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PRELIMINARY THERMAL ANALYSIS OF AN AERODYNAMICALLY SHAPED HEAT SOURCE FOR USE WITH THE ISOTOPE BRAYTON SPACE POWER SYSTEM

by Raymond K. Burns
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

ABSTRACT

A two-dimensional thermal analysis was used to demonstrate the thermal advantage of using an isotope heat source (Isoloaf) aerodynamically shaped for predictable orientation during individual heat source atmospheric reentry. One side of the heat source, designed to lead during reentry, is insulated for thermal protection. The opposite side (uninsulated) is used as a heat transfer path during power system operation. This approach is intended to eliminate the conflict between reentry and steady state operation thermal requirements which exist for the present Pioneer-type design being considered for use with the Brayton power system.

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SUMMARY

A two-dimensional thermal analysis was made of an aerodynamically shaped isotope heat source (informally called "Isoloaf") during steady state operation with the Isotope Brayton power system and during individual heat source atmospheric reentry at orbital velocities. The Isoloaf heat source configuration represents a design approach to reduce the conflict between steady state operation and reentry thermal requirements which exist in present designs. This is done by designing the exterior shape of the heat source to provide a predictable orientation during reentry and therefore eliminating the need for including thermal insulation completely surrounding the fuel capsule.

The results are used to show that steady state temperatures of an Isoloaf heat source are significantly lower than for a Pioneer-type heat source when an adequate amount of reentry insulation is included. In an Isoloaf heat source the amount of insulation necessary for reentry can be included without significantly increasing steady state operation temperatures over the uninsulated case. The results indicate that if the heat source remains in the intended orientation throughout the reentry heat pulse, the capsule can be thermally protected by insulation covering only the leading side.

INTRODUCTION

One of the energy sources being considered for a Brayton cycle power system being developed by NASA-Lewis Research Center for generation of auxiliary electrical power in space is radioisotopes (see ref. 1). The isotope fuel is contained within refractory metal capsules which are surrounded by reentry protection materials. Each fueled capsule and its individual reentry protection is referred to as a heat source (HS). For the Brayton application, heat sources are arranged in a close-packed, circular, planar array which together with the support plate form the heat source unit (HSU) (see ref. 2). The HSU radiates thermal energy from one side of the HS array to the heat source heat exchanger (HSHX). The HSHX transfers the energy to the Brayton cycle working fluid heating it to the 1600° F turbine inlet temperature.

The entire HSU is an integral part of a reentry vehicle (HSRV) which is designed to insure safe, intact reentry should atmospheric reentry ever occur. In addition, should an individual HS ever become separated from the HSU and the HSRV its individual reentry materials are intended to provide it with safe reentry capability. Present HS designs (such as a Pioneer-type HS which will be described later) utilize graphitic materials as reentry protection. During individual HS reentry these materials can reach temperatures as high as 5000° F. Since it is required that the present platinum-20% rhodium oxidation resistance clad on the isotope capsule be kept below its melting temperature (~3400° F) during reentry, it is necessary to include an insulating material between the isotope capsule and the graphitic reentry ablative material. In present HS designs, the reentry insulation must completely surround the capsule because of their omnidirectional reentry characteristics. As a result the thermal energy of the capsule is constrained to be transferred through the reentry insulation during power system operation. The thermal results presented in reference 3, however, show that including any insulating layer which surrounds the capsule results in a significant thermal penalty (i.e., a significant temperature increase in the capsule) during steady state power system operation. As shown in reference 3, for the Brayton application, if the thermal conductivity and emissivity of the insulating layer are raised until the steady state temperatures are within desirable limits, the reentry capability is significantly reduced.

The Isoloaf heat source configuration (which will be described in more detail later) represents a design approach which will allow the heat source to meet both steady state and reentry thermal requirements more easily than present heat source designs. The objective of the Isoloaf approach described here is to provide the HS with an aerodynamically stable, preferred orientation during reentry. The insulation layer is then included only on the side of the HS designed to lead during reentry. In steady state power system operation the thermal energy of the capsule is transferred in the opposite direction toward the Brayton heat source heat exchanger. Since it is not necessary to transfer the thermal energy through the insulation material during steady state operation, insulation properties can be determined by the reentry requirements with a minimal effect on steady state thermal conditions.

The purpose of this analysis is to examine the thermal feasibility of the Isoloaf in the Isotope Brayton application. Steady state operation thermal conditions of the Isoloaf are compared to those of a Pioneer-type heat source. The sensitivity of the Isoloaf steady state thermal conditions to the properties of the reentry insulation are examined to show that the amount of insulation necessary for reentry protection can be included without excessively increasing steady state operational temperatures.

Thermal calculations of an Isoloaf during individual HS reentry were made to examine the feasibility of thermally protecting the capsule by including insulation only on the leading side during reentry in the intended HS orientation. For these calculations it was assumed that the Isoloaf remained in the intended stable orientation throughout the reentry heat pulse. The actual dynamic motion and the resultant effect of this motion on the thermal conditions, although a necessary part of a final design analysis, were not included in this preliminary study.

THERMAL ANALYSIS

Isoloaf Description

The Isoloaf configuration considered in this thermal analysis is shown in figure 1a. The exterior of the reentry material is in the shape of a loaf, hence the name Isoloaf. The shape is intended to make the HS stable only in the flat-side-leading, side-on-stable orientation during reentry. Preliminary qualitative analysis at the Ames Research Center indicates that the configuration shown in figure 1a is stable in the intended, flat-side-leading orientation. Slight changes would be necessary to eliminate or minimize the possibility of additional stable trim attitudes.

The Pioneer-type HS presently being evaluated for use with the Brayton power system is shown in figure 1b. Both heat sources in figure 1 consist of a refractory metal capsule which contains the fuel and is surrounded by reentry protection materials. The fuel capsule is cylindrical with hemispherical ends. The capsule structural member is a tantalum alloy (T-111) which is protected by a platinum-20% rhodium oxidation resistance clad. The Pioneer-type HS shown in figure 1b differs from that currently being considered for the Pioneer mission in that the fuel capsule length has been increased from 4.8 to 6.3 inches and the fuel loading decreased from 875 watts to 400 watts. Each of the heat sources in figure 1 utilizes the same fuel capsule.

In both heat sources the exterior reentry protection material is POCO graphite. Carb-I-Tex graphite end plugs are used in both cases. In the case of the Isoloaf, reentry insulation material is included between the capsule and the POCO only on the side of the HS designed to lead during reentry. Because of its omnidirectional reentry characteristic the reentry insulation material completely surrounds the capsule in the Pioneer-type HS. During steady state power system operation the thermal energy of the capsule in the Isoloaf HS is transferred to the HSHX through the POCO (which has a relatively high thermal conductivity) on the side opposite the insulated side. In the Pioneer-type HS the thermal energy of the capsule is transferred through the reentry insulation during power system operation.

Thermal Model

For the purpose of this analysis, a two-dimensional thermal model of the HS was used in both the steady state and reentry calculations. The thermal model, a network of nodes representing one half of a HS, is shown in figure 2. The Isoloaf HS model in figure 2a differs from the Pioneer-type HS model in figure 2b only in dimensions of the POCO graphite nodes and in the extent of the reentry insulation nodes. The insulation nodes extend all around the capsule for the Pioneer-type HS and only around half of the capsule for the Isoloaf HS. The temperature distributions were determined using these models and the CINDA-3G computer code (see ref. 4).

In the steady state analysis the top surfaces of the POCO in the models in figure 2 radiated to the HSHX which was taken to be at 1670° F, the hot spot temperature predicted in reference 2. The radiative exchange factors between the HS and HSHX were calculated using an emissivity of 0.8 for POCO and 0.85 for the HSHX. The presence of the adjacent HS was included in this calculation. All other POCO surfaces were assumed to be adiabatic, a slightly conservative approach.

In the reentry analysis, all external surfaces of the POCO were subjected to a convective heat pulse and all surfaces radiated to space, which was taken as a 0° F sink. The convective heat flux distribution was input using the heating factors in figure 3. These are the ratios of local heating on the Isoloaf in the flat-side leading, side-on orientation to that at the stagnation point of a one-foot radius sphere. Only convective heating in continuum flow was considered and surface recession was neglected. The heating factors were therefore assumed to remain constant throughout the heating pulse.

The thermal properties of the nodes in the region denoted in figure 2 as reentry insulation were varied according to the type of insulation being considered. It was assumed that there is a radiation gap between the POCO and the insulation and between the insulation and the clad. When pyrolytic graphite insulation (PG) was considered, a radiation gap was assumed to exist between the separate layers. The emissivity of the POCO was taken as 0.8 and of the clad as 0.85. During reentry, the presence of a gas such as air or CO in these gaps, or the presence of partial contact between the surfaces, would increase the capsule temperatures. These effects were not considered.

As explained in reference 3, in order that the two-dimensional model simulates the actual three-dimensional heat source, an effective power density must be used for the fuel in the thermal model. This effective power density is a function of three-dimensional effects. Estimates of this quantity were made in reference 3 for a Pioneer-type HS as a function of capsule length. Subsequent to reference 3, a three-dimensional analysis has been performed for a Pioneer-type design. It indicated that the correct value of effective power density which should be used in a two-dimensional model varies somewhat depending on the exact design but the estimates in reference 3 are in the correct range. Based on preliminary results of a three-dimensional thermal analysis, a value of 20 W/in^3 for the effective fuel power density was selected for use in this analysis. It was held constant for all cases considered.

RESULTS AND DISCUSSION

Steady State Operating Conditions

Steady state operating temperatures for the Isoloaf are given in figures 4 through 11 as a function of the fuel effective power density. As explained previously, a value of 20 W/in^3 is estimated as the value to use for the present case. In figures 4 through 9 the reentry insulation properties are varied parametrically. In each case the insulation is taken as a 200 mil thick layer which surrounds the bottom half of the capsule. Insulation thermal conductivities of 1.0, 5.0, and 20.0 BTU/hr-ft-^{o}F and insulation surface emissivities of 0.5 and 0.8 are considered. In figures 10 and 11, the insulation is taken as three separate layers of pyrolytic graphite (PG) with a total thickness of 200 mils. Two values of emissivity, 0.5 and 0.8, are considered for the pyrolytic graphite.

Two sets of curves are given in each of figures 4 through 11. One gives the key hot spot temperatures in the HS and the other gives the temperatures radially through the reentry materials at the top of the HS. Comparison of these figures with the similar figures for a Pioneer-type HS given in reference 3 shows the thermal advantage of the Isoloaf configuration (the hot spot temperatures in figures 4a through 11a will later be compared to the hot spot temperatures for a Pioneer-type HS). The radial temperature profiles at the top of the Isoloaf HS in figures 4b through 11b show the thermal penalty of the reentry material at the top of the HS. Unlike the Pioneer-type HS, the thermal energy in the Isoloaf is not constrained to transfer through insulation, eliminating a significant thermal resistance at the HS top. However, the POCO thickness at the top of the Isoloaf is greater than at the top of a Pioneer-type HS. Since the thermal conductivity of POCO is relatively high, this additional thickness does not result in a large thermal penalty. Figures 4b through 11b show that in all cases considered the temperature rise across the radiation gap is greater than that through the POCO. Also, for the power densities of interest, the temperature gradient radially through the POCO is less than 50^{o} F.

In figure 12 the T-111 (capsule strength member) hot spot temperatures for both the Pioneer-type design and the Isoloaf are compared. As shown, the only cases considered which yield temperatures lower than the Isoloaf are those for which the reentry protection material is taken to be all POCO with no insulation. The Pioneer-type HS shows a marked sensitivity in steady state operating temperature to changes in properties of the insulation layer. However, since the insulation extends only around the bottom of the capsule, the Isoloaf T-111 hot spot temperature is relatively insensitive to the properties of the insulation. This is the objective of the Isoloaf approach.

Although some thermal penalty is incurred by including the layer of insulation around the bottom of the capsule (as indicated by comparison of the Isoloaf results to the results for the all POCO case in figure 12), the penalty is not significantly increased when the amount of insulation is increased. It is therefore possible to include the amount of insulation necessary to meet reentry requirements without reaching the excessively high temperatures predicted for the same amount of insulation in a Pioneer-type HS. For example, in the Pioneer application the reentry insulation currently being considered is three layers of PG with a total thickness of 200 mils. However, in the Brayton application, figure 12 with an estimated effective power density of 20 W/in^3 for a 6.3-inch long capsule shows that this amount of insulation on a Pioneer-type HS would result in steady state temperatures exceeding the 2200° F upper limit assumed in reference 3 for the strength member. For this case, use of the Isoloaf approach would reduce the steady state T-111 hot spot temperature by 300° F for PG emissivity of 0.5 and by 175° F for PG emissivity of 0.8.

In figures 13 and 14, the T-111 temperatures at the top and at the bottom of the capsule are shown as a function of the reentry insulation thermal conductivity for the Isoloaf and for a Pioneer-type HS. The reentry insulation material emissivity is taken as 0.8 in figure 13 and 0.5 in figure 14. These figures illustrate several points in the comparison of the Isoloaf and Pioneer-type HS. As shown, when the thermal conductivity of the insulation is decreased, for better reentry thermal protection, the steady state temperatures of the Pioneer-type design increase at an increasing rate. However, the steady state Isoloaf temperatures change slowly with changes in insulation conductivity. Also shown in these figures is that the circumferential temperature gradient and, therefore, heat transfer in the T-111 is greater for the Isoloaf than for the Pioneer type HS. This together with the fact that the T-111 hot spot temperature in the Isoloaf is insensitive to the insulation properties indicates that in the Isoloaf a high percentage of the thermal energy is transferred circumferentially within the capsule and then from the top half of the capsule to the POCO, bypassing the insulation.

Individual HS Reentry Conditions

A thermal analysis of an individual Isoloaf HS reentering the atmosphere at orbital velocity was performed in order to examine the thermal feasibility of such a design approach. For this purpose it was assumed that the Isoloaf remained oriented in the flat-side leading, side-on stable position throughout the trajectory. Initial reentry angles of -0.5° (representative of long, shallow trajectories) and -2.15° (representative of shorter trajectories which result in higher POCO surface temperatures and could result from launch abort) were chosen. The convective heat pulse was input using the heating factors given in figure 3 which are expressed in terms of the heat flux to the stagnation point of a one-foot radius sphere. For the two trajectories considered here, the pulse to a one-foot sphere is given in figure 15. The effects of ablation or POCO surface changes on input heat pulse, on heating factors, on the Isoloaf orientation, or on Isoloaf thermal response are not included here. These factors would have to be considered in a more complete analysis but for the present purpose were not included.

In figures 16 and 17 the temperatures of the reentry materials on the leading side and of the capsule clad on the leading and trailing sides are given for the two trajectories considered. The reentry insulation was taken as three layers of PG of total thickness of 200 mils, the insulation currently being considered for the Pioneer application. The PG emissivity was taken as 0.8. It was shown in figure 12 that this amount of insulation in the Isoloaf HS yields steady state operation temperatures within the acceptable limits assumed in reference 3. Figures 16 and 17 show that the peak clad temperatures are also acceptable, being well below the clad melting temperature ($\sim 3400^{\circ}$ F). The temperature gradients through the POCO and PG layers and across the radiation gaps, which are assumed to exist between each, show the contribution of each to the thermal protection of the capsule on the leading side. These figures also show that the clad temperatures on the trailing side remain relatively low, demonstrating that the circumferential heat transfer through the POCO, bypassing the insulation, to the trailing side is not sufficient to cause a temperature problem.

