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I. Introduction

A new concept for fusion reactor blanket design based on the idea of shifting the neutron spectrum incident on the first structural wall is receiving increased attention. This concept was first proposed by Conn and Kulcinski[1] and similar ideas have been described by Powell and Lazareth[2]. Such blanket designs are referred to as Internal Spectral Shifter and Energy Converter, or ISSEC concepts. The basic design is to introduce a neutron moderator, usually a graphite layer that is 5 to 25 cm thick, between the first structural wall and the plasma. Its purpose is to reduce radiation damage to the structural materials so that frequent replacement of the first wall can be avoided. This will significantly simplify first wall design and maintenance problems. It will also reduce material resource problems and can reduce the level of induced radioactivity.

The limiting factor on the thickness of the spectrum shaping zone, called the ISSEC zone, is related to heat transfer. The maximum temperature of the graphite in magnetic confinement systems is limited to approximately 2000°C because at this temperature, the vapor pressure of the graphite becomes comparable to the pressure in the vacuum chamber, i.e. $\sim 10^{-5}$ torr. The thermal energy received in the ISSEC zone must be transferred by conduction to the surface facing the first wall. This thermal energy will than be transferred to the blanket either by radiation, conduction, or some other device, such as heat pipes. The 2000°C temperature limitation determines the thickness of the ISSEC zone which, in turn, determines first wall life. For this study, it is conservatively assumed that only radiative transfer is available to remove heat from the graphite ISSEC zone.

The requirement that heat be transferred to the back surface of the ISSEC and radiated to the first structural wall implies a high temperature on the front surface of the graphite which limits the thickness. Powell and Lazareth[2] proposed the partial ISSEC concept in which a graphite zone is used to protect only the inner blanket, nearest the axis of a torus in a Tokamak where access and maintenance is most difficult. Further, the ISSEC zone can radiate heat to both the inner and outer blankets which allows thicker zones for protection of the inner blanket. The outer blanket, however, remains unprotected from radiation damage. A modified ISSEC design which will provide protection for the entire blanket yet have acceptable heat transfer characteristics will be developed in this report. In this paper, we concentrate on the heat transfer aspects of these various ISSEC designs.

II. Description of ISSEC Concepts

It has been suggested that bulk graphite or three dimensional woven graphite fibers can be used as ISSEC materials.[1] An advantage of graphite in fibrous form is its flexibility and strength. However, the effective density of such a woven system is typically about 50% of the actual density of the fibers themselves which means the physical thickness of a woven ISSEC zone would have to be twice that of bulk graphite to achieve the same neutronic effect. The resulting temperature in the woven ISSEC will turn out to be much higher than that in bulk graphite. For this reason, bulk graphite is used as the ISSEC material in this paper. Since the ISSEC is not a load bearing structure, the lower strength available in the bulk graphite is not critical. The properties of bulk graphite are listed in Table I.

The thermal connection between the ISSEC and the blanket has a significant effect on the maximum temperature in the graphite zone. Thermal connection to the first structural can either be by radiation, contact conductance, heat pipes, or a combination of any of the above. Thermal radiation is the simplest and the most reliable way, if not the most efficient. For the work here, only thermal radiation between the ISSEC zone and the blanket is assumed.

The following three different ISSEC designs have been studied:

1. Basic ISSEC: The basic ISSEC consists of a continuous layer of graphite located between the plasma and the blanket. The blanket consists of 5% structure and 95% natural lithium for the model calculations to be performed. The thermal energy received by the ISSEC will be conducted to the surface facing the blanket and radiated to the first structural wall. The basic ISSEC design provides the most uniform protection of the blanket but poses the most difficult heat transfer problem due to the long conduction path. A schematic design of a Basic ISSEC is shown in Fig. 1.

2. Partial ISSEC: A partial ISSEC provides protection only to the inner blanket nearest the centerline. The outer blanket has a low Z liner to protect the plasma but this zone is optically thin to neutrons and has little effect on the spectrum. The carbon curtain[3] is one manifestation of this idea. The thermal energy received by the ISSEC will be radiated to both the inner and outer blankets. The outer blanket consists of 90% lithium and 3% structure whereas the inner blanket consists of 97% salt (50% LiF and KF) and 3% structure.[4] A schematic design of a partial ISSEC system is shown on Fig. 2.

The purposes of the basic ISSEC and partial ISSEC are very different. The basic ISSEC reduces radiation damage to the entire blanket which simplifies blanket design, and significantly reduces material resource and radioactive material storage problems. The partial ISSEC, on the other hand, protects only part of the blanket and does not simplify the outer blanket design.

3. Modified ISSEC: A modified ISSEC is proposed to combine the advantages of both the above ideas. A schematic of a modified ISSEC system is shown on Fig. 3. The inner ISSEC is a continuous layer of graphite and provides maximum protection to the inner blanket. The outer ISSEC graphite zone has a broken pattern design as shown on the insert of Fig. 3. This design takes advantage of the fact that neutrons and thermal radiation come from different directions. It provides protection for the structure as well as a radiation sink for heat transfer from the hotter side of the ISSEC zone.

III. Neutronic and Heat Transfer Calculations

1. Basic ISSEC

Neutronic Calculations: The neutronic results for a basic ISSEC were calculated by R. Conn.[5] The results are summarized on Fig. 4 and discussed in detail in reference 5. The shift in the first wall neutron spectrum due to the graphite ISSEC zone causes the displacement damage rates, gas production rates and long term radioactivity in the first structure wall to be significantly reduced. An increase in the life of the first structural wall by an order of magnitude requires an ISSEC zone thickness equivalent to 15-20 cm of solid graphite.

The softer neutron spectrum in the breeding blanket does however lead to a reduction in the breeding ratio. For an ISSEC thickness of more than about 5 cm, the breeding ratio drops below 1. This can be remedied by including beryllium or other neutron multiplier in the spectral shaper zone as indicated on Fig. 4. The neutron multiplier, however, can increase the thermal load slightly in the ISSEC while reducing its effective thermal conductivity.

Heat Transfer Calculations: With the heating rates shown on Fig. 4 as input, the temperature of the basic ISSEC is calculated as a function of neutron wall laoding, surface heat loading, ISSEC thickness and thermal conductivity of the graphite. The results are summarized on Figs. 5, 6, and 7. It can be seen that the maximum temperature changes rapidly with all those parameters. (As discussed earlier, the maximum temperature for magnetic confinement is about 2000°C).

For a neutron wall loading of 1 MW/m^2, a surface heat loading of 10 W/cm^2, and a thermal conductivity of 0.42 W/cm-°C, the allowable thickness of a basic ISSEC is only 6 cm. This thickness reduces the radiation damage to the first structural wall by only a factor of 2 or 3. The full advantage of the ISSEC is, therefore, not easily obtainable with the simplest manifestations of the idea due to temperature limitations. Good thermal contact between the ISSEC zone and the first wall improves this result considerably, but we have not studied the details of achieving this good contact.

