heat source development has considerably lagged thermoelectric converter development. The present state-of-the-art of silicon-germanium technology is for example such that long-life reliable thermoelectric converters may be built for operation at hot side temperatures approaching 2000°F. Heat sources capable of operating at temperatures up to 2300°F would have to exist for the complete utilization of such converter hot side temperatures.

Although the development of high temperature nuclear heat sources was initiated several years ago, partly for use with thermoelectric converters and partly for use with devices that make use of other forms of energy conversion, the development is not yet complete. Even though material compatibility and related problems generally increase with increasing temperatures, considerable progress has been made to date on the development of high temperature heat sources; for example, it is presently possible to propose realistic radioisotope thermoelectric systems for space applications which make use of fuel capsules that operate at a surface temperature of the order of 2000 to 2100°F. It should be emphasized, however, that still higher fuel capsule temperature capabilities are desirable in order to fully utilize available silicon-germanium thermoelectric technology. The gains in generator performance and weight reduction are appreciable with increased fuel capsule operating temperatures.

It is the purpose of the present memorandum to illustrate the effect of heat source operating temperatures on the performance of a thermoelectric generator designed for space applications. It is hoped that the present results will serve to emphasize the importance of continuing and even expanding the development effort on high temperature heat sources. Because of the immediacy of the use of radioisotope thermoelectric generators in various deep space and planetary probes, the discussion will concern itself with generators of that type. Similar arguments can be made, however, with respect to generators that use other types of heat sources, such as nuclear reactors.

PHYSICAL MODEL

A model of a radioisotope thermoelectric generator was assumed for the purpose of quantitatively illustrating generator performance as a function of fuel capsule temperature. The model makes use of a representative re-entry-type refractory metal fuel capsule and silicon-germanium Air-Vac thermocouples; both selections are based on their ability to operate at relatively high temperatures. The fuel capsule, cylindrical in shape, is assumed to be surrounded by the thermocouples which are mounted to a radiator-frame. For enhanced heat transfer, the radiator frame includes radiation fins on its surface.

The fuel capsule is assumed to consist of a number of concentric shells of hollow cylindrical form closed at both ends by hemispherical end closures. Proceeding from the inside towards the fuel capsule surface, the shells include an inner fuel liner, the fuel (assumed to be plutonium oxide), an outer fuel liner, a structural shell and diffusion and oxidation barriers. The fuel capsule is coated with a high emittance coating. The fuel capsule is surrounded by graphite felt that acts as a shock absorber. The fuel capsule and graphite felt are contained in a graphite shell that gives the assembly re-entry protection. The diameter of the heat source, including the graphite shell, is assumed to be 3.5 inches.

The silicon-germanium Air-Vac thermocouples, radiatively coupled to the heat source, have square hot shoes one inch on the side and 0.100 inch thick. The n-and p-type thermoelements are one inch long and are attached to a cold stack that includes at the far end a stud arrangement for fastening the thermocouples to the radiator-frame. The cold stack includes electrical connectors that connect each thermocouple to adjacent thermocouples for continuity. In addition, for electrical isolation from the radiator-frame, the cold stack also includes an electrical insulator. The Air-Vac thermocouples are embedded in multi-foil insulation that enables shunt heat losses to be minimized. To prevent electrical shorting by the multi-foil insulation and to minimize heat losses between the thermocouple legs, each thermoelement is surrounded by a thin layer of fibrous-type insulation, the gap between the n - and p-type legs being completely filled by it. The spacing between adjacent thermocouple hot shoes has been set at 0.040 inch.

The radiator-frame is assumed to be made of aluminum and includes six equally spaced radiation fins some nine inches long. At the ends of the generator, end closures attach to the radiator-frame. Inside the end closures are support structures for the fuel capsule and additional foil insulation for minimizing end heat losses.

It has been calculated that for a system that produces about 100 watts of electrical power at the end of 12 years, the total un-fueled system weight is about 31 pounds, of which some 18 pounds is total converter weight, including end closures,with the remainder in the fuel capsule and graphite. It should be noted that, as will be discussed later, the area of the n-and p-type thermoelements has been allowed to vary in the parametric studies that were conducted as a part of the present study. The resultant small trade-off between thermoelement weight and the weight of insulation that surrounds the thermoelements has been ignored in all of the results. This simplification has a negligible affect on the results but enables the converter weight to be treated as essentially independent of fuel capsule temperature and of the heat flux at the fuel capsule surface. The un-fueled fuel capsule weight has similarly been treated as a constant. Fuel weight, however, has been allowed to vary with the heat flux at the fuel capsule surface; each value of heat flux thereby corresponds to a different level of fuel loading of the capsule. Depending on the heat flux, it has been calculated that within the range covered by the present study, fuel weight contributes some 3 to 11 pounds to total system weight for a system capable of producing of the order of 100 watts of electrical power at the end of 12 years.