Should the HS not stabilize, but spin or tumble throughout the heat pulse, the peak temperatures would be lower than those predicted for the cases considered here. This is indicated, for example, by the results given in reference 3 for a Pioneer-type HS.

CONCLUDING REMARKS

A two-dimensional thermal analysis of an Isoloaf HS during steady state operation in the Brayton application and during individual HS atmospheric reentry at orbital velocities was made. The purpose was to examine the thermal feasibility of the Isoloaf approach and determine the thermal advantages over a Pioneer-type HS during power system operation.

The results presented show:

(1) Steady state operating temperatures for an Isoloaf HS are significantly lower than for a Pioneer-type HS with the same amount of reentry insulation. For reentry insulation consisting of three layers of PG with a total thickness of 200 mils and an emissivity of 0.8, the Isoloaf steady state T-111 hot spot temperature is predicted to be 175° F lower than for a Pioneer-type HS. If the emissivity of PG is 0.5 the Isoloaf temperatures are predicted to be 300° F lower than for the Pioneer type.

(2) Steady state operation capsule (T-111) temperatures for an Isoloaf HS are insensitive to reentry insulation thermal properties indicating that such an approach largely uncouples reentry and steady state thermal requirements. Insulation properties can be specified to satisfy reentry requirements without significantly affecting steady state thermal conditions. The Isoloaf approach significantly reduces the conflict between reentry and operational thermal requirements shown in reference 3 to exist for Pioneer-type designs.

(3) The temperature gradient through the POCO at the top of an Isoloaf HS during steady state operation is less than 50° F for power densities of interest.

(4) The individual HS reentry cases considered indicate that if a HS such as an Isoloaf remains in the predicted side-on stable orientation throughout the heat pulse the capsule can be more than adequately thermally protected by insulation covering only the leading side. Further analysis is necessary to determine the actual dynamic motion of such a HS during reentry and the resultant effect on HS thermal conditions.

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4. Lewis, D. R.; Gaski, J. D.; and Thompson, L. R.: Chrysler Improved Numerical Differencing Analyzer for 3rd Generation Computers. Rep. TN-AP-67-287, Chrysler Corp. (NASA CR-99595), October 20, 1967.

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APPENDIX

Nomenclature

HS	Heat source: metallic capsule containing isotope fuel surrounded by individual reentry protection material.
HSU	Heat source unit: planar array of heat sources and its supporting structure for use as Brayton engine energy source.
HSHX	Heat source heat exchanger.
HSRV	Heat source reentry vehicle: reentry protection for the heat source unit.
k	Thermal conductivity.
POCO	POCO graphite reentry protection material of a heat source (manufactured by POCO Graphite Inc.).
PG	Pyrolytic graphite (reentry insulation material).
T-111	Tantalum alloy strength member of a capsule.
V_E	Initial reentry velocity.
α_E	Initial reentry angle.
ϵ	Emissivity.
Thermal Switch	A material with a thermal conductivity which switches from a relatively high value at operational temperatures to a lower value during reentry. (See ref. 5)

Subscripts

RE INS	Refers to reentry insulation material.

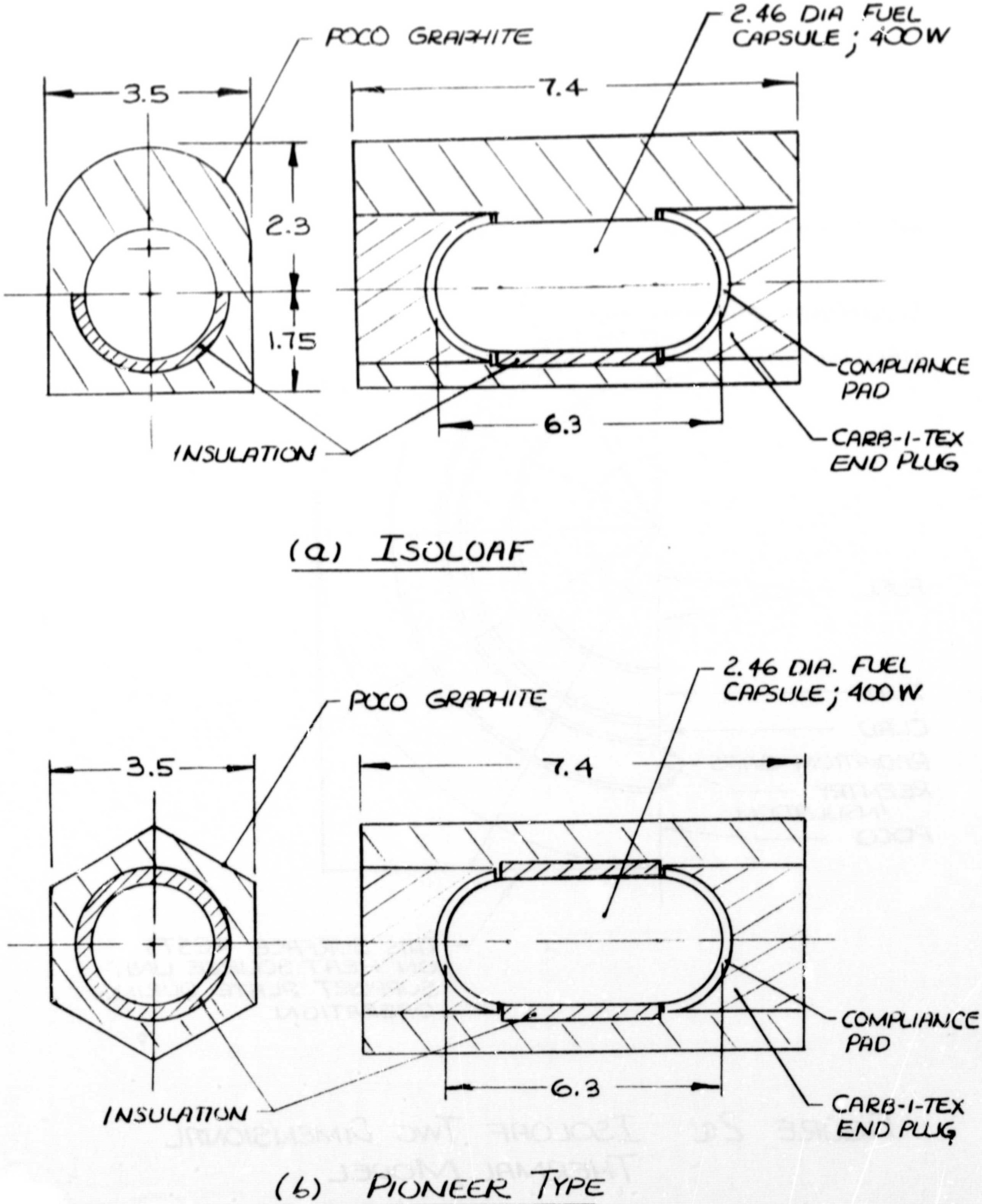


FIGURE 1 SKETCH OF HEAT SOURCES

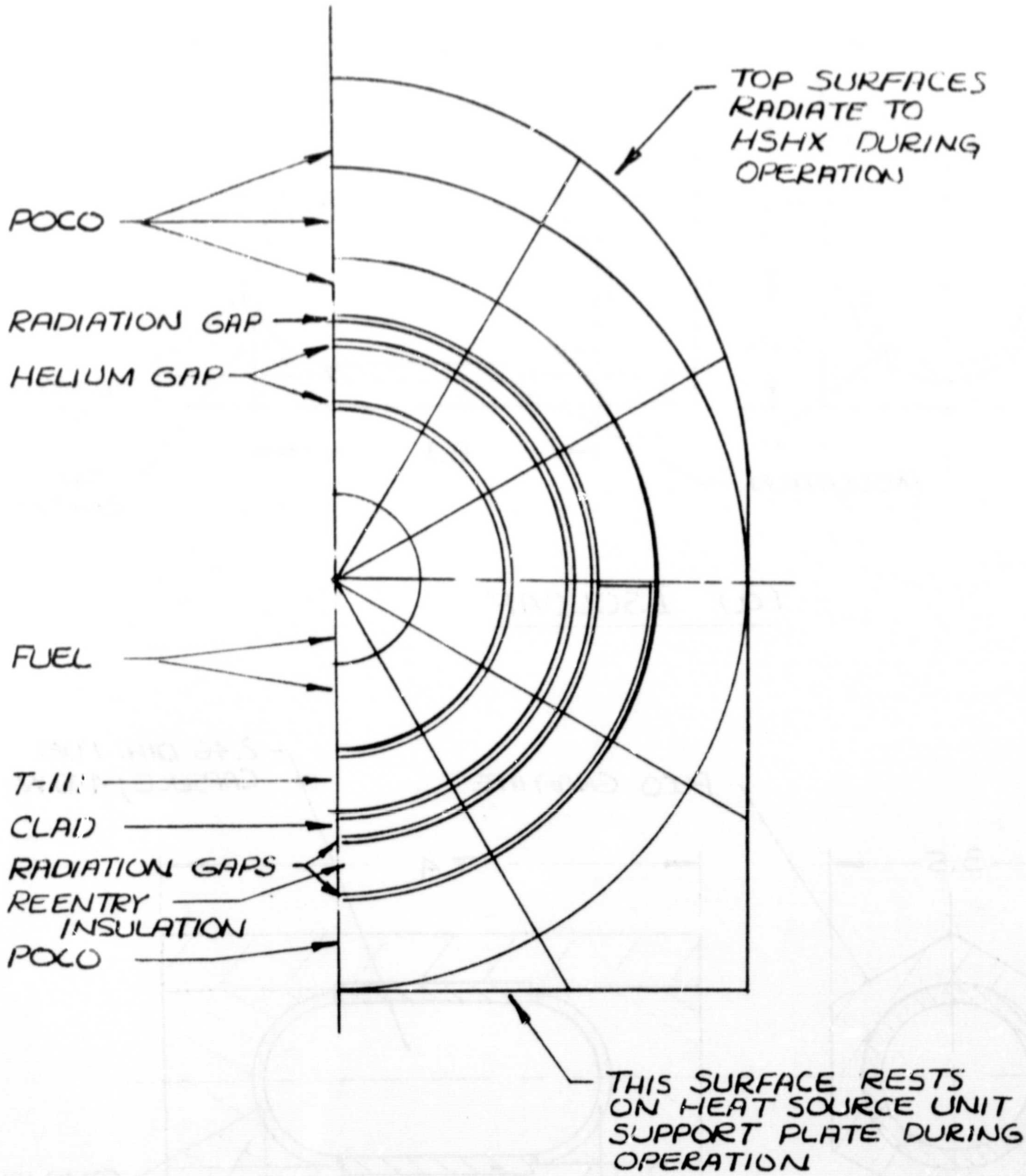


FIGURE 2a ISOLOAF TWO DIMENSIONAL THERMAL MODEL

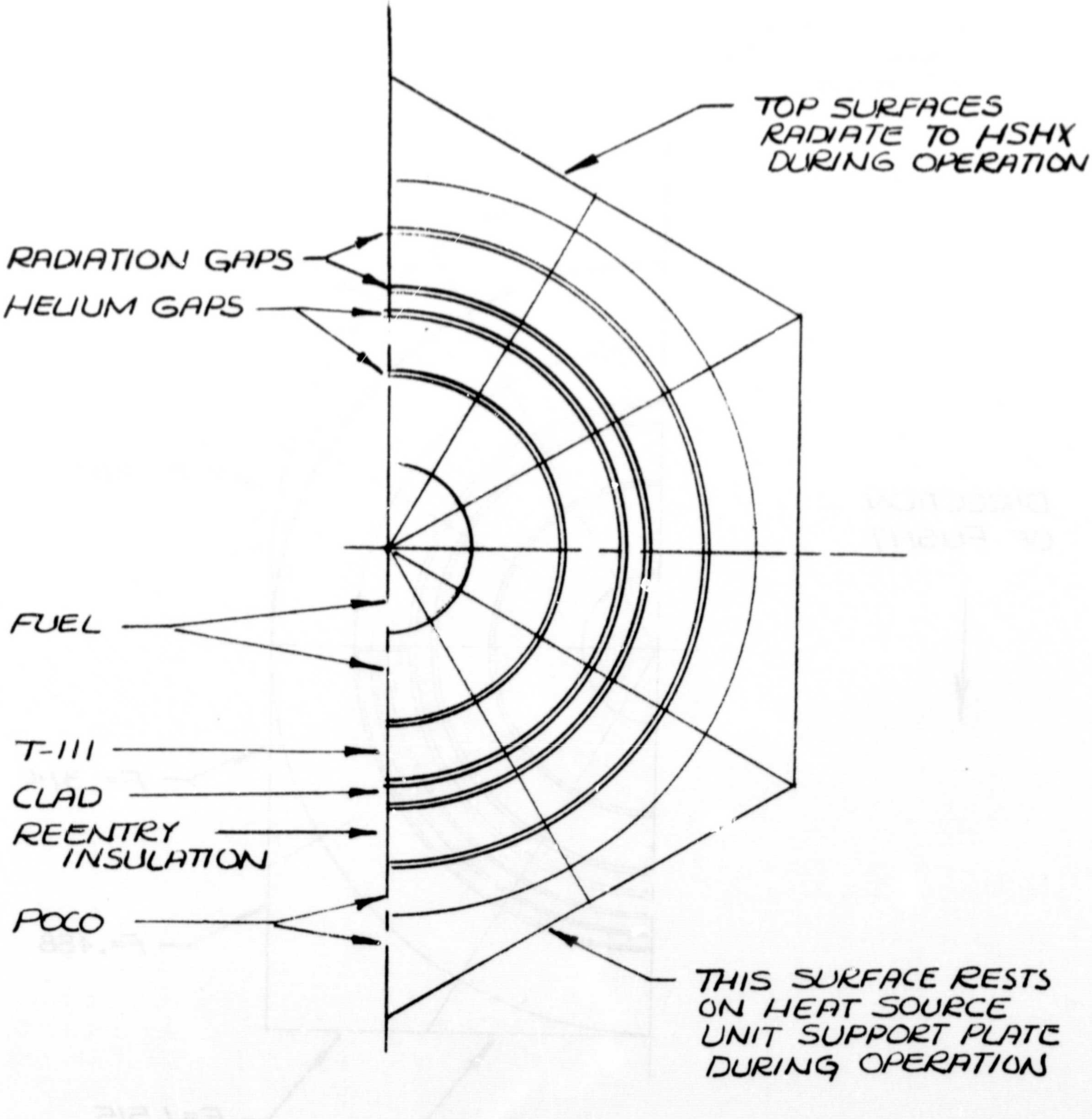


FIGURE 2b PIONEER TYPE HS
TWO DIMENSIONAL THERMAL
MODEL

$$F \equiv \frac{\text{LOCAL HEAT FLUX}}{\text{HEAT FLUX TO STAGNATION POINT 1 FT SPHERE}}$$