2. Partial ISSEC

Neutronic Calculations

The model for neutronic calculations in a partial ISSEC system is shown on Fig. 8. Due to the difference of the first wall surface area, 40% of the source neutrons are taken to be directed toward the inner blanket while 60% go toward the outer blanket. This is an approximate way to simulate a two dimensional problem with one dimensional calculations.

The ISSEC protecting the inner blanket also serves as a neutron reflector. Therefore, a breeding ratio of 1.13 is obtained even with salt as the coolant for the inner blanket. (The salt is used as the coolant instead of lithium to reduce MHD effects.)

The reduction of the DPA and He production rates in the first wall behind the partial ISSEC, as a function of the ISSEC thickness, is the same as shown in Fig. 4. The design goal is again to prolong the life of the first wall by an order of magnitude.

Heat Transfer Calculations

The maximum temperature and the highest surface temperature of the ISSEC zone are calculated as functions of neutron wall loading, surface heat loading, ISSEC thickness and thermal conductivity of the graphite. The results are shown on Figs. 9, 10, 11 and 12. Unlike the basic ISSEC case, the temperature of a partial ISSEC system is relatively insensitive to the surface heat load and the thermal conductivity. The reason is a partial ISSEC is cooled from both sides by radiation so that only a fraction of the thermal energy has to be conducted to the back side.

For the case of 1 MW/m^2 neutron loading, 10 W/cm^2 surface heat loading and a thermal conductivity of 0.42 W/cm-°C, the maximum temperature of the partial ISSEC will reach 2000°C for an ISSEC thickness of 28 cm. If the surface temperature is the controlling temperature, an indefinite thickness of a partial ISSEC zone can be used since the surface temperature never exceeds 2000°C. It therefore appears possible to design the inner blanket as a fixed element of the reactor which does not require periodic replacement. However, if the neutron wall loading exceeds 2 MW/m^2, temperature limitations will again limit the ISSEC thickness and the inner blanket will have to be replaced prior to full plant life.

3. Modified ISSEC

Neutronics Considerations

A neutronic calculation has not yet been made for a modified ISSEC system because of the complexity of the geometry. The angular distribution of the neutron flux is critical to the performance of a modified ISSEC and this is not readily simulated by one dimensional calculations. A Monte Carlo analysis is in progress. In lieu of this, the basic assumption is that source neutrons are mostly incident on the first wall in the normal direction while thermal radiation is primarily incident from the horizontal direction. The design of the modified ISSEC, as shown on Fig. 3, takes advantage of this effect. How much protection the first wall will receive can be estimated only after the directional distribution of the neutron source is available. However, zones of optically similar thicknesses should produce effects similar to that shown in Fig. 4 for the basic ISSEC design. The thermal load of the modified ISSEC is assumed to be the same as that of the basic ISSEC.

Heat Transfer Calculations

The temperature distributions within the three different regions of the modified ISSEC design are shown on Fig. 13. For an ISSEC zone of effectively 25 cm thick, the surface temperature is below 2000°C. This indicates such a design solution can potentially achieve the neutronics effects of the basic ISSEC design with heat transfer characteristics similar to a partial ISSEC.

Further development of the modified ISSEC concept will depend on detailed results of neutronics calculations. The calculation performed here, however, clearly demonstrates the feasibility of the modified ISSEC concept.

IV. Discussion and Conclusions

From this study, the following conclusions can be drawn:

1. For a basic ISSEC system, the first wall life expectancy can be doubled compared to a bare first wall.

2. The breeding ratio decreases if a neutron multiplier is not incorporated into the ISSEC zone.

3. A partial ISSEC system can allow the inner blanket lifetime to exceed the expected plant life of 30 years for a neutron wall loading of about 1 MW/m^2. The breeding ratio for the complete system can exceed 1 without the use of a neutron multiplier.

4. The modified ISSEC concept is viable from a heat transfer point of view. It may also provide enough protection of the first wall for the entire blanket to be able to last for the plant lifetime. The design allows for cooling from the hot side of the ISSEC, as in the partial ISSEC design, while extending fully around the plasma.

Additional work is required in the following areas:

1. Since the thickness of the ISSEC is temperature limited, a better thermal connection than radiation between the ISSEC and the first wall can greatly extend the usefulness of the basic ISSEC concept. One possible solution is to use heat pipes. Development of heat pipes with either nonconducting structural or nonconducting working fluid to reduce the MHD effects will be important.

2. A system similar to the modified ISSEC may be developed. The basic idea is to provide radiation cooling to the hot side of the ISSEC zone. This can be accomplished by either providing a sink, as proposed here, or rotating the ISSEC periodically to let the hot side point away from the plasma.

3. The angular distribution of the neutron source to the modified ISSEC is critical to determining the real effectiveness of this concept.

4. The upper temperature limit on the graphite needs more careful definition. Some of the relevant questions are:

   a. Is the maximum or the surface temperature the limiting criterion?

   b. Which mechanisms limit the allowable vapor pressure of the graphite, the plasma or the vacuum pumping?

Acknowledgement

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3. G. L. Kulcinski, R. W. Conn, G. Lang, L. Wittenberg, D. K. Sze, J. Kesner, D. L. Kummer, "A Method to Reduce the Effects of Plasma Contamination and First Wall Erosion in Fusion Reactors" Nuclear Engineering Dept., Report FDM-108, University of Wisconsin (Aug. 1974).

4. R. W. Conn, E. T. Cheng, D. K. Sze, Blanket Considerations Analysis for the UWMAK-III Conceptual Design (Unpublished Notes).

5. R. W. Conn et al., Nuclear Technology 26, 125 (1975).

Table 1

Thermophysical Properties of Graphite*

Density		1.6 g/cm^3
Thermal Conductivity	between	0.42 W/cm-sec
	and	0.84 W/cm-sec
Thermal Emissivity		0.9
Vapor Pressure	at 2200°C	10^{-4} torr
	2000°C	10^{-5} torr
	1700°C	10^{-9} torr

* Properties of graphite vary widely. These are typical values.