ANALYTICAL MODEL

The analytical model used in the RTG performance calculations takes into account, in fair detail, the temperature drops across all active and passive components of the structure, including radiative temperature drops across non-metallurgical interfaces. Parasitic electrical losses due to contact resistance and due to the resistance of passive members in the electrical circuit have been included in considerable detail. The effects due to shunt heat loss at the end closures and through the insulation surrounding the silicon-germanium thermoelements have been treated as an integral part of the calculation and are therefore considered to be accurately taken into account. Although the analytical model used in the RTG performance calculations is thus fairly complete, a few simplifying assumptions have nevertheless been made in order to speed up the computations. The more significant simplifications include the neglect of Thomson heat generation (absorption) in the thermoelements, the neglect of transverse heat flow in thermoelement hot shoes and the neglect of axial temperature gradients, except for the end closures, in the RTG. The first of these simplifications has a negligible effect on the final RTG performance values. The latter two simplifications, although probably more important than the first, have only a minor effect on the results. In this connection it may be mentioned that the fairly thick hot shoes assumed for the Air-Vac thermocouples tend to minimize the effects of transverse heat flow in the shoes. The multi-foil insulation assumed for the end closures minimizes thermal end losses and thereby also any axial temperature gradients in the

RTG. Thermal end losses are calculated to be less than five percent of total available heat for all cases considered in the present study.

The thermoelectric property data used in the present study for the silicon-germanium alloys have been derived from the results of various material studies performed under AEC (the SNAP-10A program) and NASA (Contract No. NAS 5-3410) sponsorship and reflect the properties of silicon-germanium alloys after some 12 years of operation. Even though these property data are extrapolations, it is believed that they reasonably represent silicon-germanium alloys in long-term operation.

In all of the calculations performed in the present study it has been assumed that the n-type legs of the Air-Vac thermocouples have a cross-sectional area 1.8 times that of the p-type legs. The ratio of load to internal electrical resistance has been maintained at the fixed value of 1.3 even though both of these factors should be precisely determined through optimization for each case considered. It is known on the basis of past experience that the given factors will, in most cases, result in very-nearly optimum performance values for a silicon-germanium generator.

The calculated sequence has considered the performance of the silicon-germanium RTG under a variety of temperatures and heat fluxes at the fuel capsule surface. The RTG configuration, except for thermoelement cross-sectional areas, has been kept fixed for each case considered. Thermoelement cross-sectional areas, subject to the fixed ratio of 1.8 of the n - to p-type leg areas, have been determined for each case in such a way as to yield self-consistency in the overall calculation. Because the RTG configuration has been thus kept essentially fixed throughout the study, the results do not necessarily represent optimum performance of silicon-germanium RTG's under the different fuel capsule and heat flux conditions. In order to determine the optimum generator performance for each case considered, it would be necessary to vary the configuration of most key components in detail. Therefore, although not necessarily optimum, the present results are indicative of the performance dependence of silicon-germanium RTG's on fuel capsule temperature and heat flux.

RESULTS AND DISCUSSION

The performance of a typical silicon-germanium RTG as a function of temperature and heat flux at the fuel capsule surface has been assessed in terms of specific power (watts per pound) and conversion efficiency. Figure 1 shows the specific power of the RTG as a function of fuel capsule surface temperature for four values of heat flux. The large dependence of specific power on fuel capsule temperature is quite apparent as is also its dependence on heat flux. It is noted that at any given fuel capsule temperature there exists a value of heat flux that maximizes specific power (minimizes weight). The higher the fuel capsule temperature, the higher the heat flux at which weight is minimized. This point will be more apparent in a subsequent Figure. Figure 1 also indicates that in order to minimize RTG weight at relatively low hot side temperatures, it is preferable to use reasonably small values of heat flux. The use of small values of heat flux at higher operating temperatures, however, severely penalizes system weight.

Because weight considerations represent only one aspect of RTG selection for any given space application, it is of importance to also consider the behavior of conversion efficiency under different generator operating conditions. Figure 2 shows plots of conversion efficiency as a function of fuel capsule temperature for the same values of heat flux as in Figure 1. The results for conversion efficiency are nearly opposite to those of specific power. In order to optimize efficiency it is desirable to still make use of high fuel capsule temperatures, but unlike the case of specific power, higher efficiency values for any given value of fuel capsule temperature occur at lower values of heat flux. The reason for this phenomenon lies in the fact that whereas conversion efficiency of a thermoelectric device largely depends on the temperature difference across the thermoelements, the power output additionally has an important inverse dependence on the ratio of thermoelement length to cross-sectional area. The dependence of efficiency on this latter factor is usually only of second order. For any given fuel capsule temperature, the thermocouple hot side temperature decreases with increasing values of heat flux. This effect is quite pronounced because of radiative heat transfer that occurs at several interfaces between the fuel capsule proper and the thermocouple hot shoes. Because of greater heat rejection demands at the radiator, the cold side temperature of the RTG increases with increasing values of heat flux. The temperature difference across the thermoelements and consequently the conversion efficiency of the device therefore decrease with increasing values of heat flux. As the heat flux increases, however, the thermoelements must be capable of transmitting increased amounts of heat; this at decreasing values of temperature differential across them. A way in which it is possible to satisfy this requirement is to increase the conductance of the thermoelements. Thermoelement conductance may be increased by increasing their cross-sectional areas and/or decreasing their length. In either case the result is a decreased ratio of thermoelement length to cross-sectional area. This tends to enhance power output (hence the specific power) and in many instances, such as illustrated in Figure 1, is sufficient to override the square dependence of power output on the temperature differential across the thermoelements.