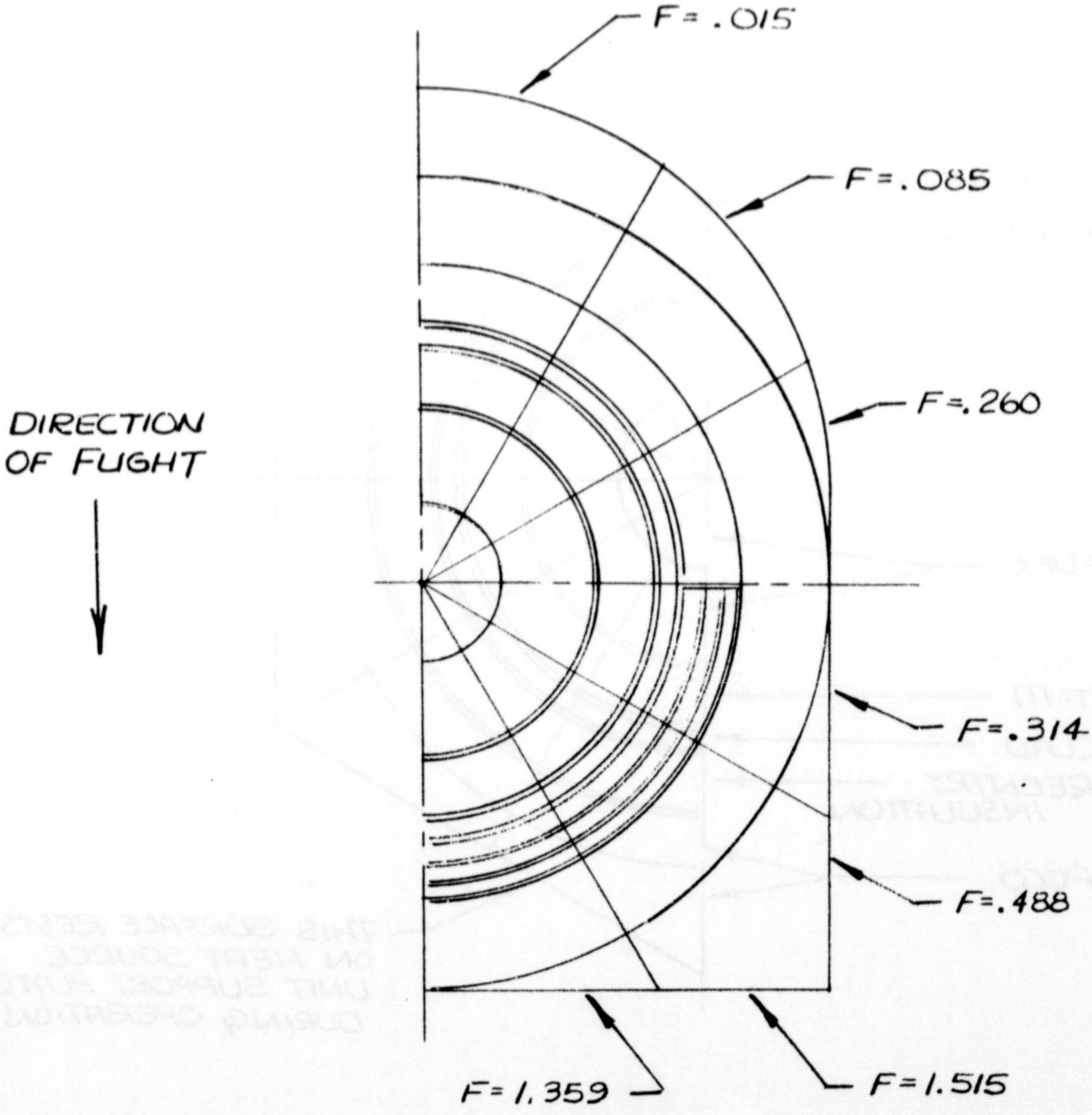


FIGURE 3 CONVECTIVE HEATING FACTORS

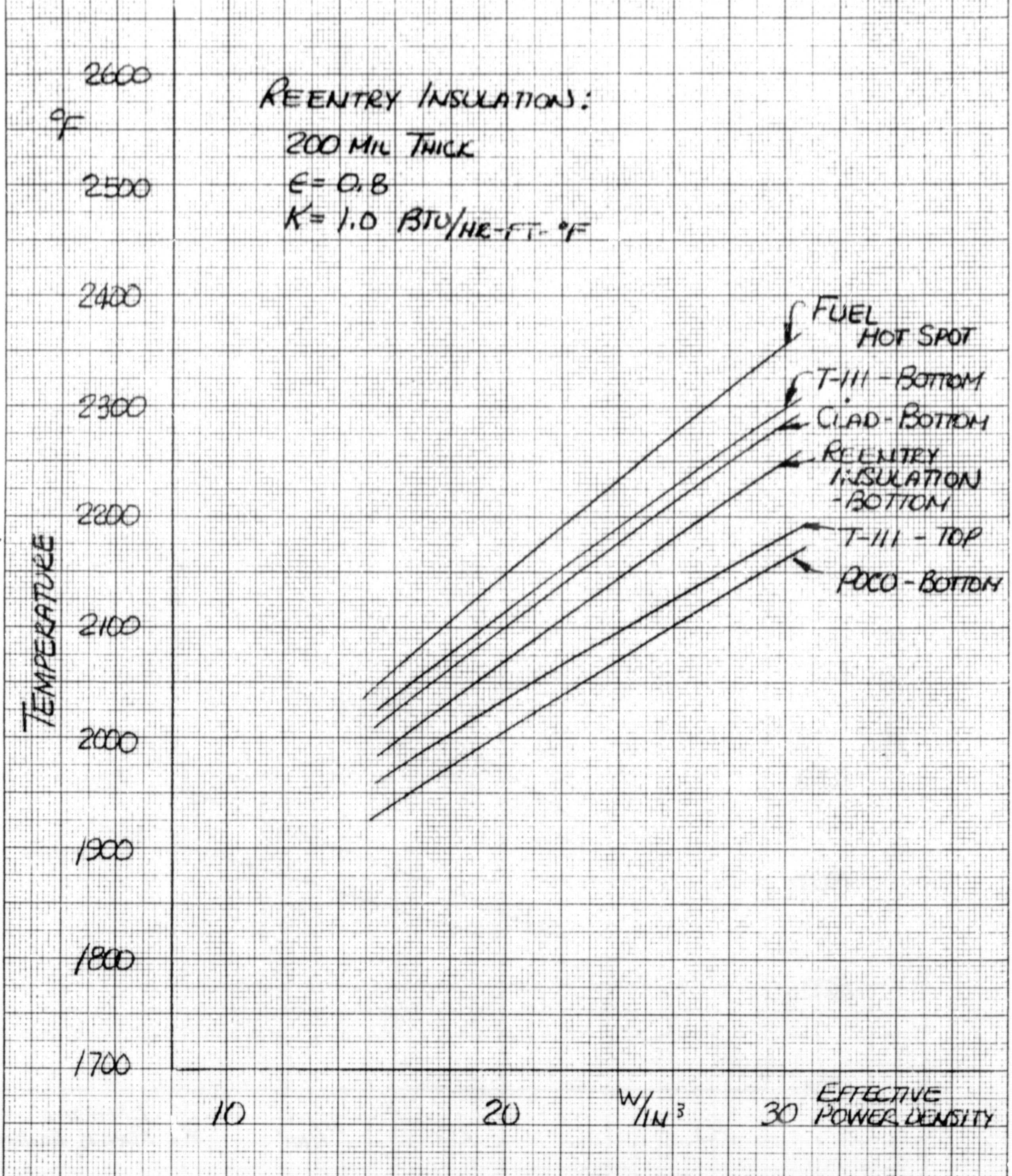


FIGURE 4a ISOLOAF HS HOT SPOT TEMPERATURES; $T_{SINK} = 1670°F$

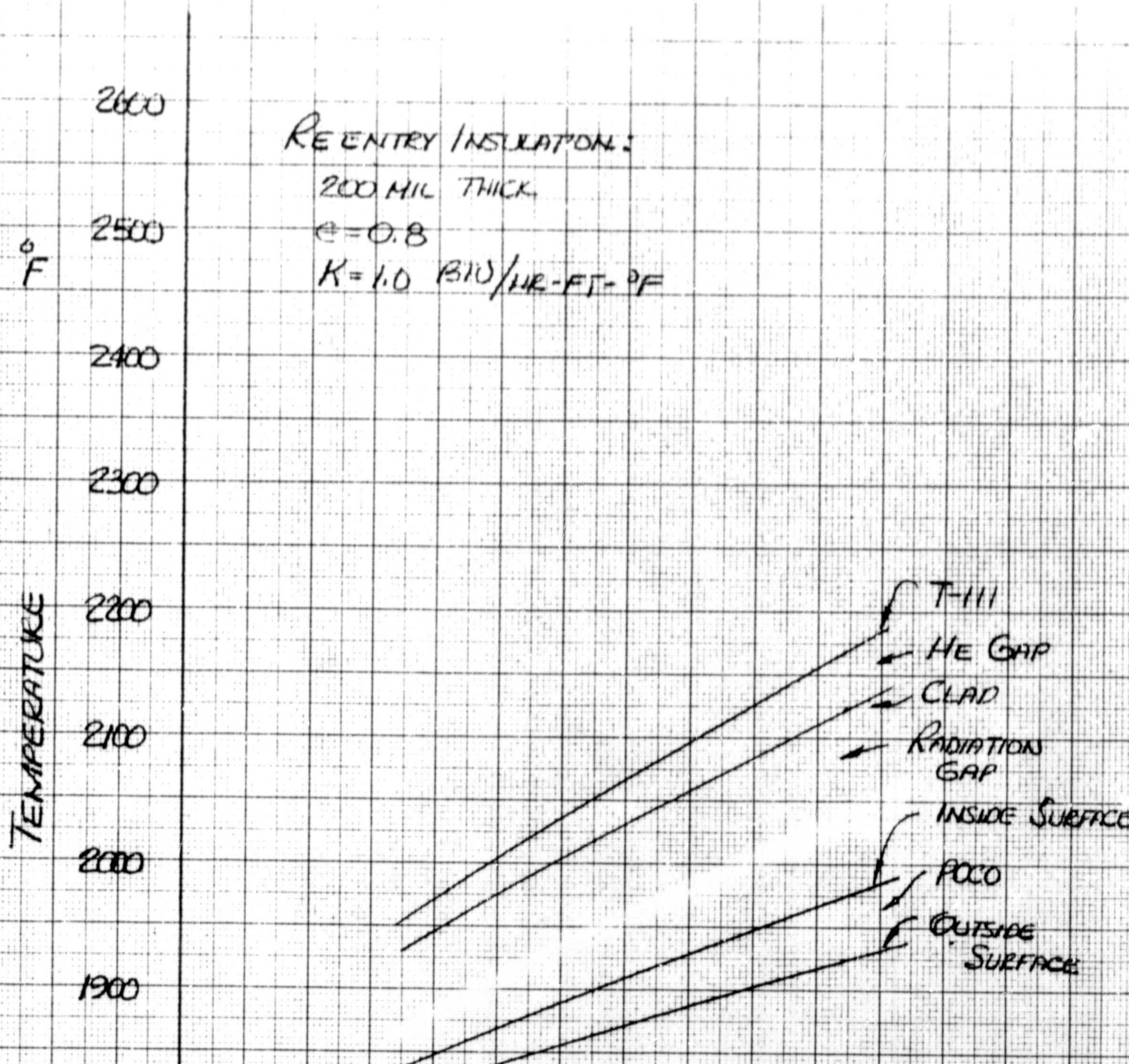


FIGURE 4 b TEMPERATURES AT TOP OF ISOLOAF HS ; T_{SINK} = 1670 °F

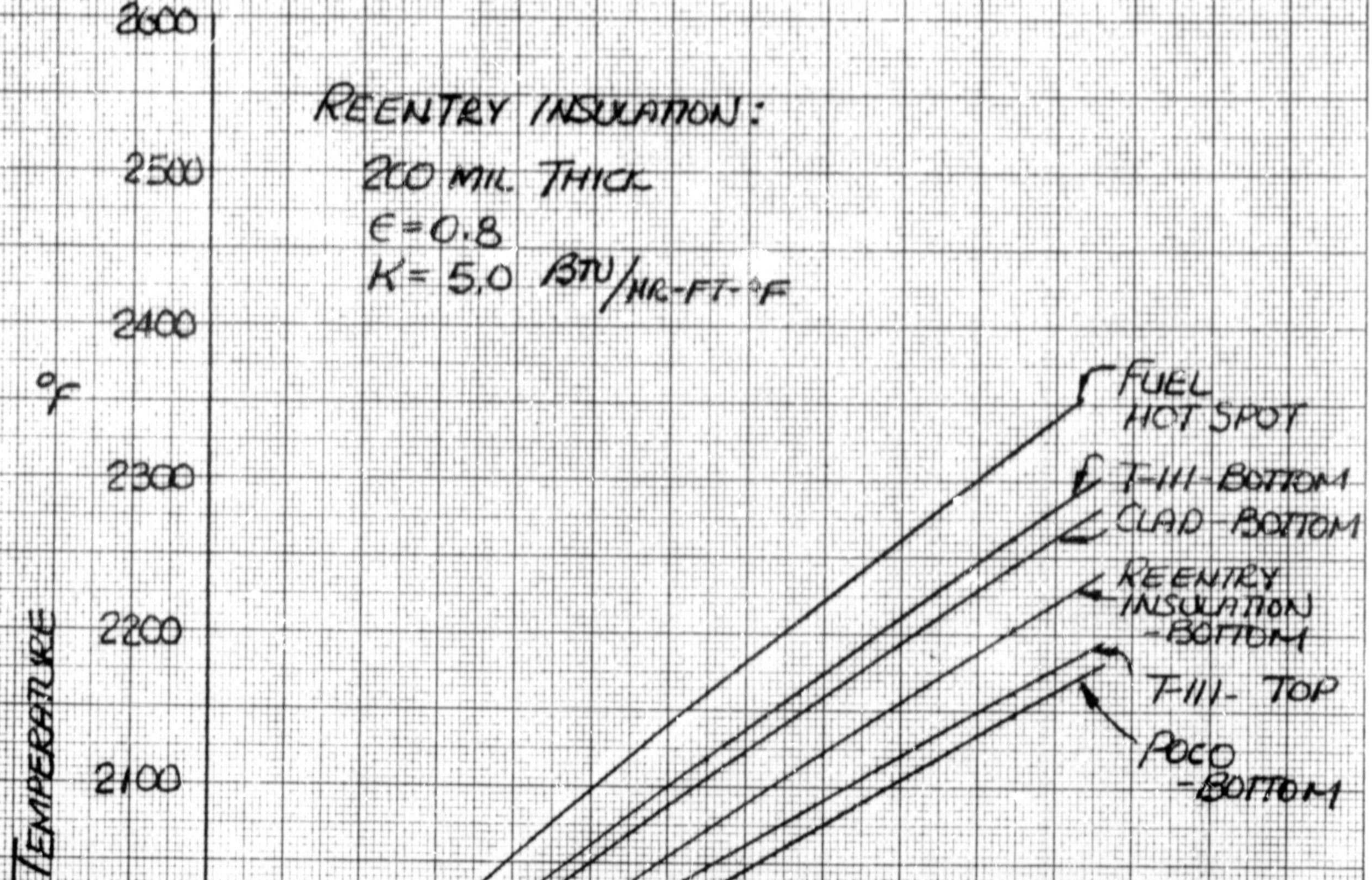


FIGURE 5a ISOLOAF HS HOT SPOT TEMPERATURES; T_{SINK} = 1670°F