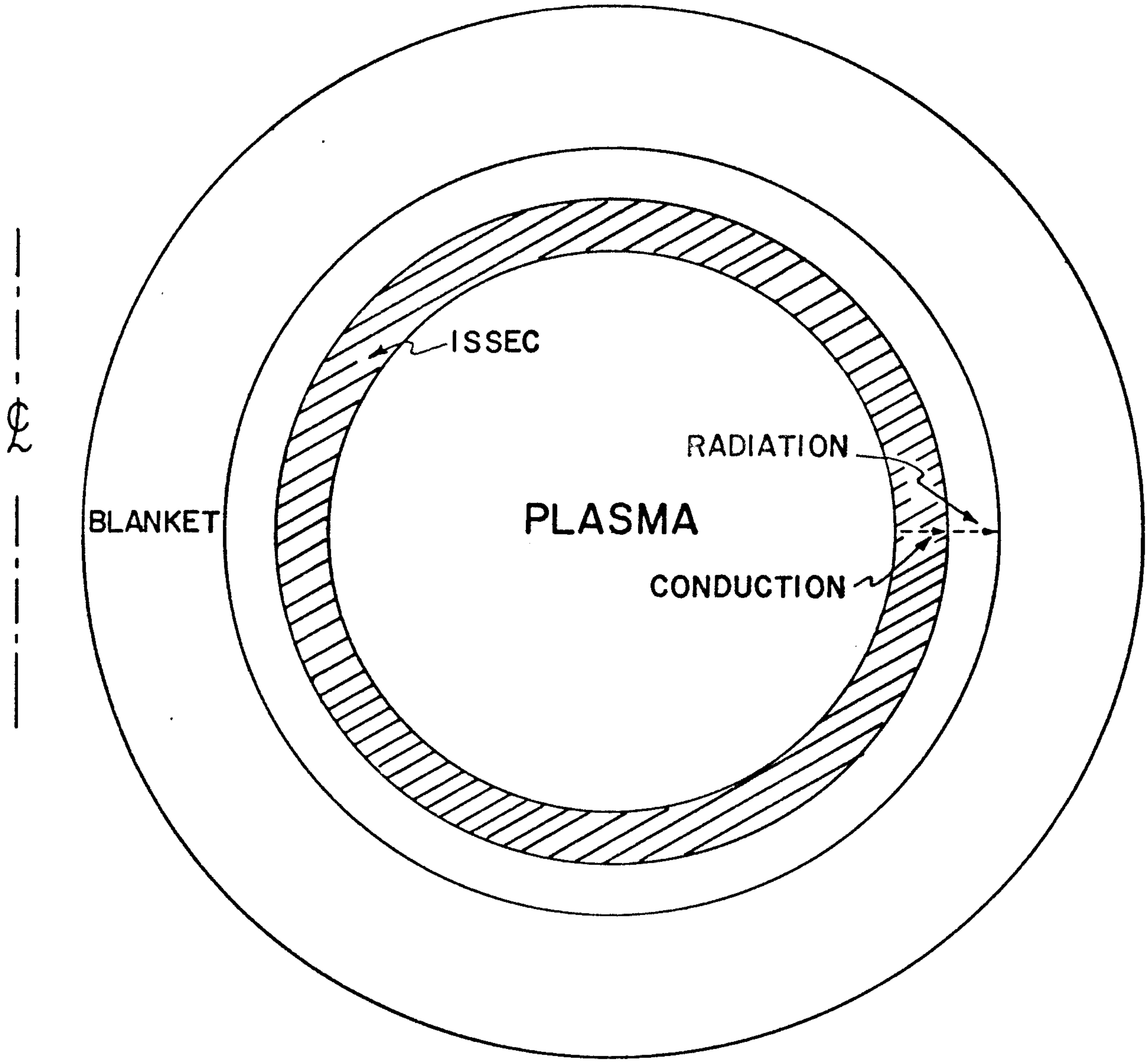


FIG. I SCHEMATIC DRAWING OF A BASIC ISSEC SYSTEM

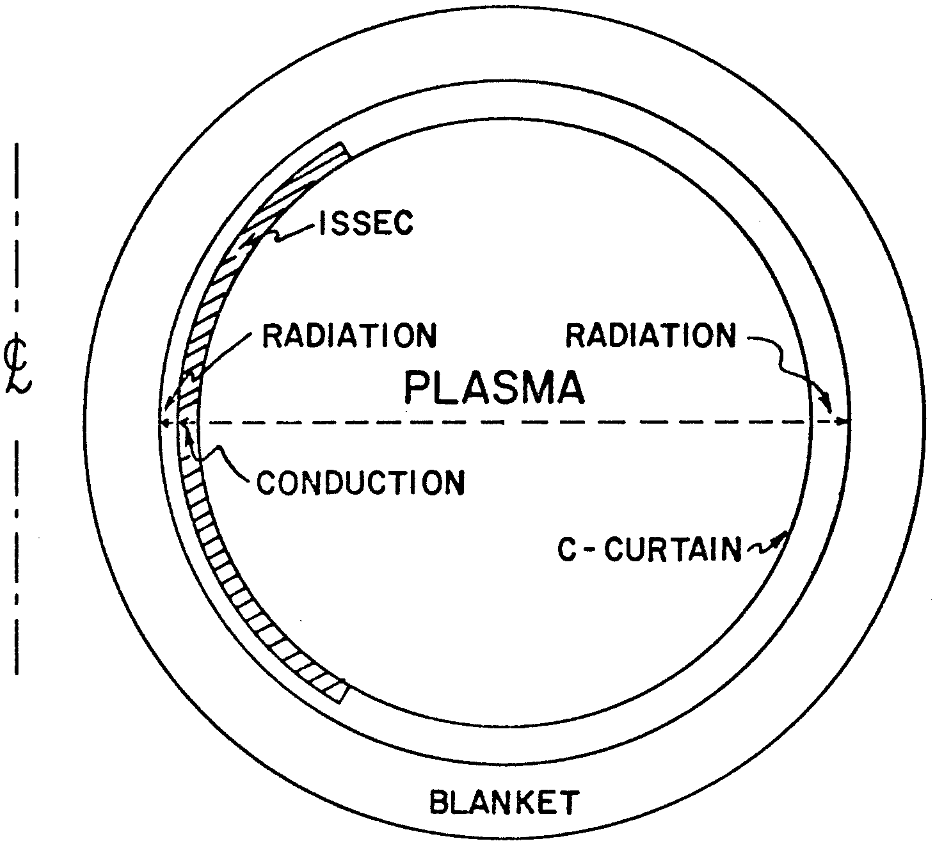


FIG. 2 SCHEMATIC DRAWING OF A PARTIAL ISSEC SYSTEM