It should be noted that in addition to or instead of only increasing the conductance of the thermoelements, as done in the present study, to increase the ability of the converter to satisfy increased heat transfer requirements with increasing values of heat flux, it is possible to also increase radiator size and thereby decrease the cold side temperature of the generator. The consequently increased temperature differential across the thermoelements results in increased power output values. Unlike the case of increased thermoelement conductance, which either decreases converter weight or leaves it nearly constant, increased radiator size, however, generally increases system weight and therefore reduces its specific power. In fact, for optimum generator weight it is usually advisable to make use of a fairly small radiator and relatively highly conductive (short and squat) thermoelements. As seen in connection with Figures 1 and 2, efficiency optimization, however requires the opposite approach because in this case it is necessary to make use of as large a temperature differential across the thermoelements as possible.

Figure 3 summarizes the above discussion in connection with Figures 1 and 2 by showing plots of efficiency as a function of specific power for different values of fuel capsule temperature and heat flux. It is noted that for each value of fuel capsule temperature there exists a value of heat flux for which specific power is optimized (minimum weight). It is also noted, however, that the optimum value of specific power corresponds to a value of conversion efficiency that is not at its highest. In an actual RTG design it is for this reason that a compromise is usually made between efficiency and specific power. It should be further noted that for each value of heat flux there exists a fuel capsule temperature at which conversion efficiency and generator power output vanish. In each case it is at this fuel capsule temperature that the temperature differential across the thermoelements goes to zero because the hot and cold junction temperatures of the thermocouples become equal.

To summarize the data of Figures 1 to 3, it may be stated as a general observation that both the efficiency and specific power of a RTG increase with increasing fuel capsule temperatures. At any fuel capsule temperature, however, it is the heat flux that determines the relative degree of efficiency and specific power optimization. Low heat fluxes generally result in high efficiency systems whereas somewhat higher heat fluxes are required for minimum weight systems.

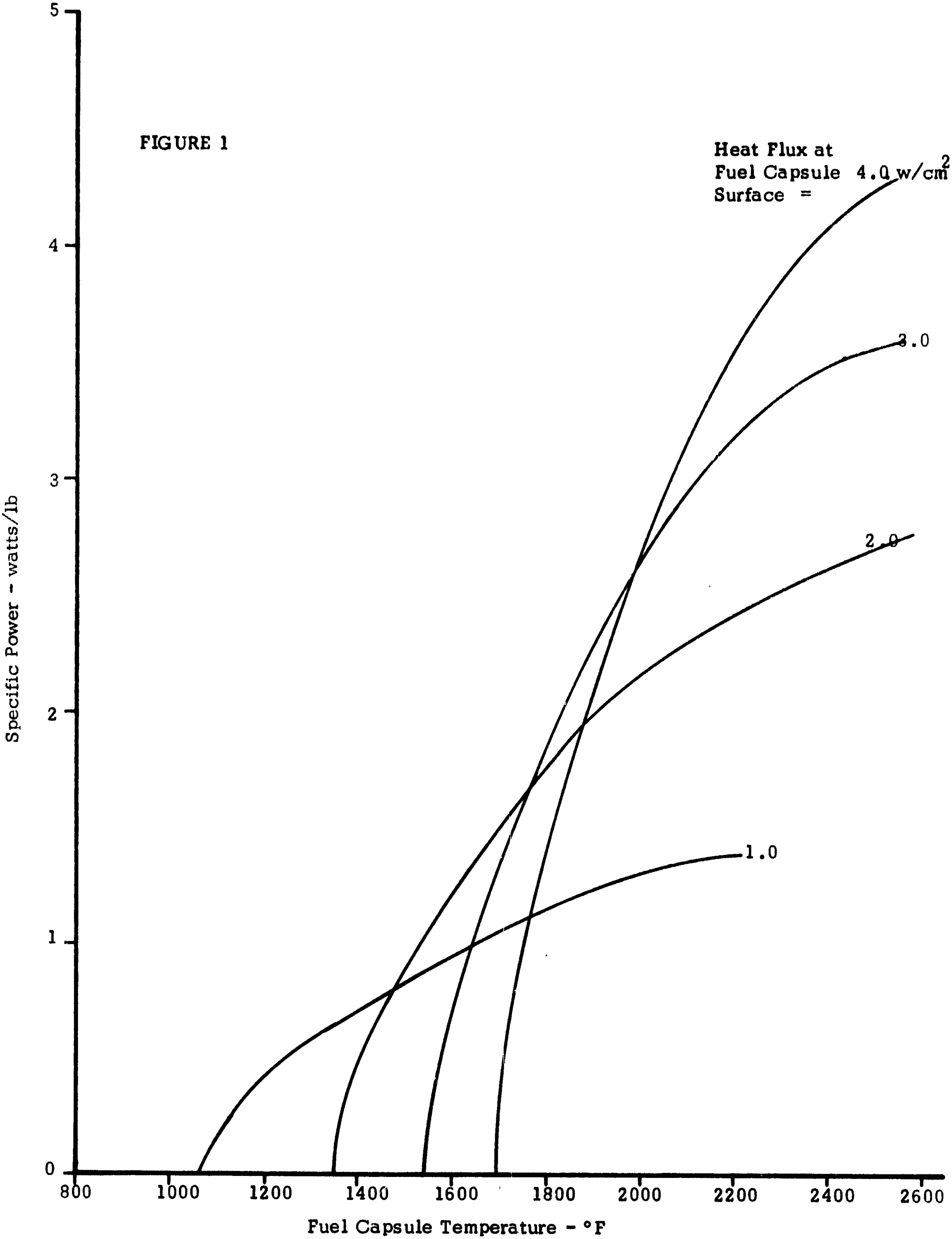
Figures 4 and 5 illustrate the effect of fuel capsule temperature and heat flux on the temperatures of other key components in the RTG. Figure 4 shows outer fuel liner and thermocouple hot shoe temperatures and Figure 5 shows effective radiator temperature. The relatively large temperature drops on the hot side of the RTG, as reflected by Figure 4, are primarily due to a number of interfaces at which heat transfer occurs essentially by radiation. In addition to the radiative interface between thermocouple hot shoes and the graphite re-entry protection shell, it has been assumed that radiative heat transfer also takes place at the graphite-graphite felt as well as graphite felt-fuel capsule interface. A similar assumption has been made for the diffusion and oxidation barrier interface inside the fuel capsule. It should be noted that conductive temperature drops across all solid components in the re-entry protected fuel capsule are negligible in comparison to the various radiative temperature drops. The slight dependence of radiator temperature on fuel capsule temperature (Figure 5) for any given value of heat flux is due to the power output of the RTG. The higher the fuel capsule temperature, the higher the power output and therefore the lower the amount of waste heat that is rejected by the radiator. A lower radiator temperature naturally follows. By the same token, the higher is the heat flux, the greater the amount of rejected heat and therefore the higher the radiator temperature.