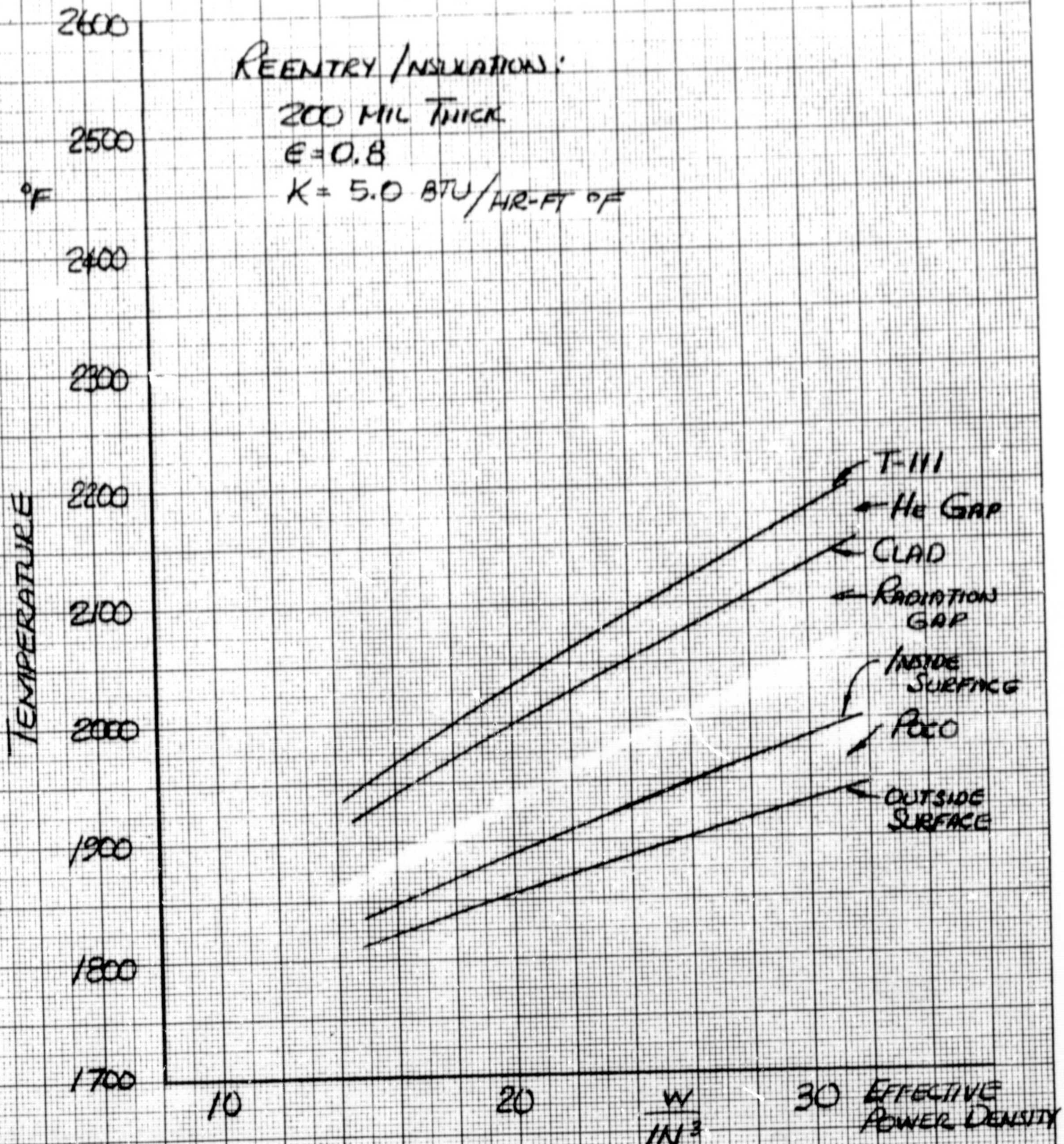


FIGURE 5b TEMPERATURES AT TOP OF ISOLOAF HS; T_{SINK} = 1670°F

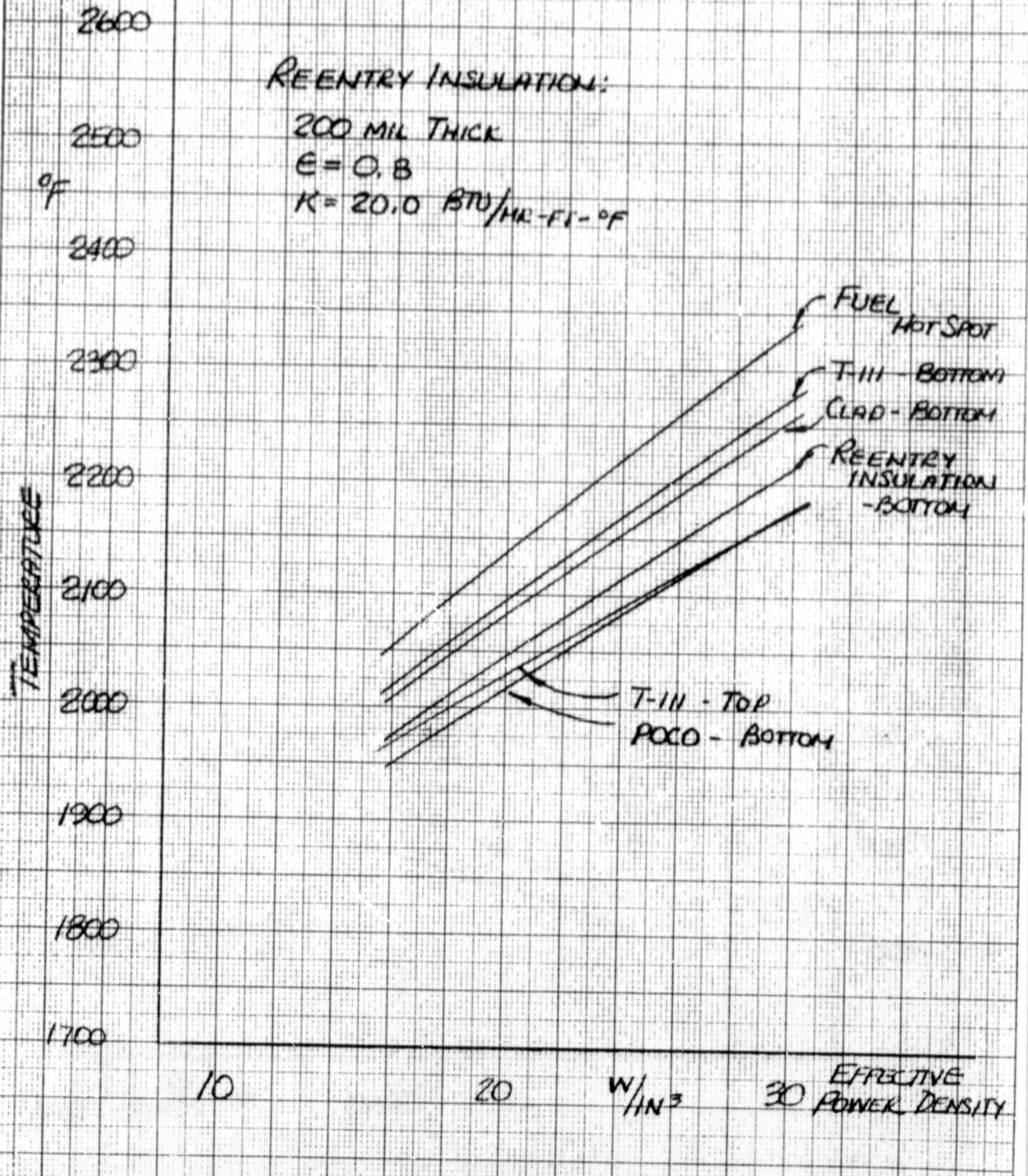


FIGURE 6a ISOLCAF HS HOT SPOT TEMPERATURES; T_{SINK} = 1670°F

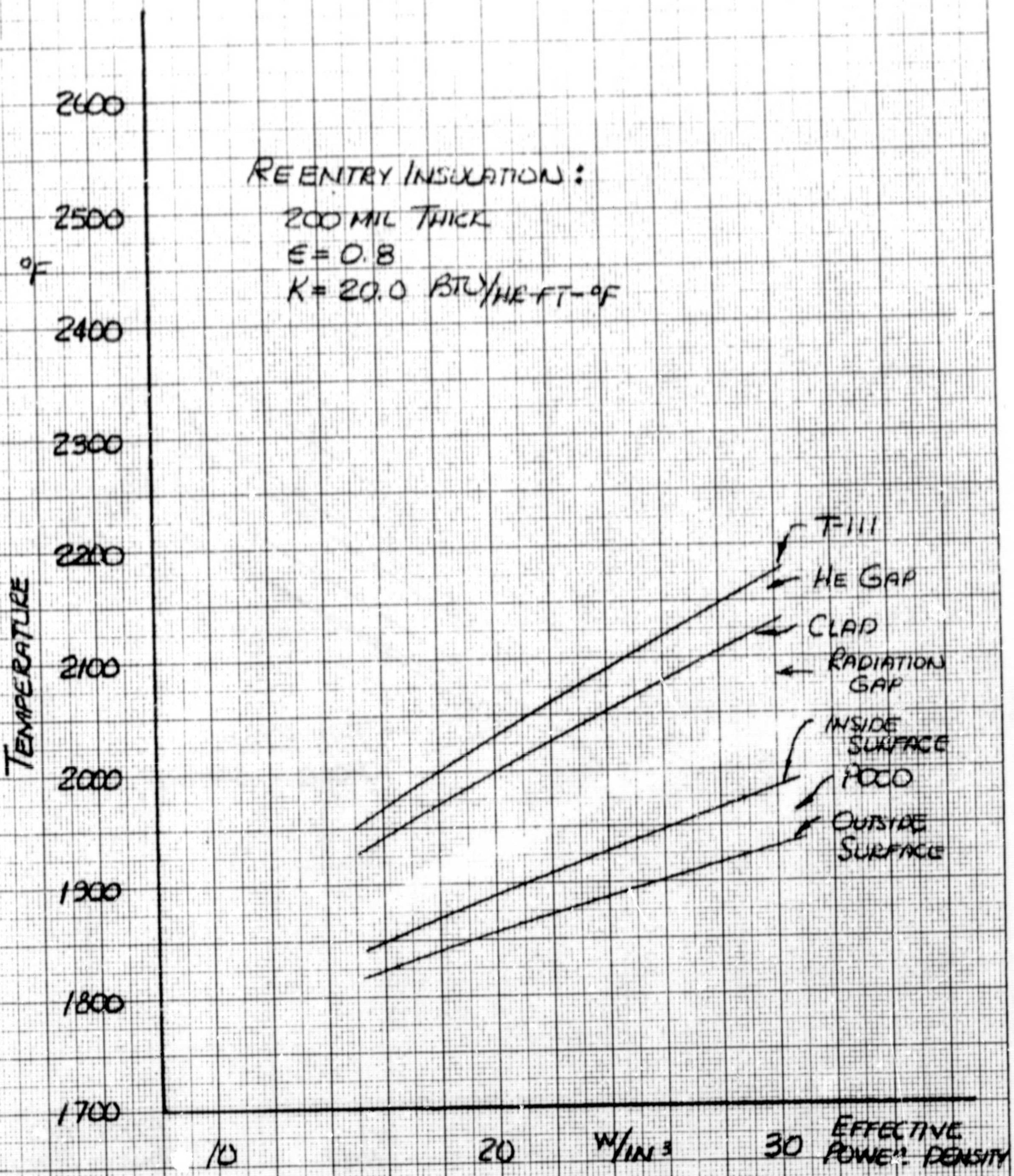


FIGURE 6b TEMPERATURES AT TOP OF ISOLOAF HS; T_{SINK} = 1670°F

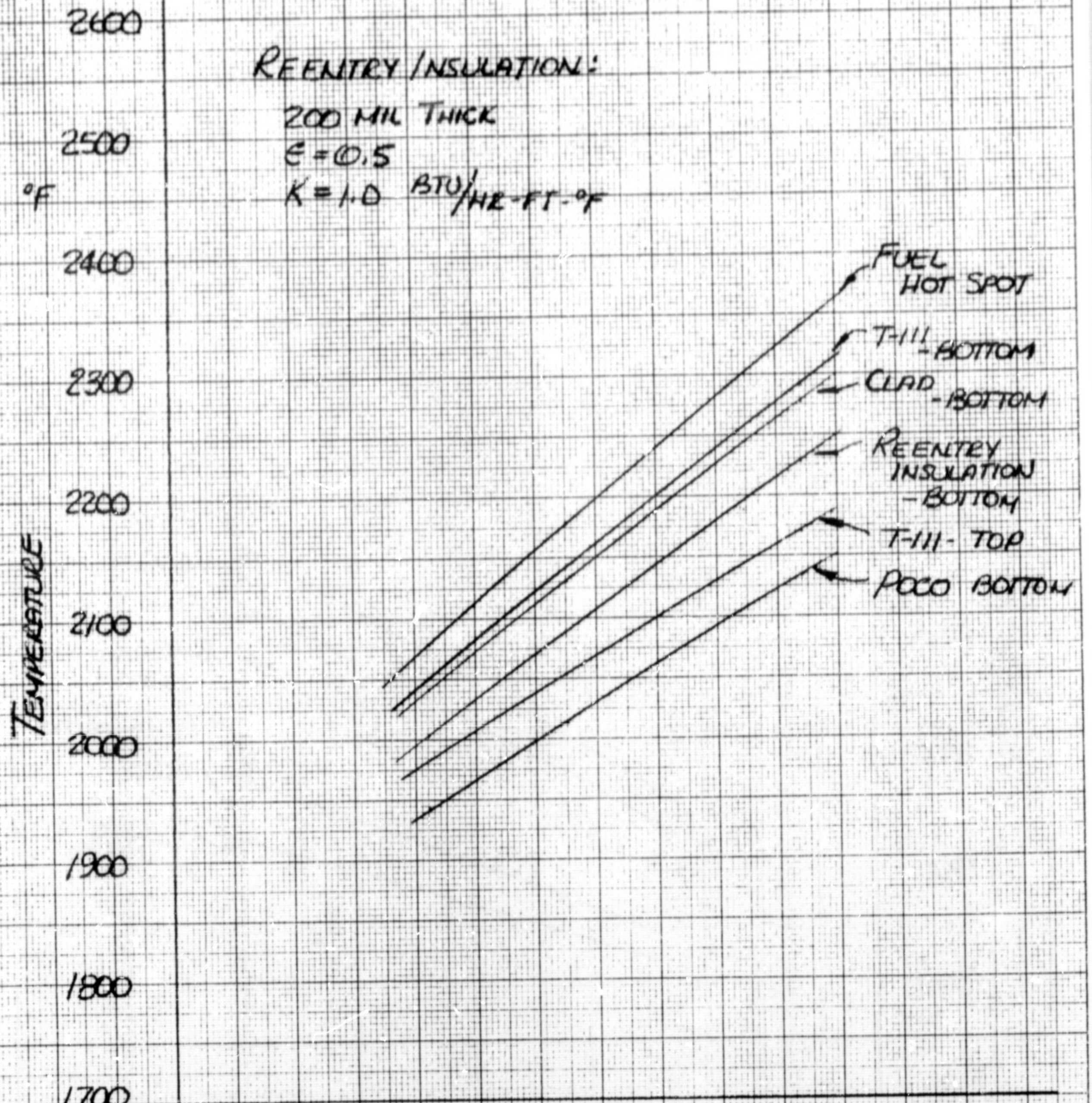