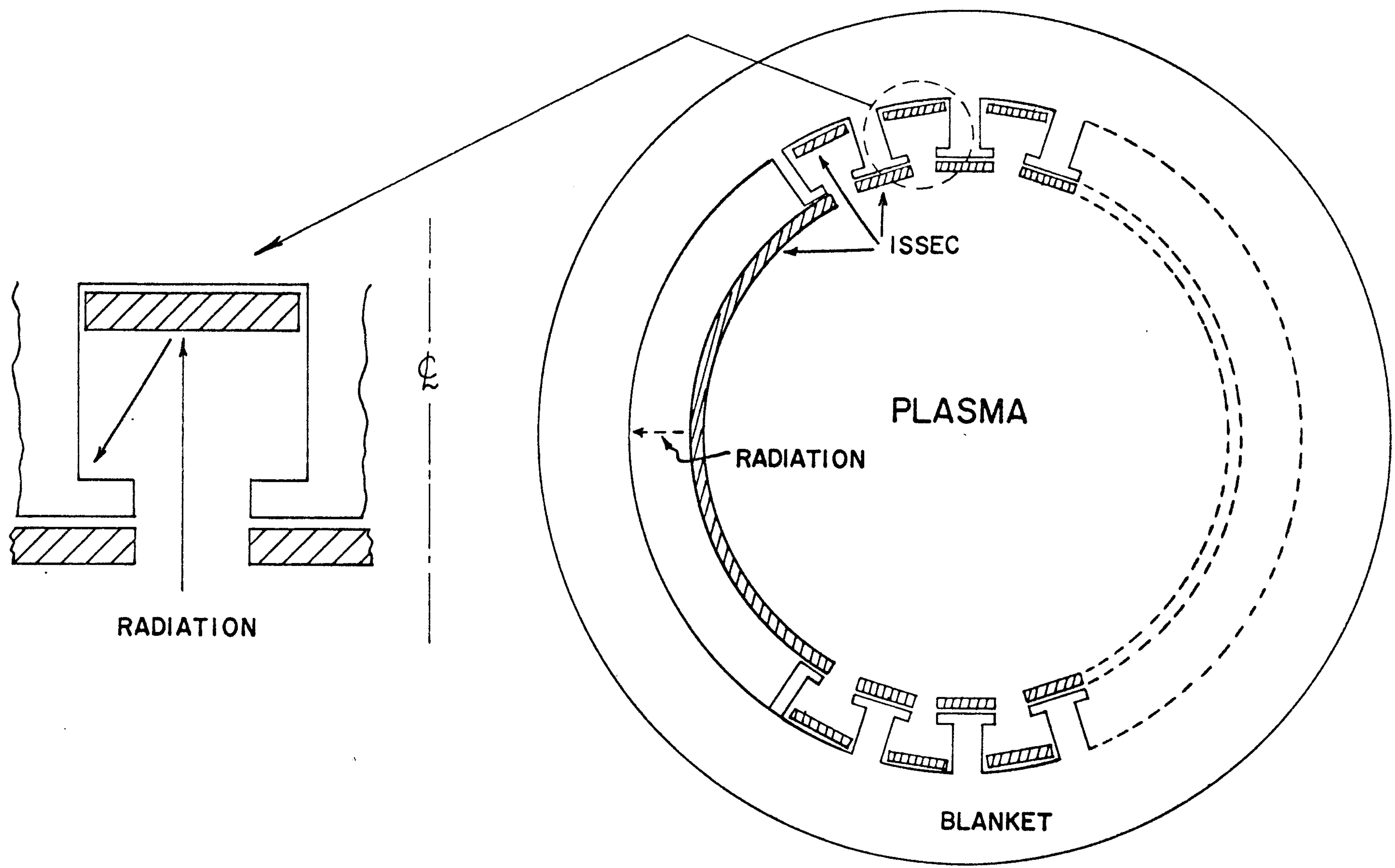


FIG. 3 SCHEMATIC DRAWING OF A MODIFIED ISSEC SYSTEM

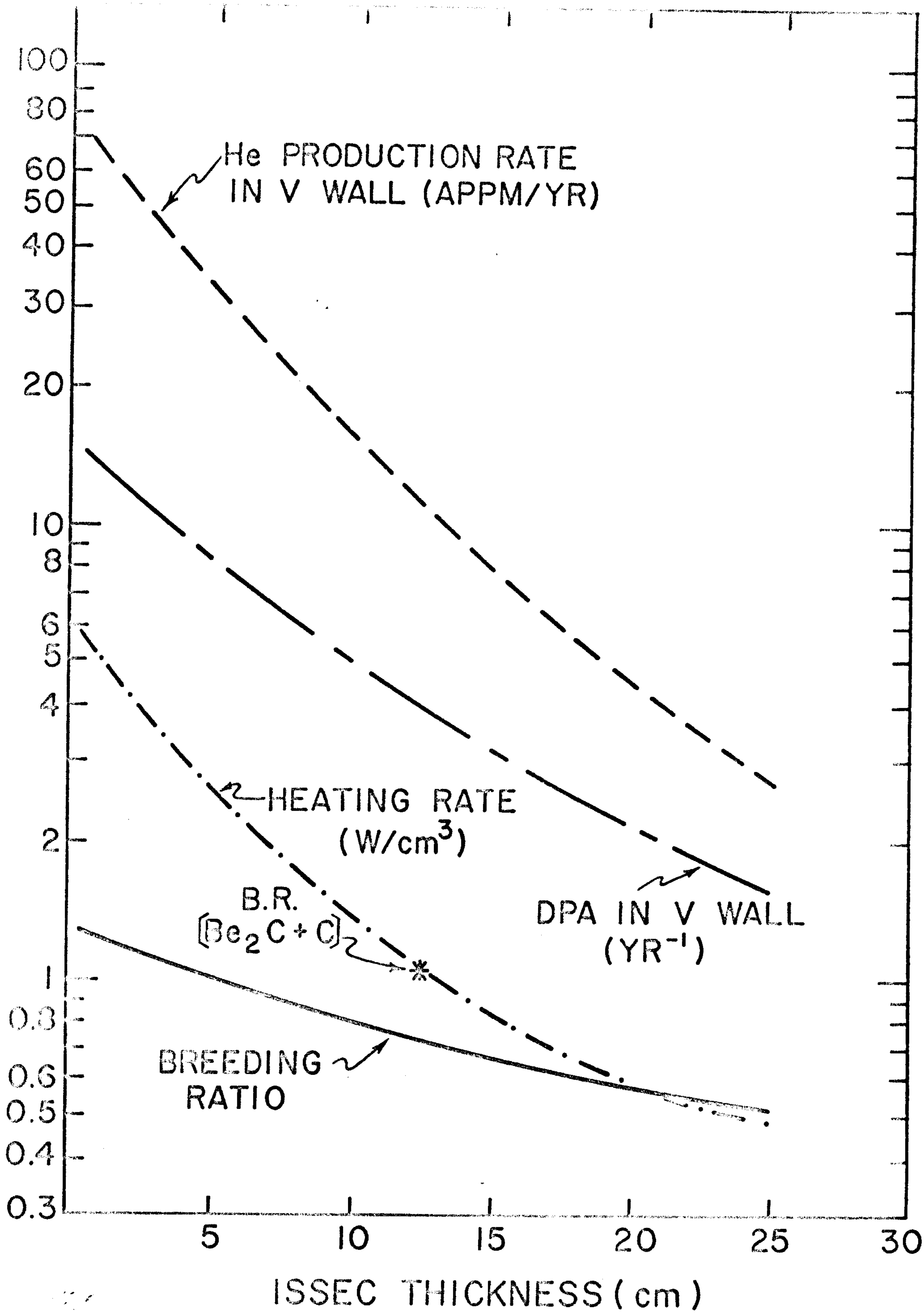