Figure 6 shows plots of the ratio of thermoelement length to cross-sectional area for the p-type thermoelements as a function of fuel capsule temperature and heat flux. As stated previously, in all cases it has been assumed that the n-type thermoelements have a cross-sectional area 1.8 times that of the p-type elements. The corresponding plots for the n-type thermoelements would therefore be similar to those in Figure 6, except all ℓ/A values would be reduced by the factor of 1.8. The data in Figure 6 may be used in conjunction with those of Figures 1 to 5 to approximately determine the performance of typical silicon-germanium RTG's as a function of operating time. A fixed value of the ratio of thermoelement length to cross-sectional area defines a fixed RTG configuration and Figure 6 gives the appropriate relationship between heat flux and fuel capsule temperature. Heat flux is directly proportional to fuel inventory in the capsule and therefore with time the heat flux decreases at the decay rate of the fuel inventory. Knowledge of the decay rate of plutonium oxide therefore enables Figure 6 to be used to determine fuel capsule temperatures as a function of time for any desired value of heat flux. This information used in Figures 1 to 5 shows the effect of fuel decay on RTG performance and temperatures. Here it must be borne in mind, however, that such estimated generator performance values implicitly assume fixed values for the thermoelectric properties of silicon-germanium alloys, viz. the 12-year property values used in the present study. Because the figure-of-merit of silicon-germanium alloys slightly decreases with time as a result of dopant precipitation in the n-type alloy, the total performance change of the RTG is really the result of a combination of fuel decay and thermoelectric material property changes. The implicit use of fixed values of thermoelectric properties therefore tends to underestimate the changes that occur in the performance of a silicon-germanium RTG with time. Approximate estimates by the suggested method are nevertheless possible when it is recognized that in the case of silicon-germanium RTG's it is fuel decay that is responsible for the bulk of all performance changes. Depending on precise operating temperatures, it may be estimated that in the first 12 years of operation some 60 to 80 percent of the performance decrease in a typical silicon-germanium RTG is due to fuel decay. After 12 years of operation, it is fuel decay alone that is responsible for practically all of the performance reduction.

SUMMARY

By subjecting a silicon-germanium RTG configuration to detailed performance analyses, it has been possible to establish the effect of fuel capsule temperature and heat flux on typical RTG performance and weight. It has been found that for the most effective utilization of silicon-germanium RTG's, it is important to make use of fuel capsules that, depending on heat flux, are capable of operating at surface temperatures up to 2300° F and higher. It has been shown that at any given fuel capsule temperature, it is the heat flux that determines the relative degree of efficiency or weight (specific power) optimization. Relatively high values of heat flux are required for minimum weight (maximum specific power) systems and conversely, low values of heat flux result in high efficiency systems. It should be emphasized, however, that for all values of heat flux, it is important to operate at as high fuel capsule temperatures as possible.