FIGURE 7a ISOLOAF HS HOT SPOT TEMPERATURES; T_{SINK} = 1670°F

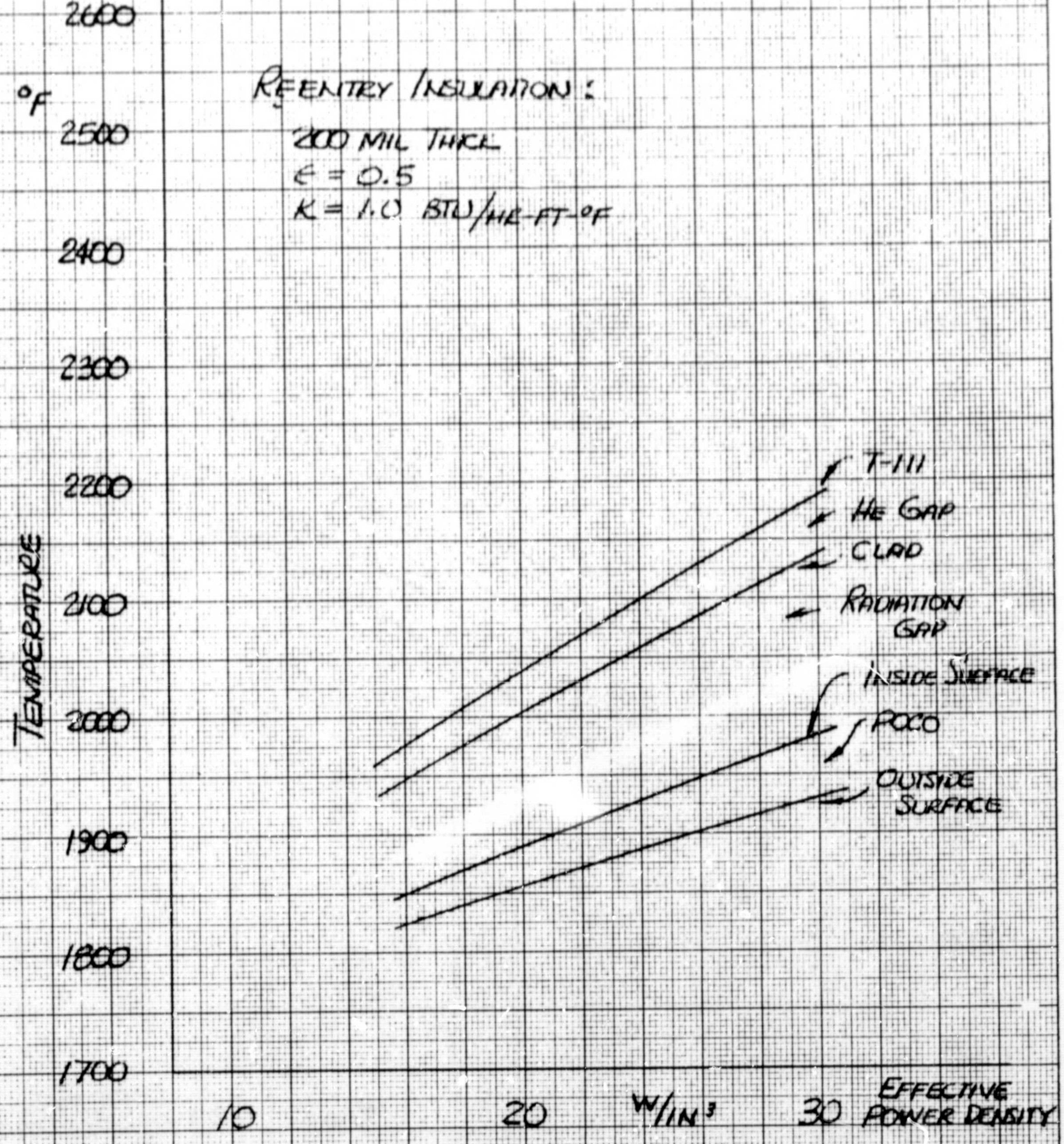


FIGURE 7b TEMPERATURES AT TOP OF ISOLOAF HS; T_{SINK} = 1670°F

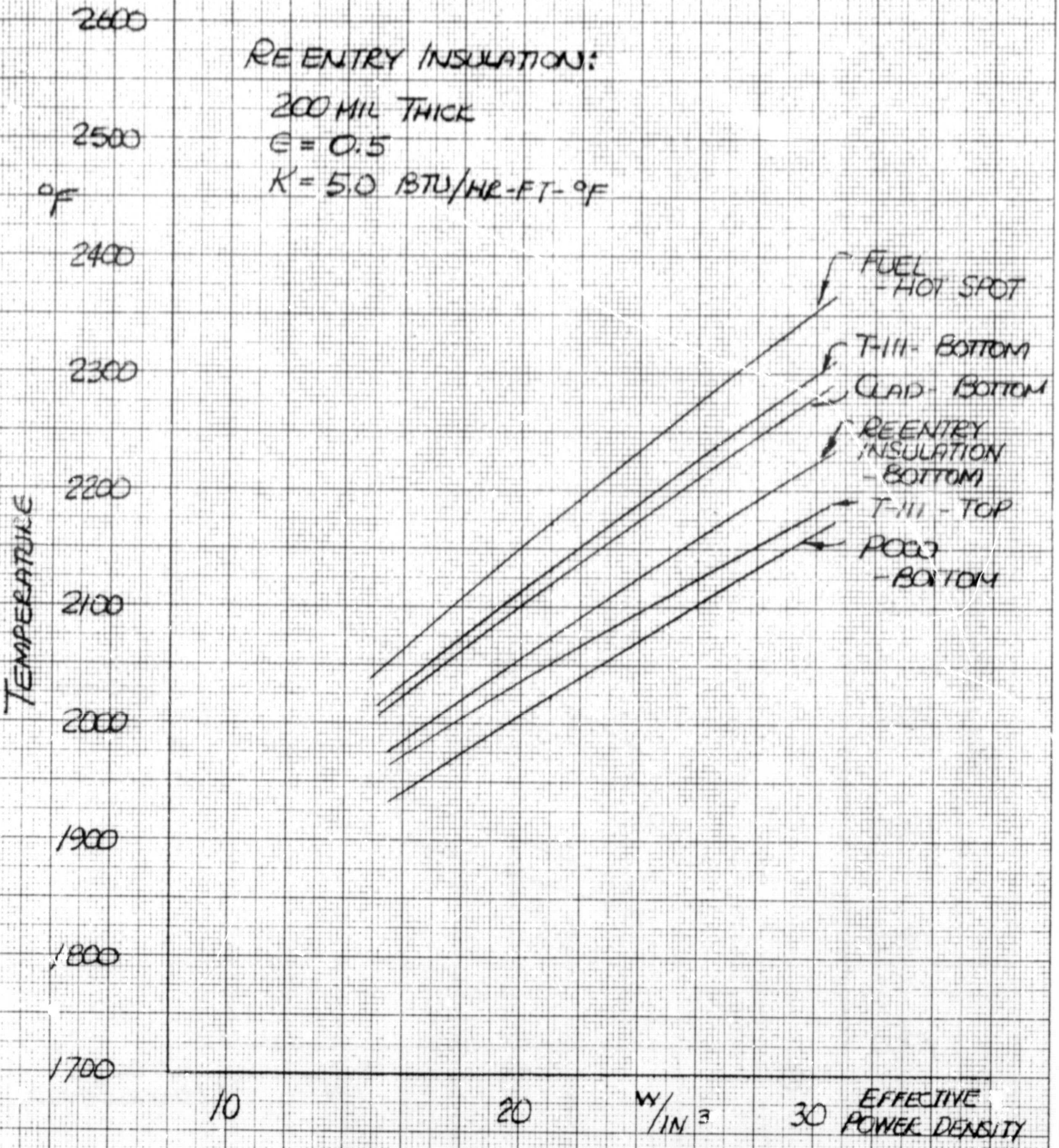


FIGURE 8a ISOLOAF HS HOT SPOT TEMPERATURES; T_{SINK} = 1670 °F

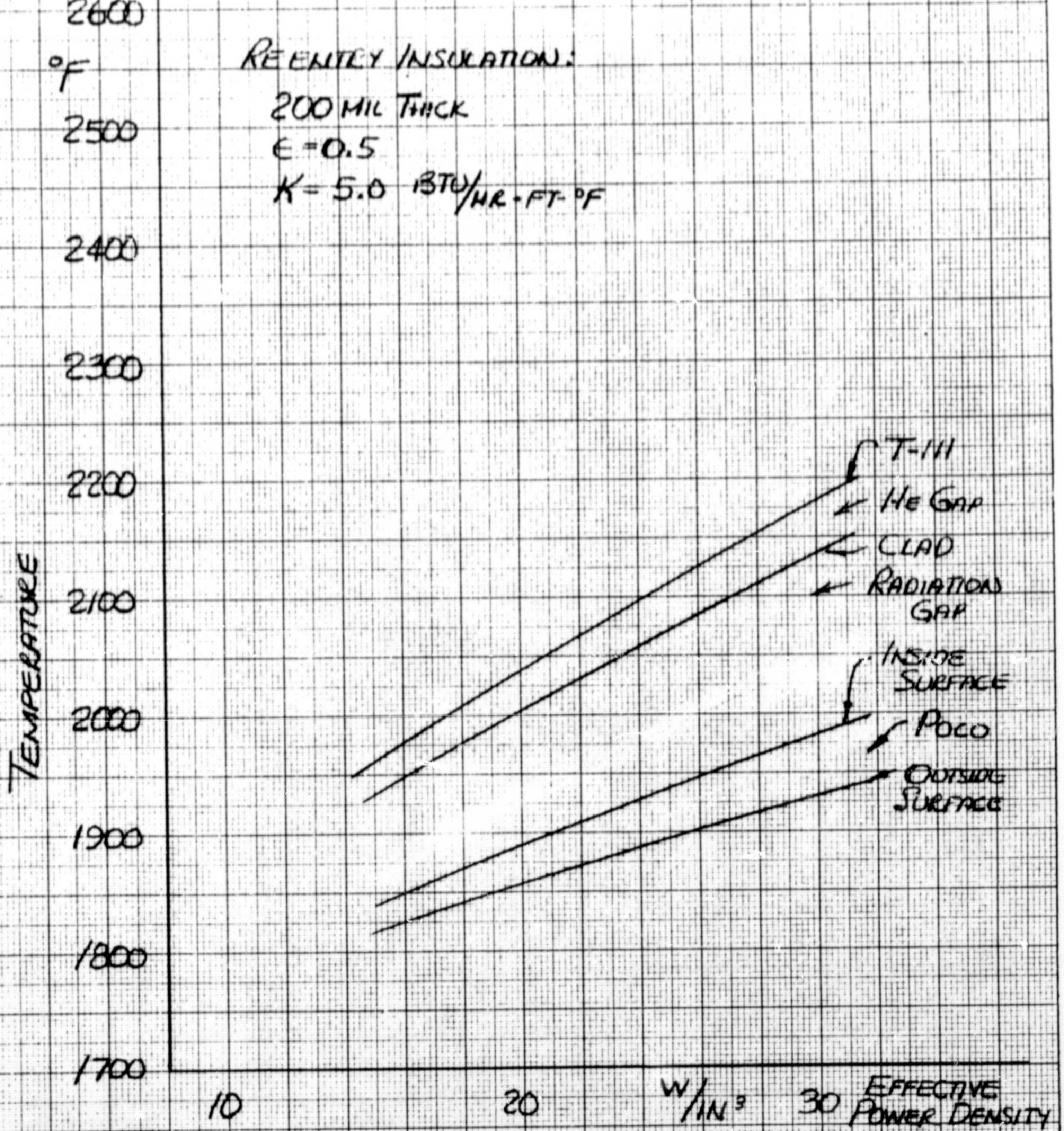


Figure 8b Temperatures at Top of Isoloaf HS; T_{sink}=1670°F