FIG. 4 SUMMARY OF NEUTRONIC RESULTS FOR A BASIC ISSEC SYSTEM

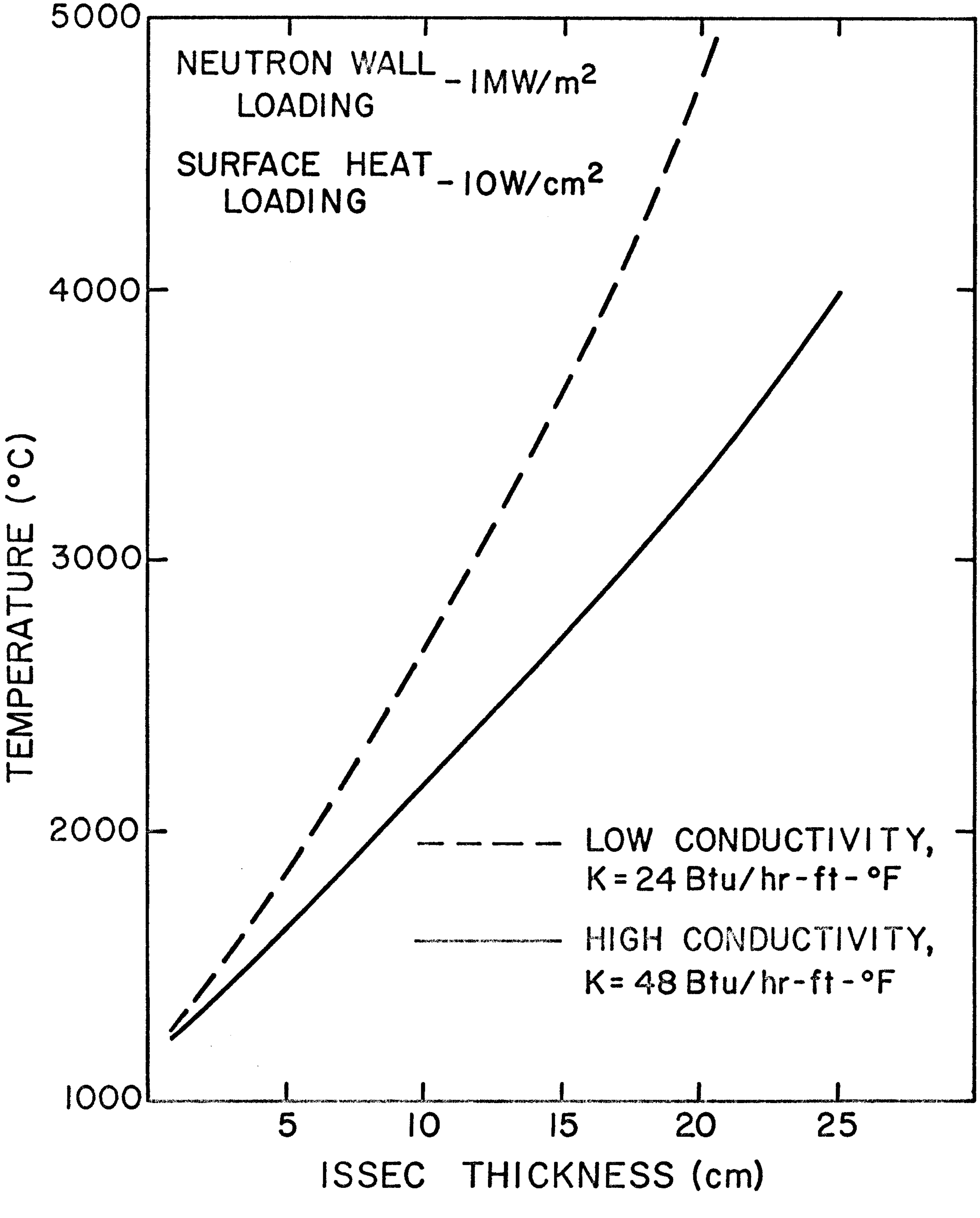


FIG. 5 MAXIMUM TEMPERATURE OF BASIC ISSEC AS A FUNCTION OF ISSEC THICKNESS