FIGURE 1



Heat Flux at
Fuel Capsule Surface = 4.0 w/cm²
3.0
2.0
1.0
Specific Power - watts/lb
0
1
2
3
4
5
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
Fuel Capsule Temperature - °F

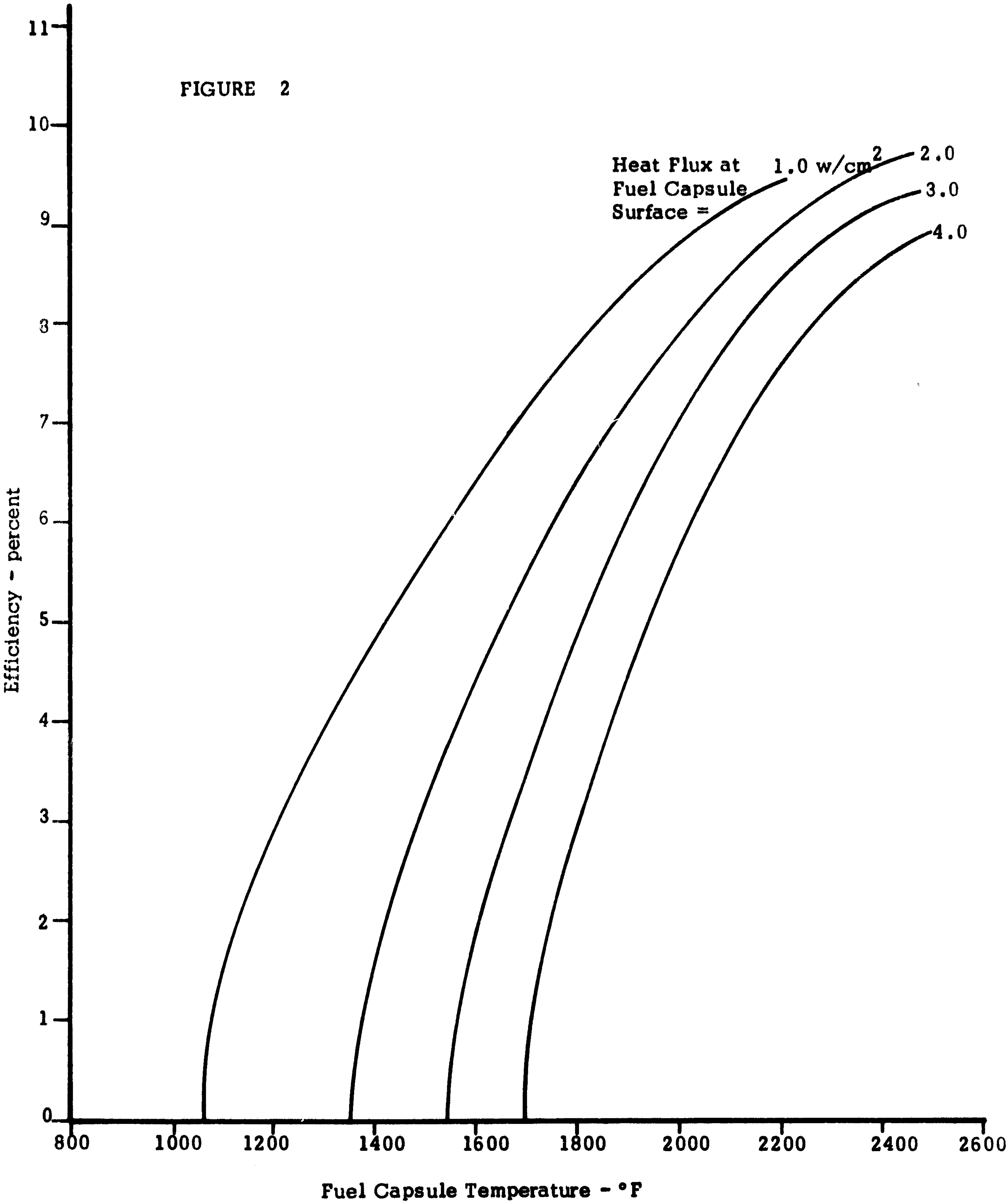


FIGURE 2
Heat Flux at Fuel Capsule Surface =
1.0 w/cm2
2.0
3.0
4.0
Efficiency - percent
0
1
2
3
4
5
6
7
8
9
10
11
Fuel Capsule Temperature - °F
800
1000
1200
1400
1600
1800
2000
2200
2400
2600