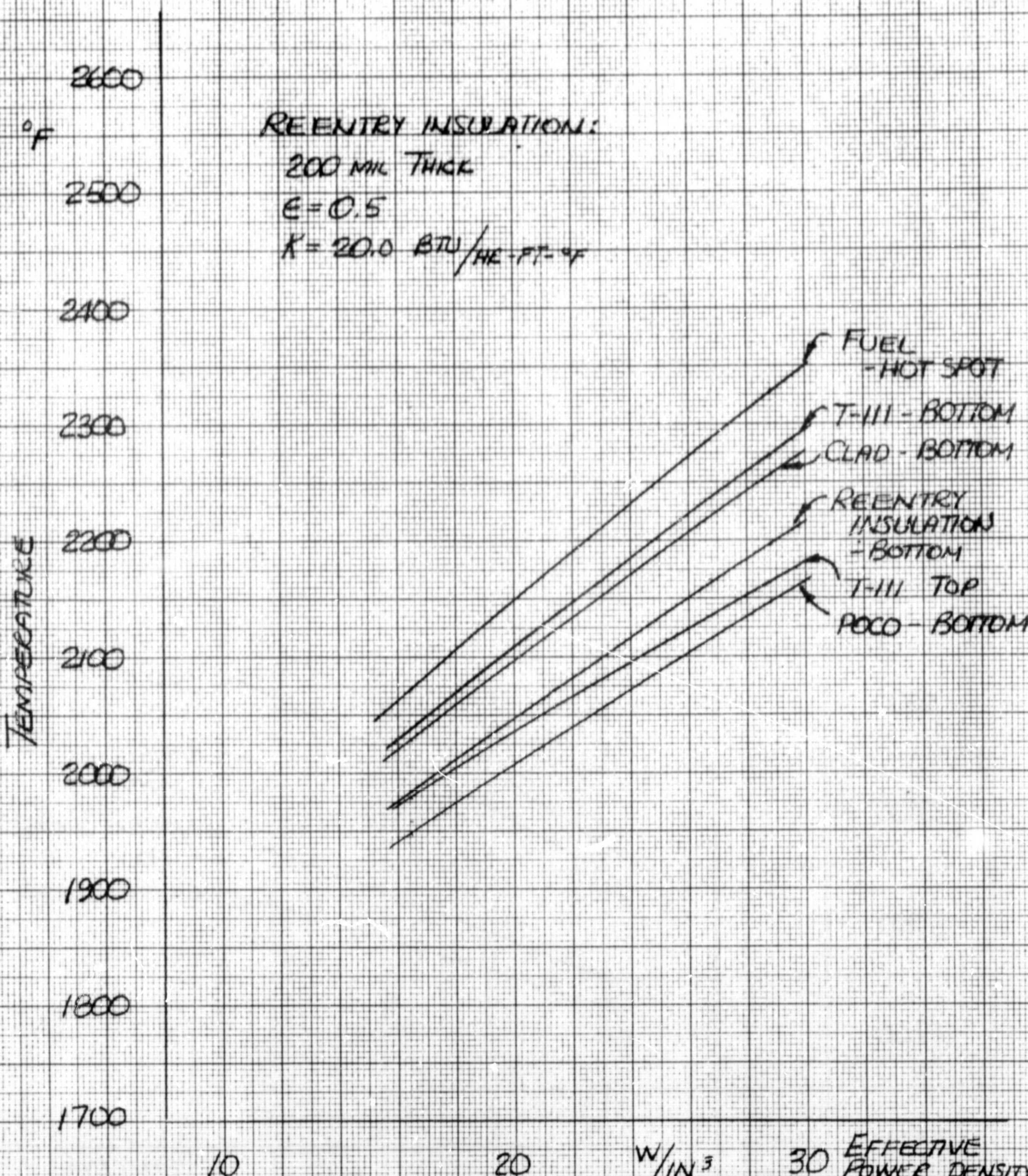


FIGURE 9a ISOLOHF HS HOT SPOT TEMPERATURES ; T_{SINK} = 1670°F

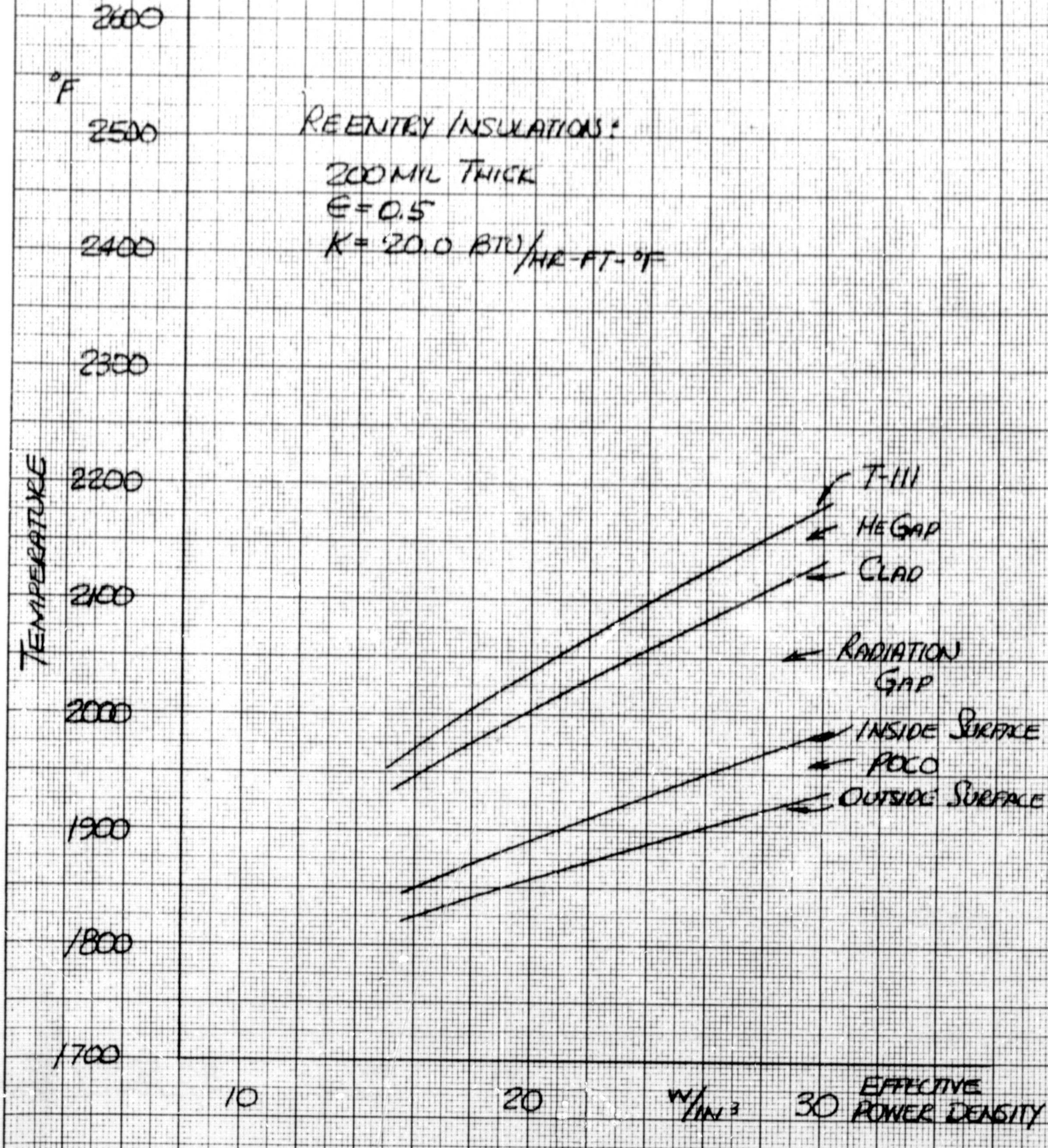


FIGURE 9b TEMPERATURES AT TOP OF ISOLO.9F HS; T_{SINK} = 1670°F

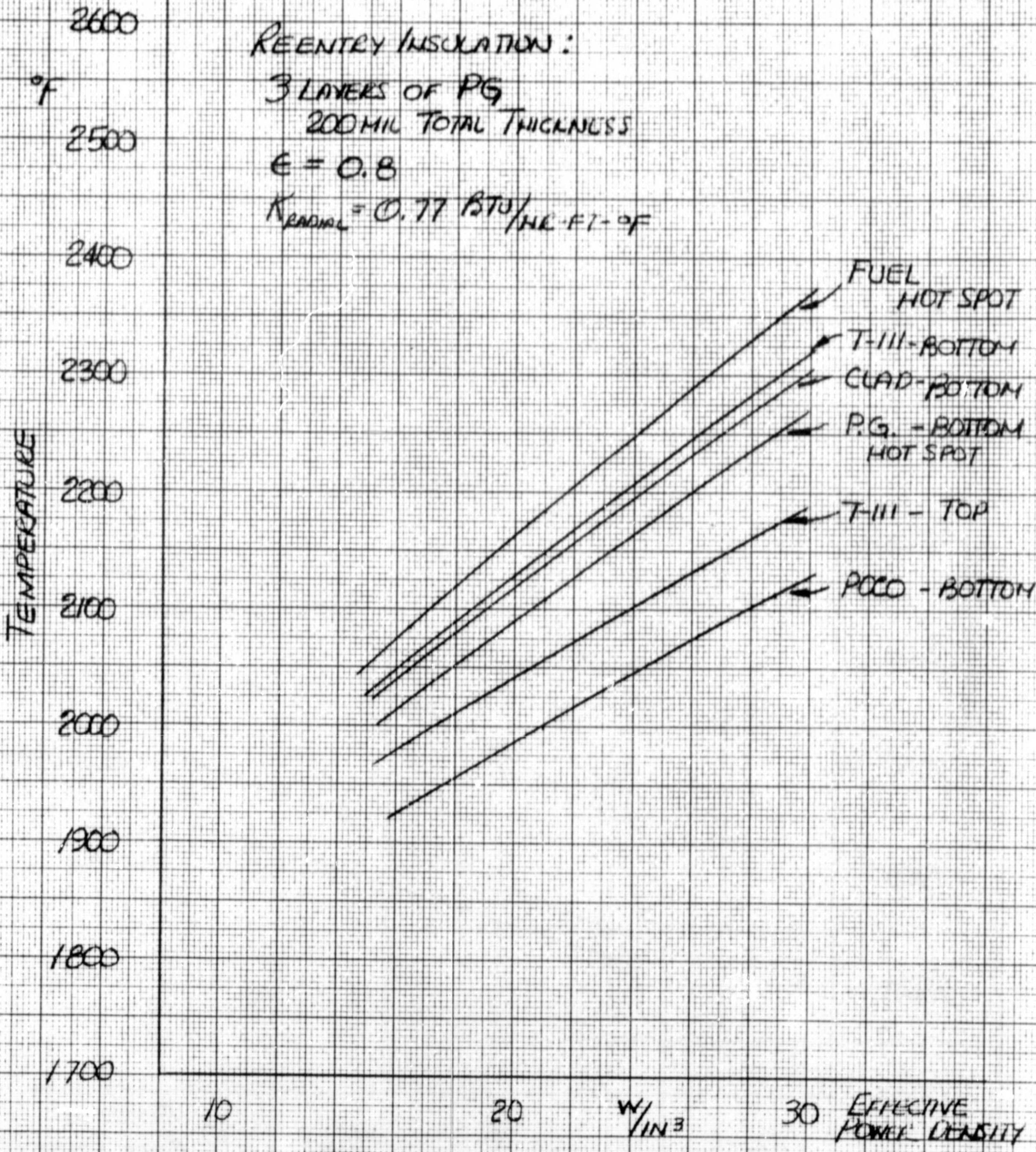


FIGURE 10a ISOLOAF HS HOT SPOT TEMPERATURES; $T_{SINK} = 1670°F$

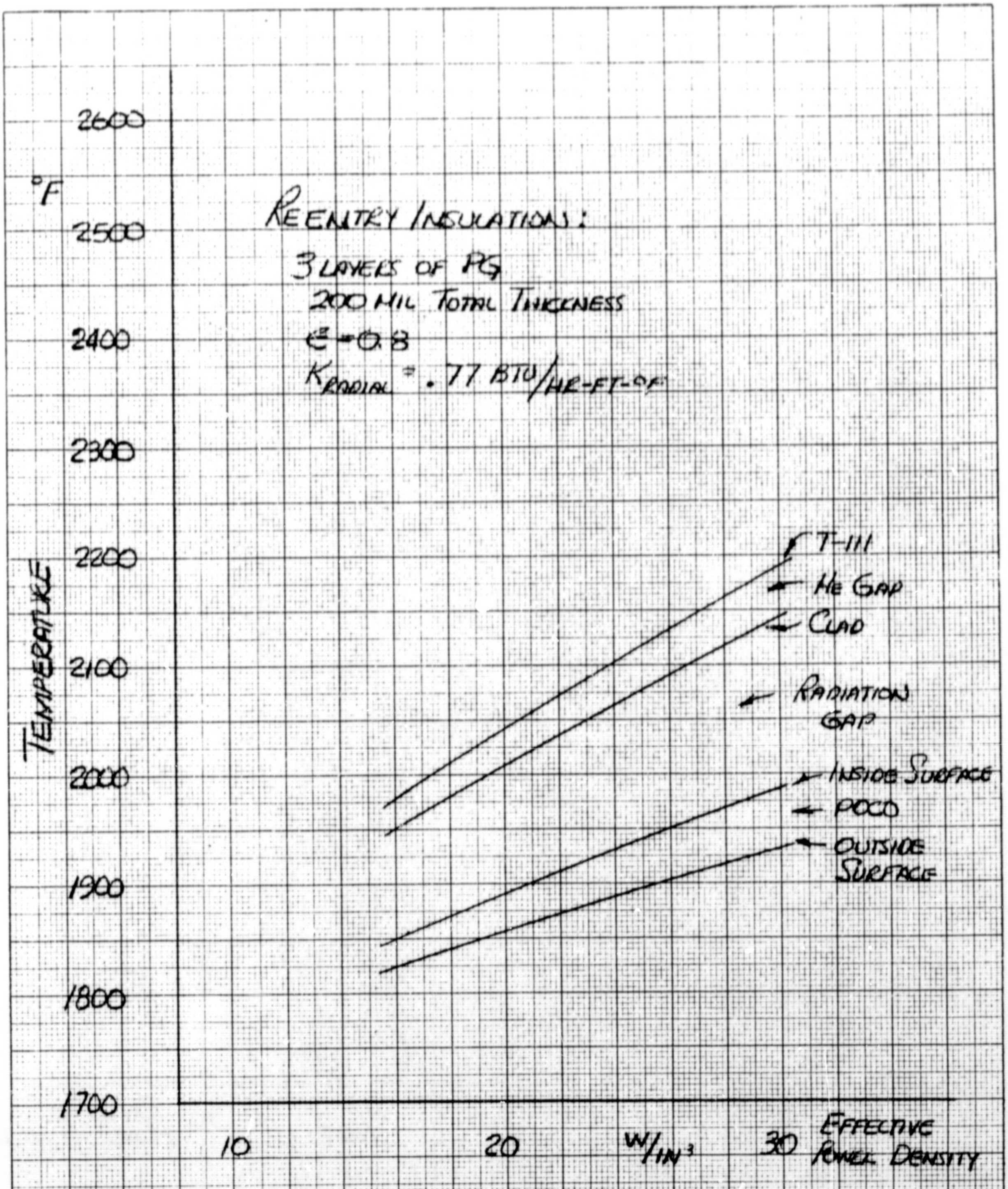
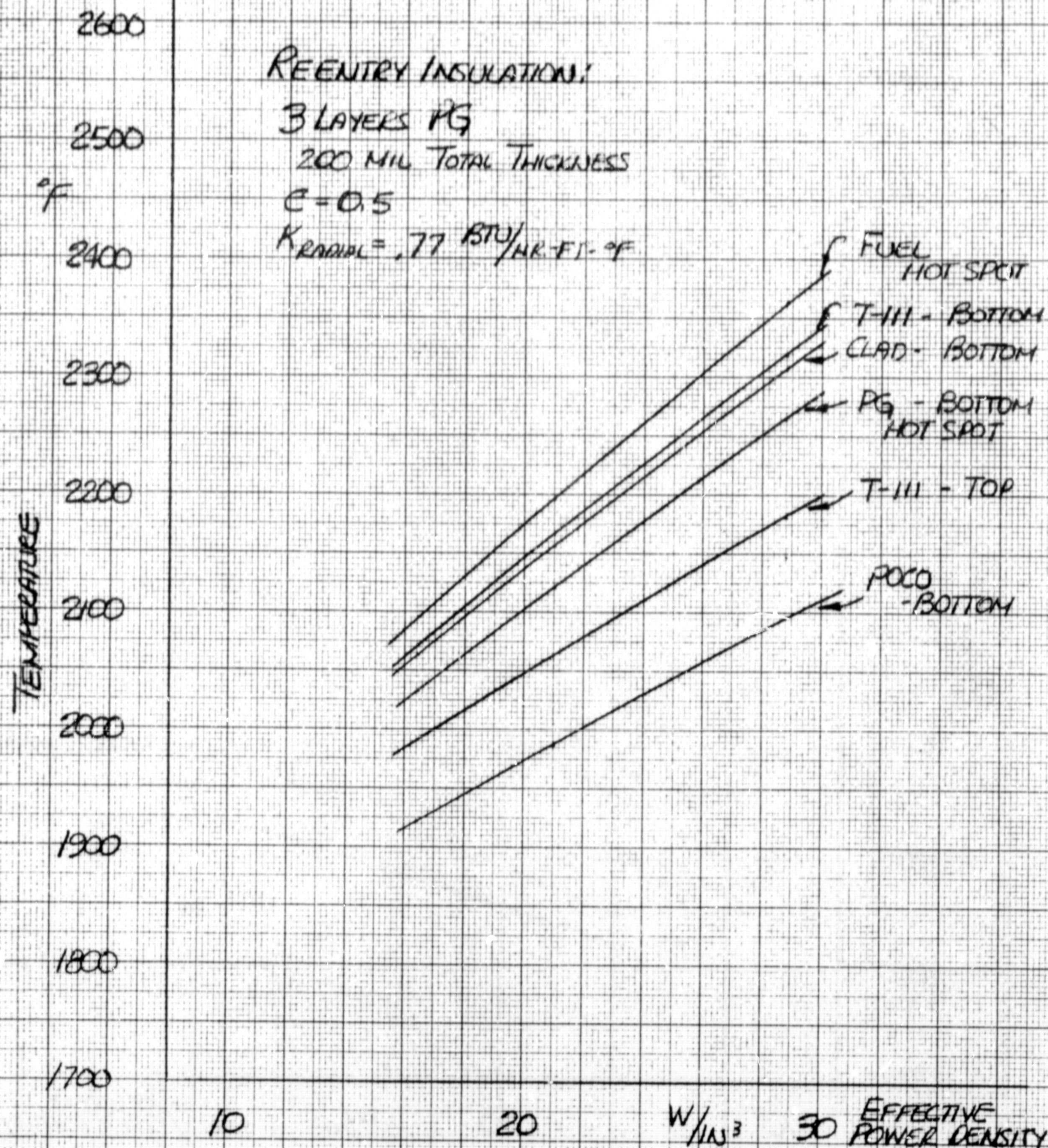