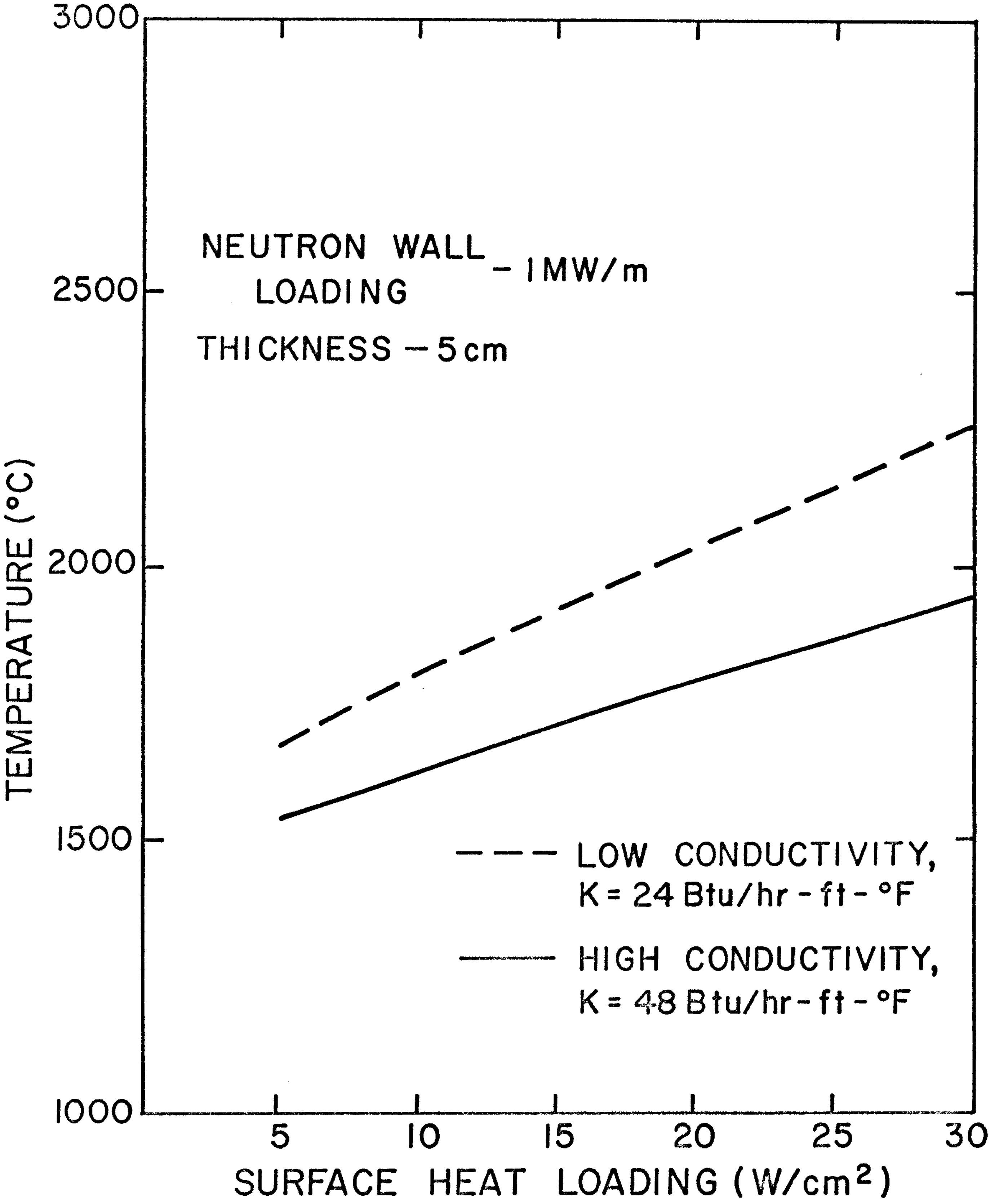


FIG. 6 MAXIMUM TEMPERATURE OF BASIC ISSEC AS A FUNCTION OF SURFACE HEAT LOAD

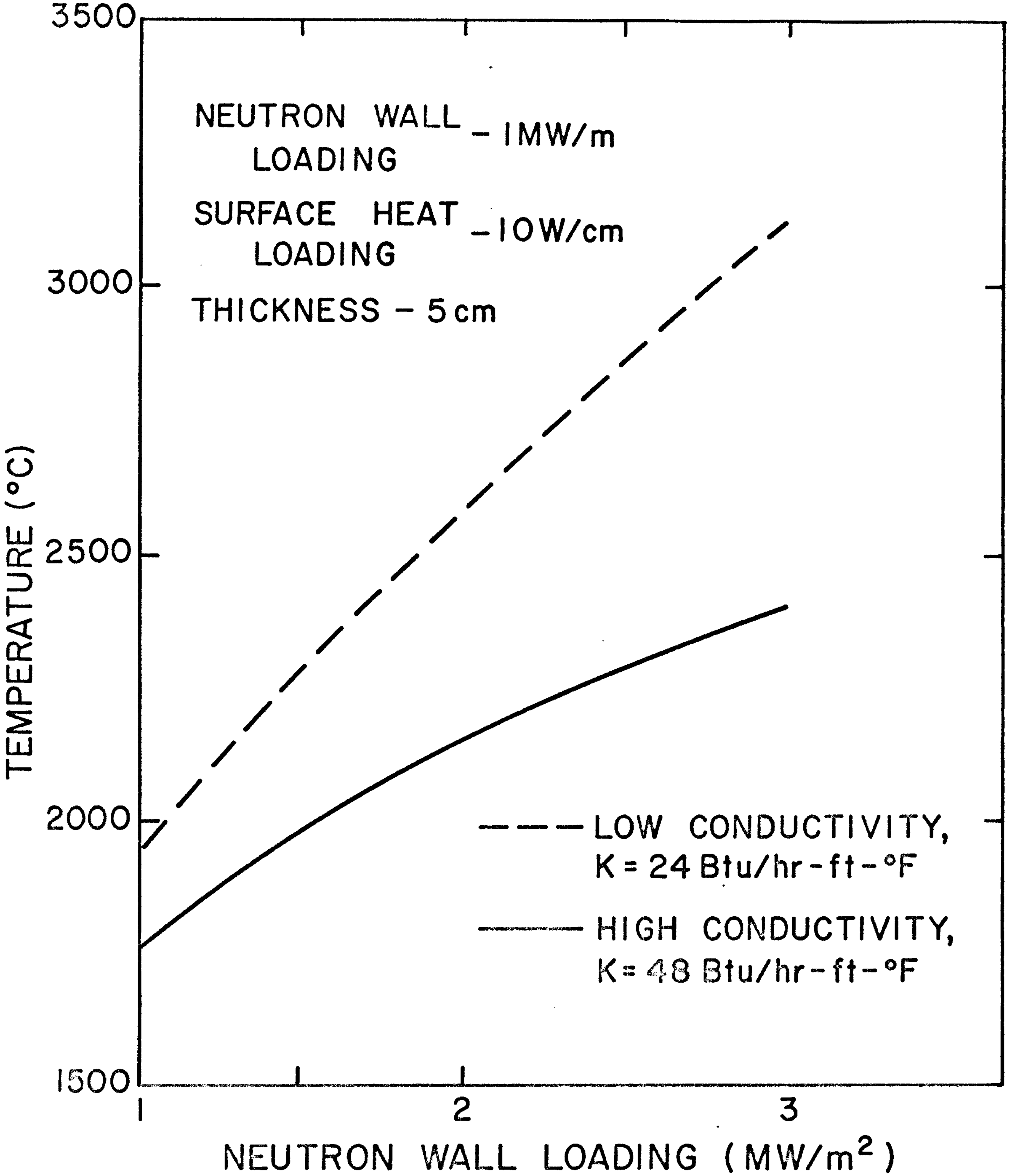