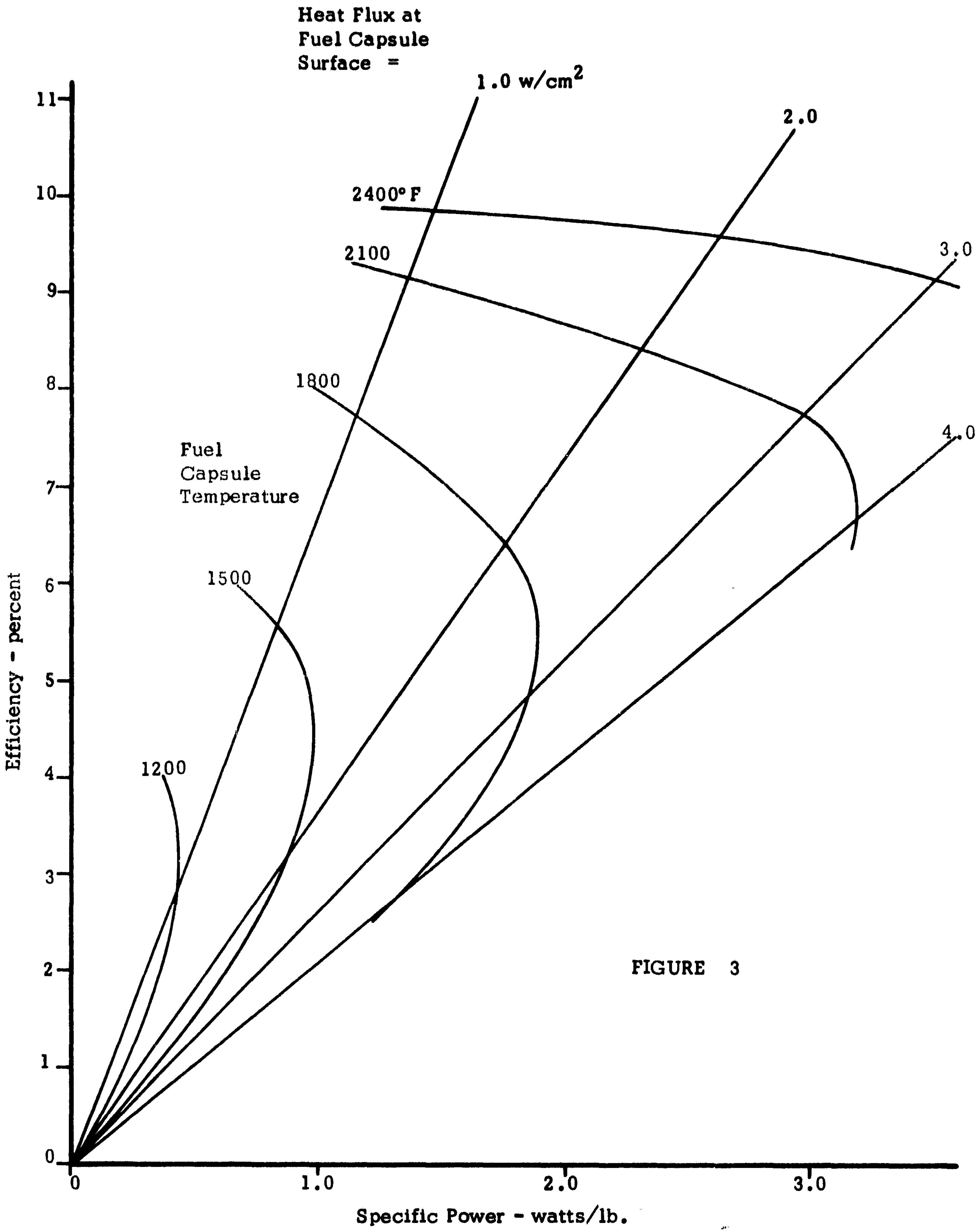
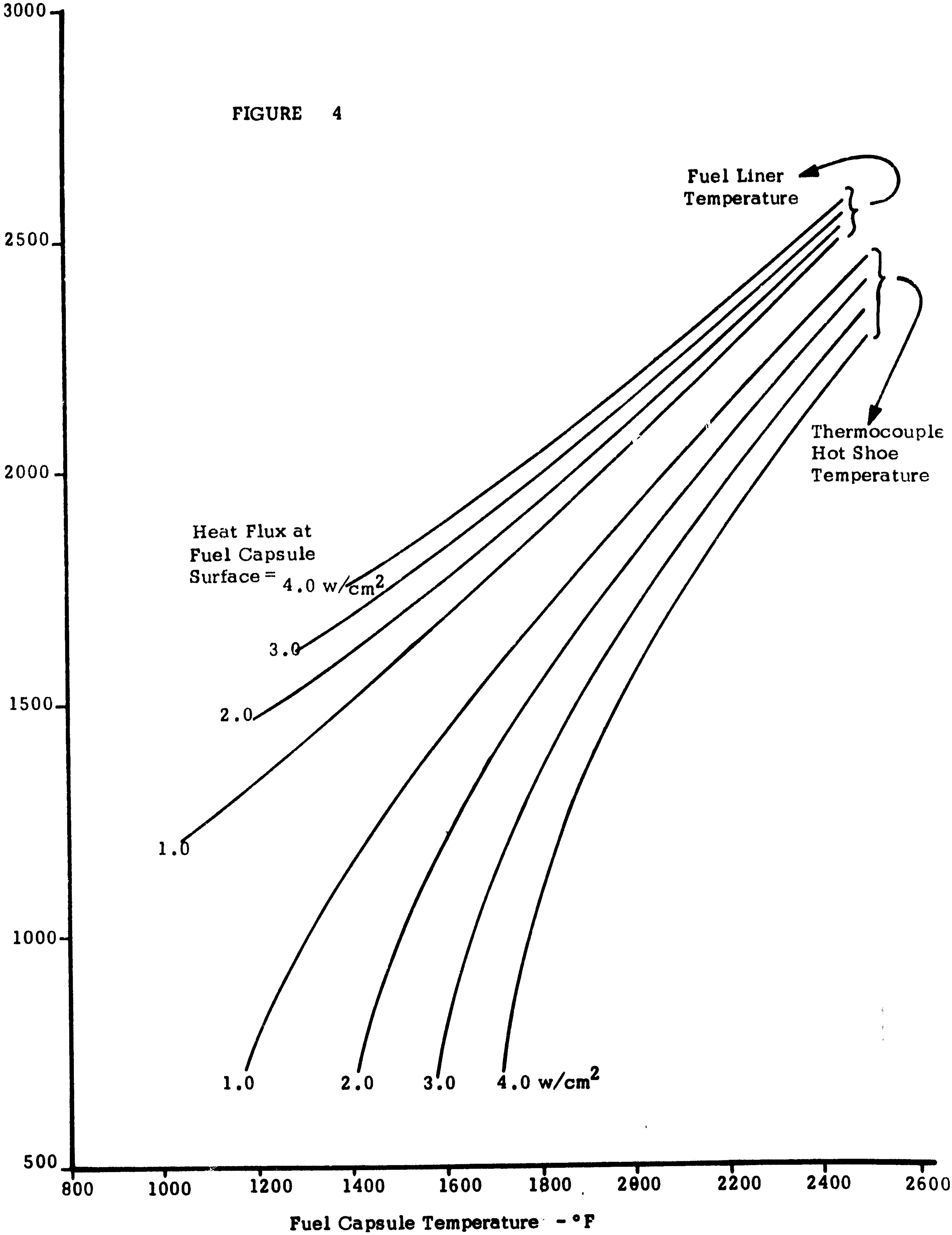