FIGURE 10b TEMPERATURES AT TOP OF ISOLOAF HS; T_{SINK} = 1670°F



FIGURES 11a ISOLOAF HS HOT SPOT TEMPERATURES; $T_{SINK} = 1670°F$

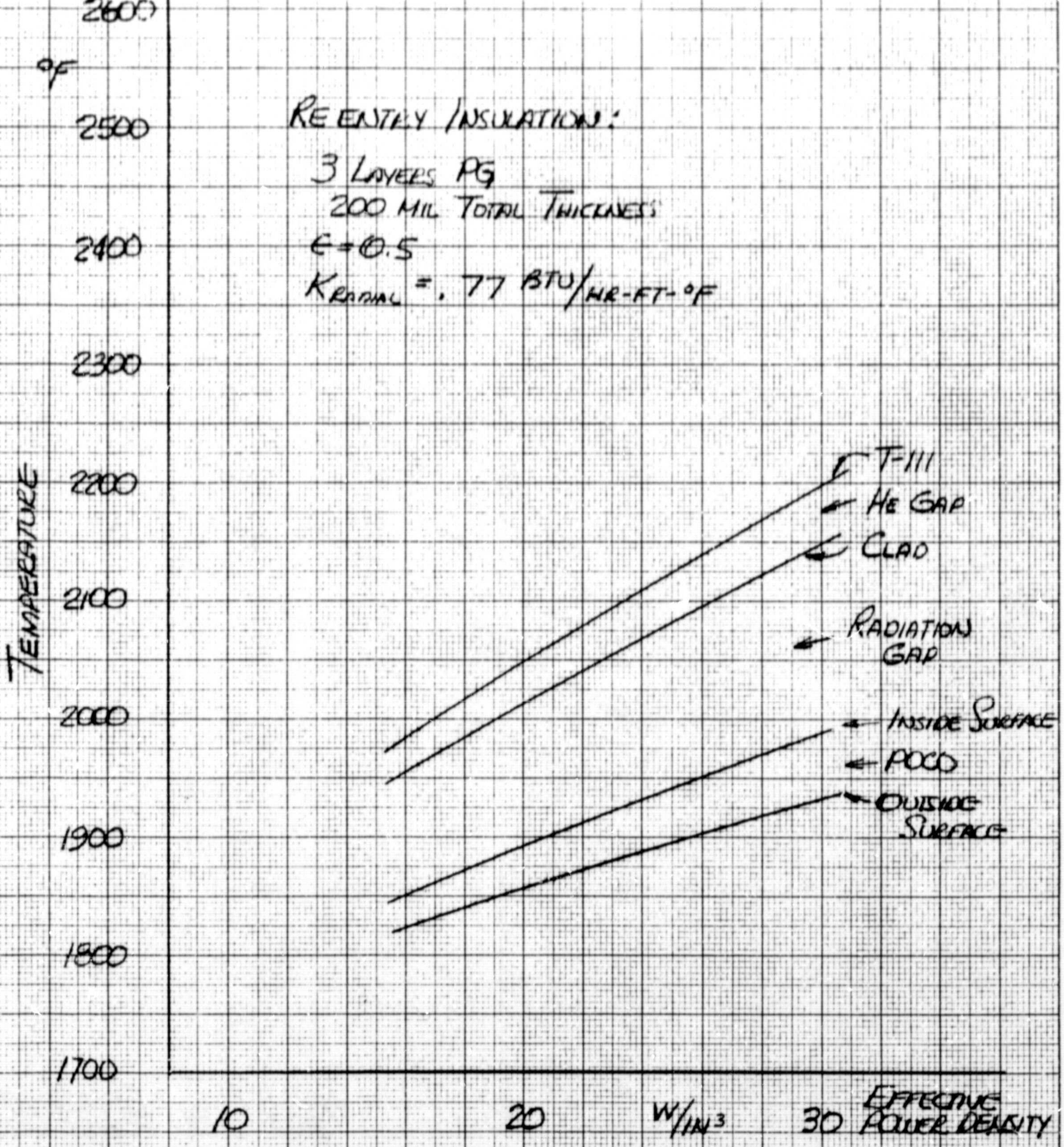


FIGURE 11b TEMPERATURES AT TOP OF ISOLOAF HS; T_{SINK} = 1570°F

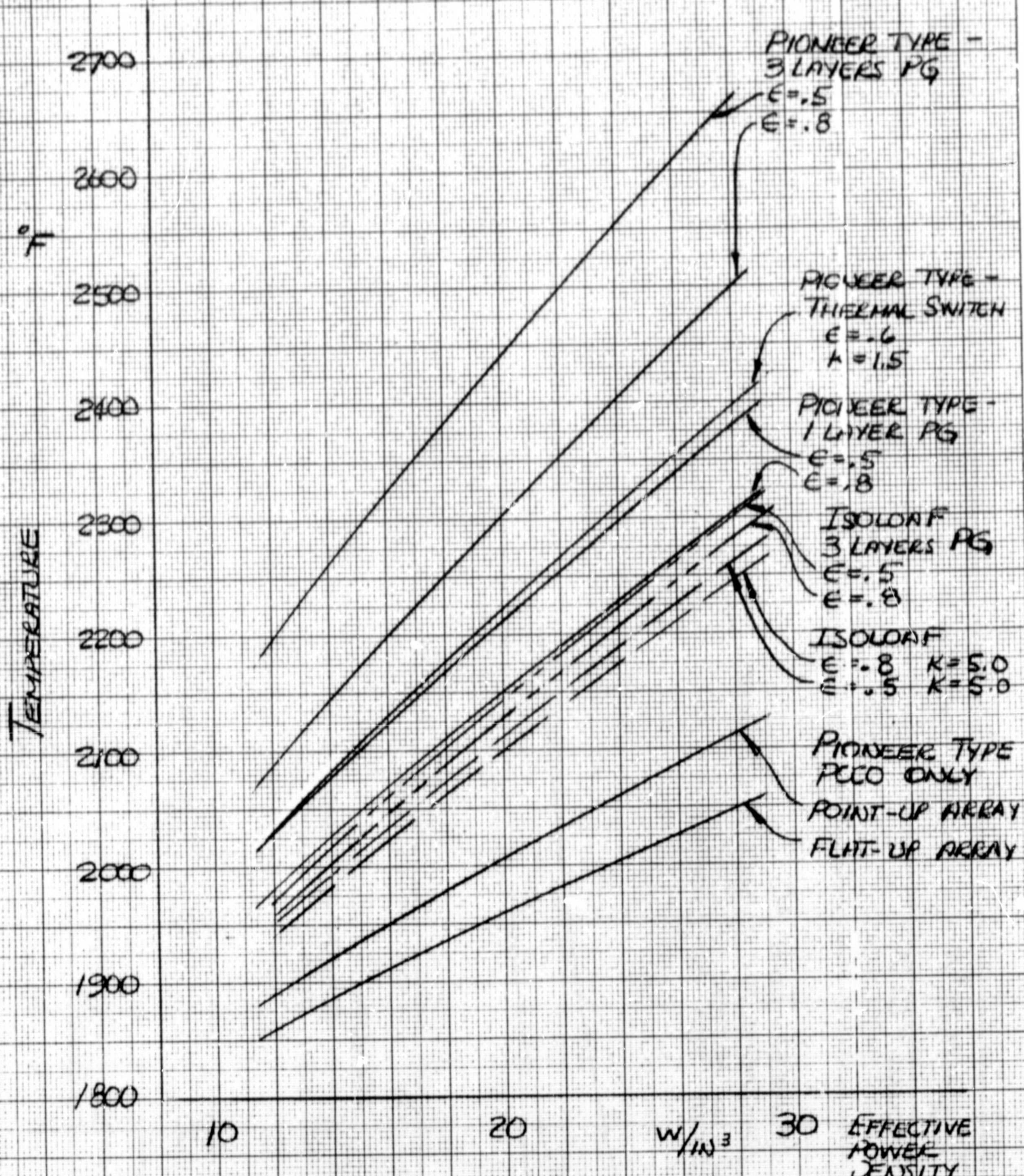


FIGURE 12 T-111 HOT SPOT TEMPERATURE, STEADY STATE OPERATION, T_{SINK} = 1670°F

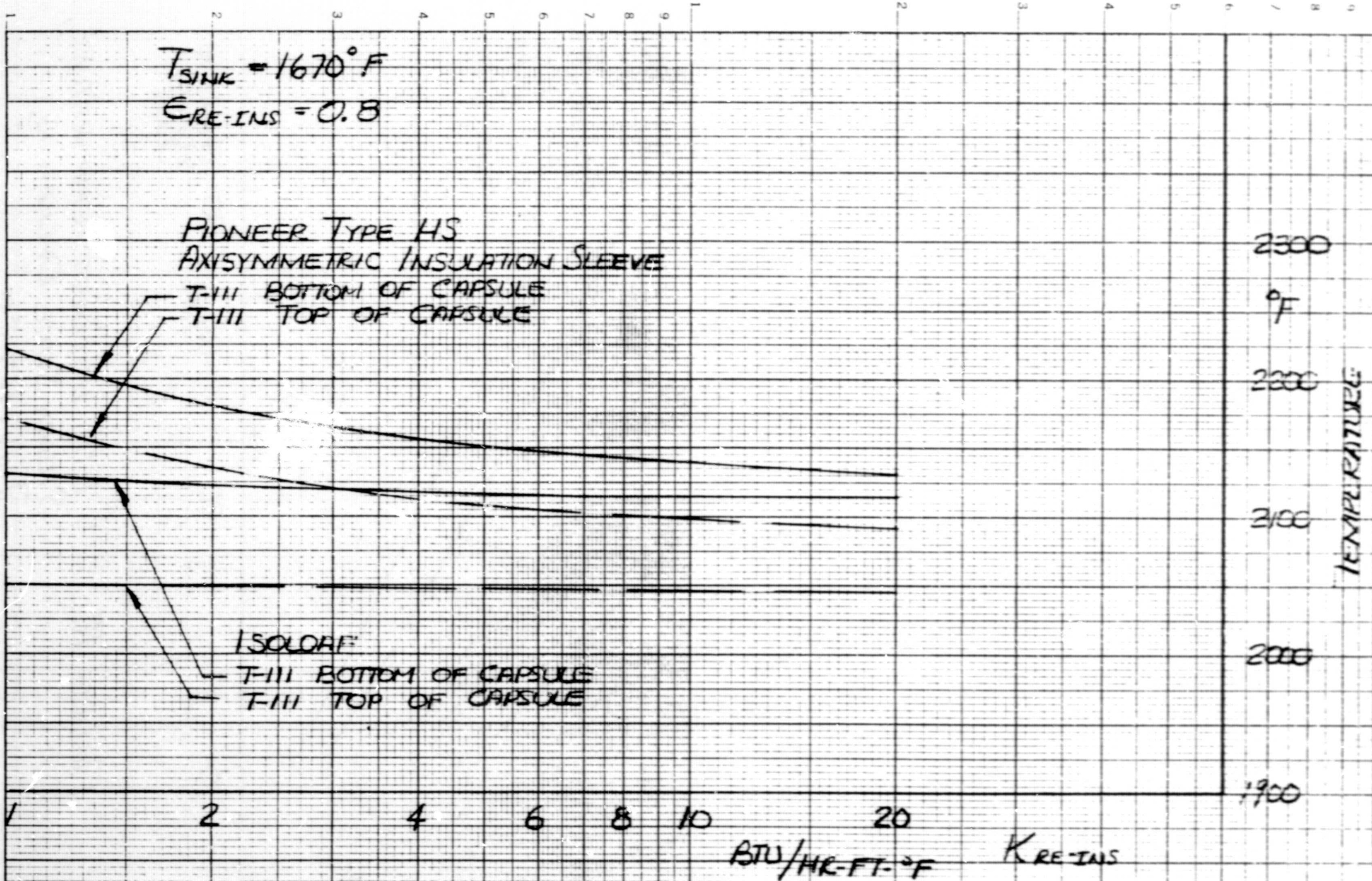


FIGURE 13 T-111 TEMPERATURE VS INSULATION THERMAL CONDUCTIVITY; STEADY STATE OPERATION; 200 MIL THICK INSULATION