FIG. 7 MAXIMUM TEMPERATURE OF BASIC ISSEC AS A FUNCTION OF NEUTRON WALL LOADING

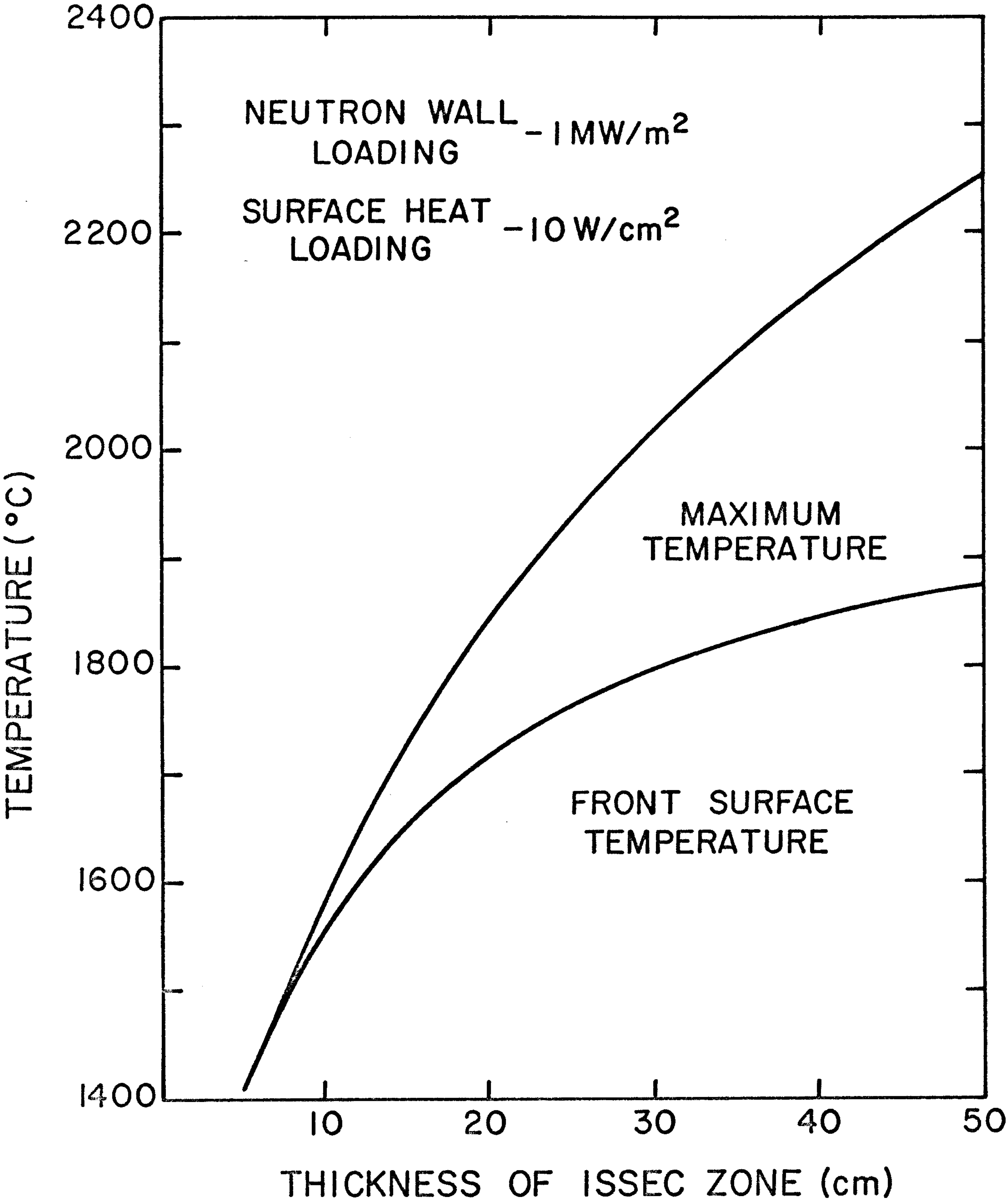
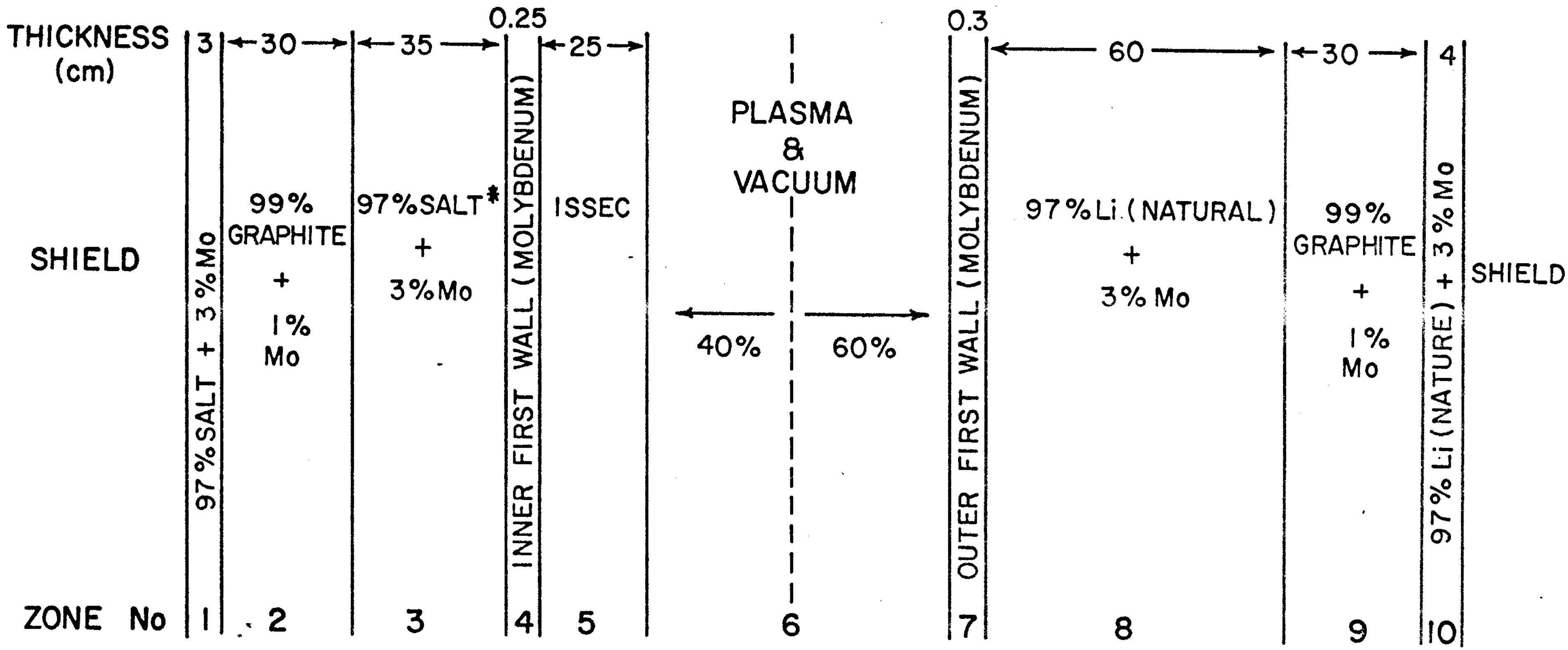