Heat Flux at
Fuel Capsule
Surface =
1.0 w/cm2
2.0
3.0
4.0
2400° F
2100
1800
1500
1200
Fuel
Capsule
Temperature
Efficiency - percent
Specific Power - watts/lb.
0
1
2
3
4
5
6
7
8
9
10
11
1.0
2.0
3.0

FIGURE 3


3000
2500
2000
1500
1000
500
FIGURE 4
Fuel Liner Temperature
Thermocouple Hot Shoe Temperature
Heat Flux at Fuel Capsule Surface = 4.0 w/cm²
3.0
2.0
1.0
1.0
2.0
3.0
4.0 w/cm²
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
Fuel Capsule Temperature - °F

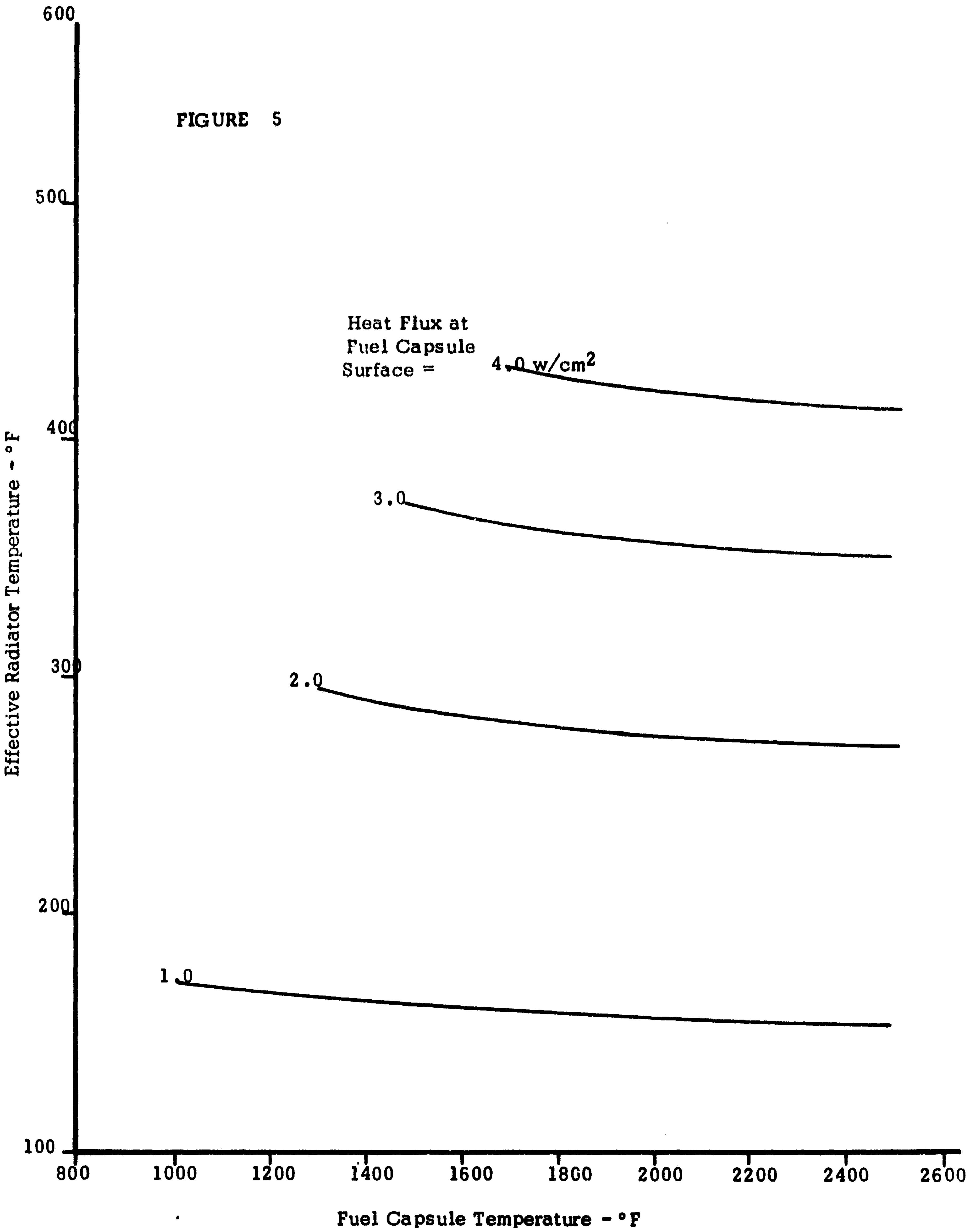


FIGURE 5
Heat Flux at
Fuel Capsule
Surface =
4.0 w/cm2
3.0
2.0
1.0
600
500
400
300
200
100
Effective Radiator Temperature - °F
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
Fuel Capsule Temperature - °F

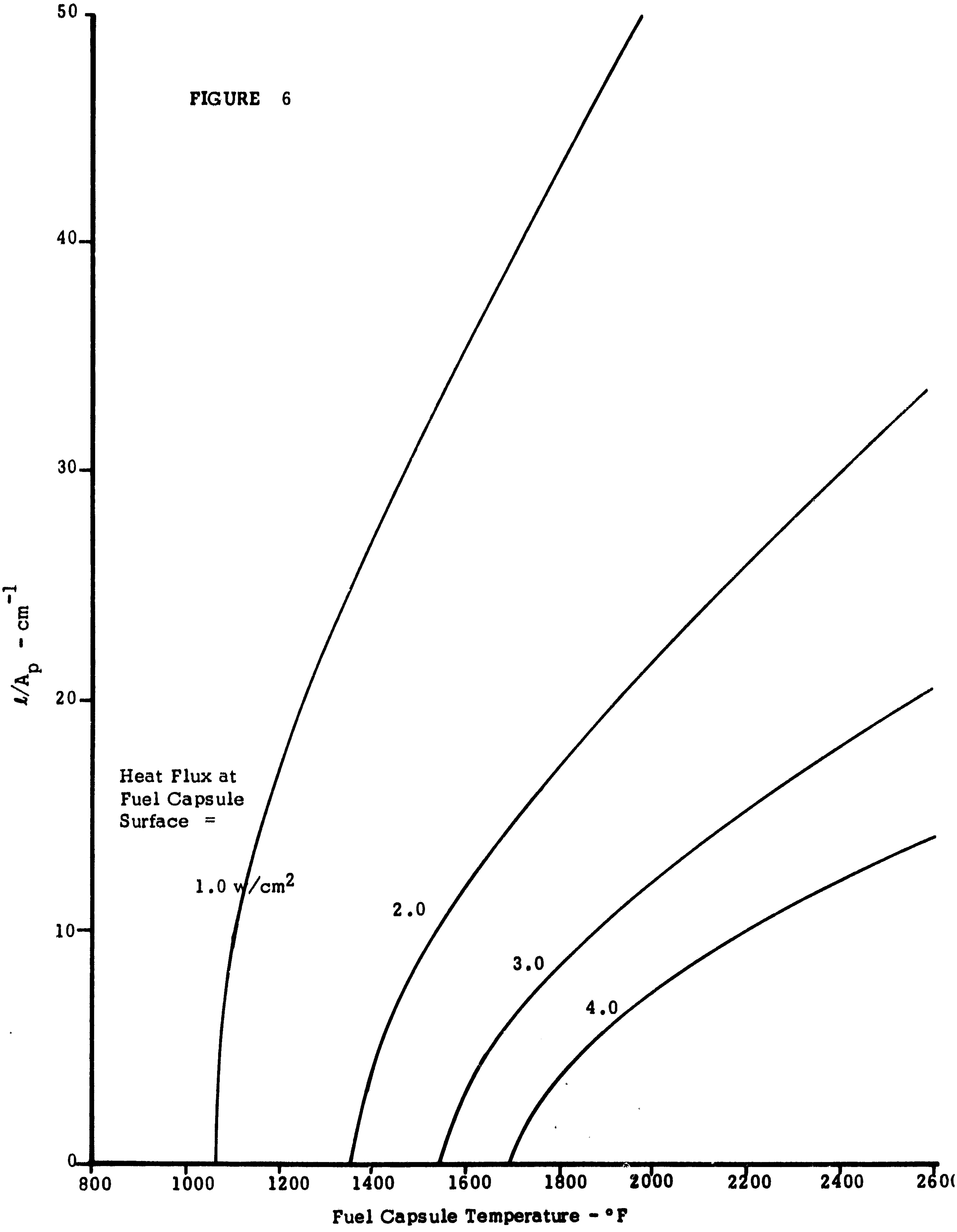


FIGURE 6
Heat Flux at
Fuel Capsule
Surface =
1.0 w/cm2
2.0
3.0
4.0
ℓ/A_p - cm^-1
50
40
30
20
10
0
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
Fuel Capsule Temperature - °F