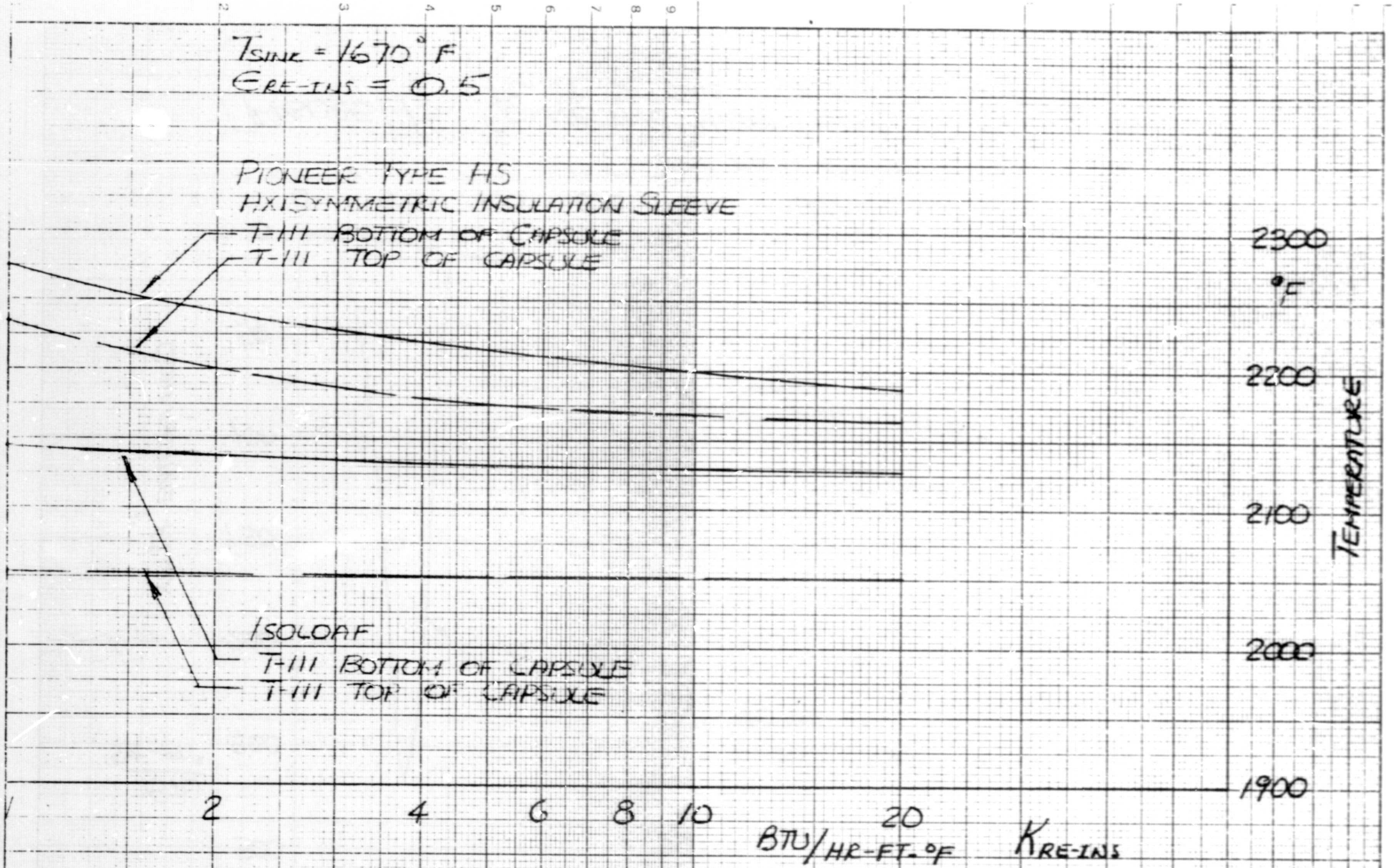


FIGURE 14 T-111 TEMPERATURE VS INSULATION THERMAL CONDUCTIVITY; STEADY STATE OPERATION; 200 MIL THICK INSULATION

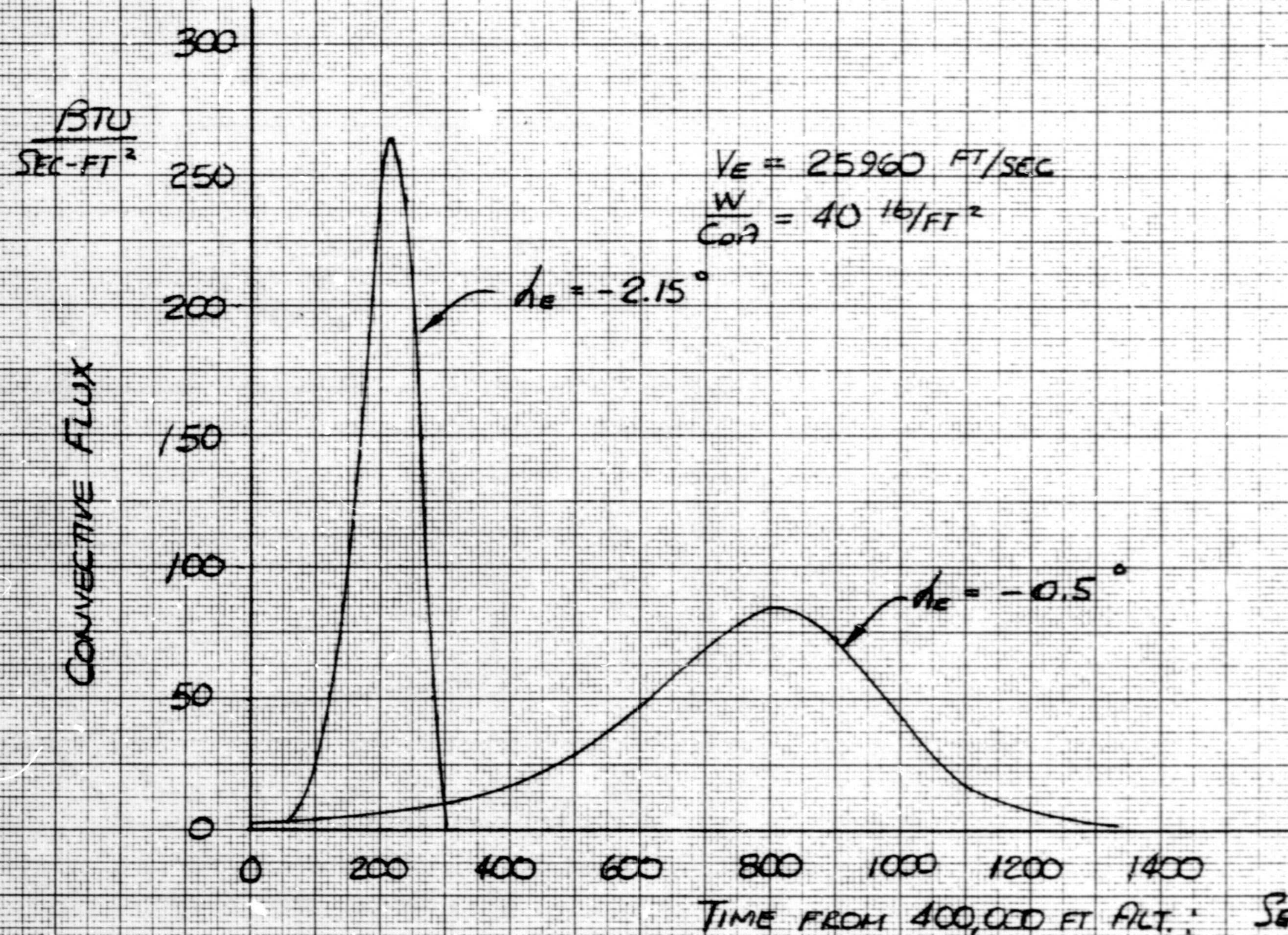


FIGURE 15 CONVECTIVE HEAT PULSE TO STAGNATION POINT OF ONE FOOT RADIUS SPHERE

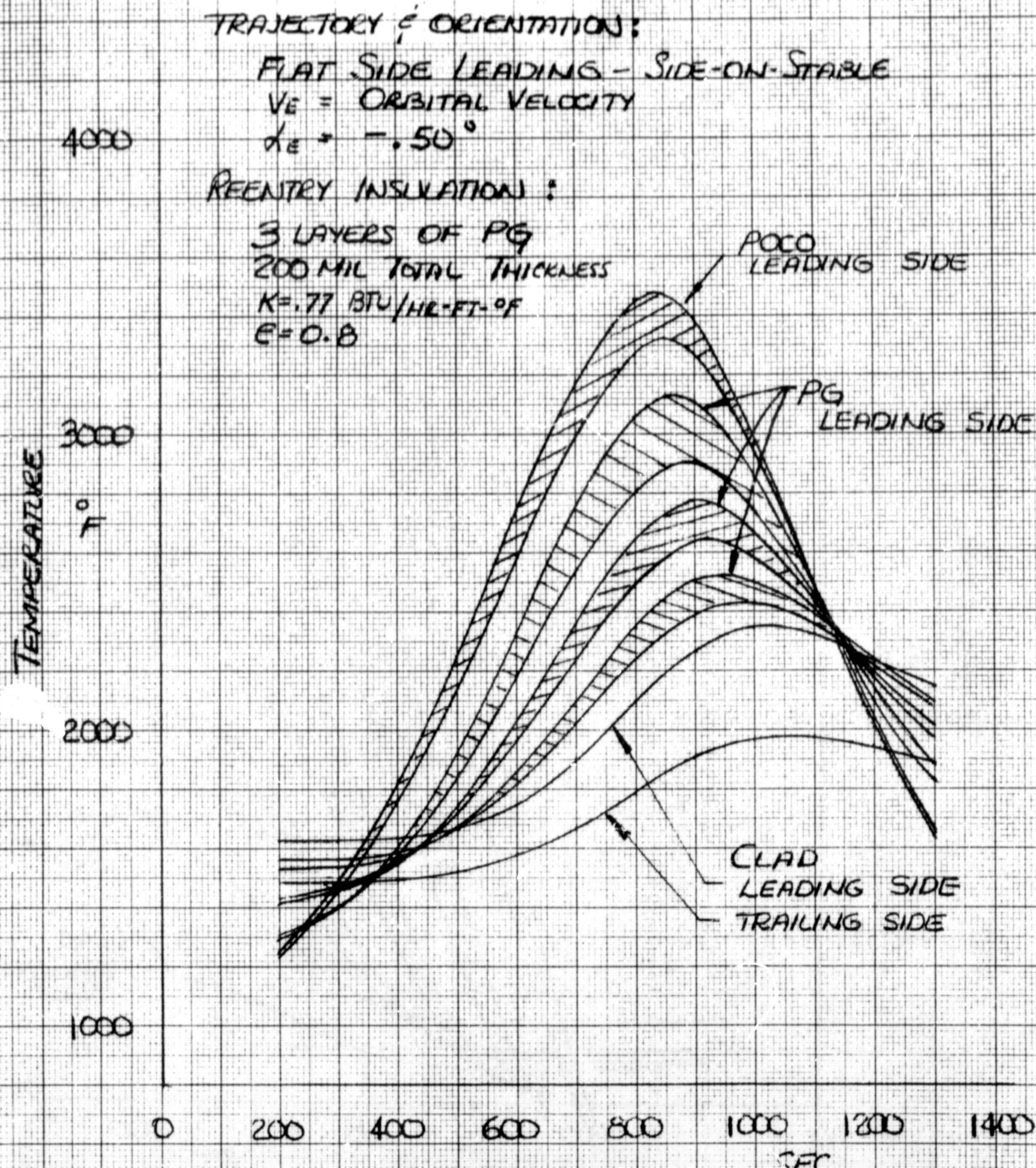


FIGURE 16 ISOLOAT HS TEMPERATURES DURING REENTRY

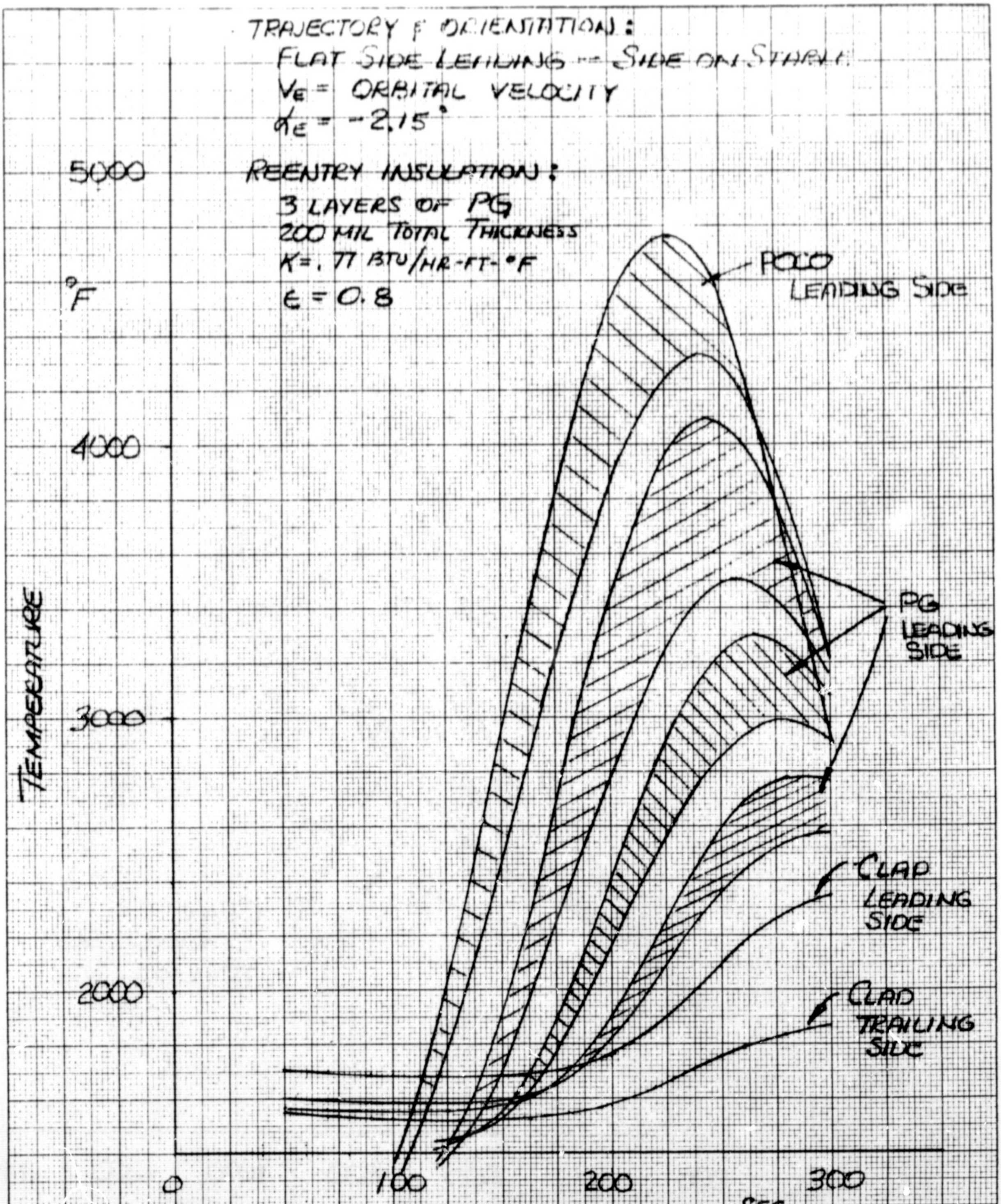


FIGURE 17 ISOLOAF HS TEMPERATURES DURING REENTRY