FIG. 9 TEMPERATURE OF PARTIAL ISSEC AS A FUNCTION OF ISSEC THICKNESS



* SALT IS A MIXTURE OF 50%LiF AND 50%KF

FIG.8 SCHEMATIC OF PARTIAL ISSEC BLANKET

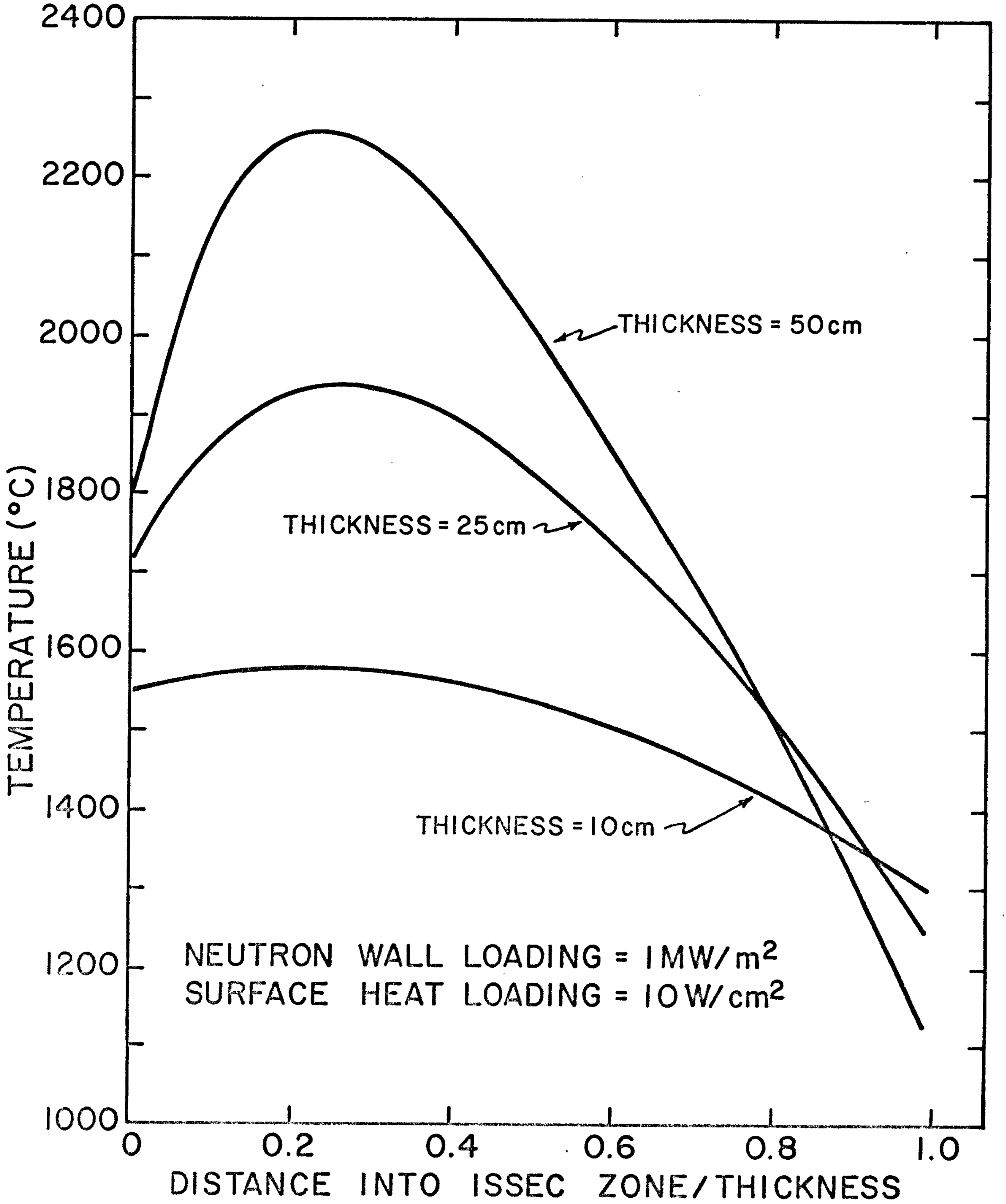


FIG. 10 TEMPERATURE DISTRIBUTION FOR VARIOUS PARTIAL ISSEC THICKNESS

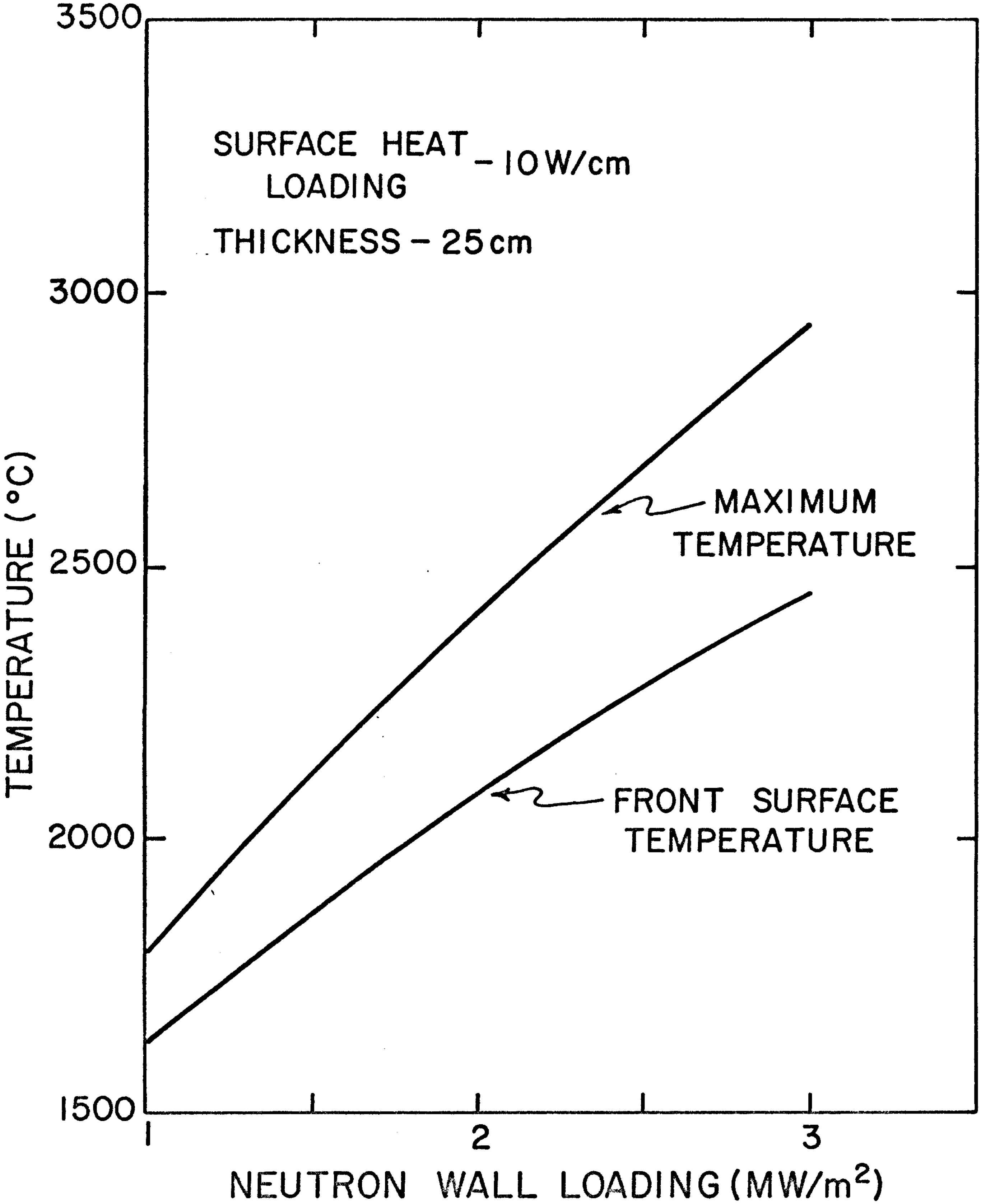


FIG. 11 TEMPERATURE OF PARTIAL ISSEC AS A FUNCTION OF NEUTRON WALL LOADING

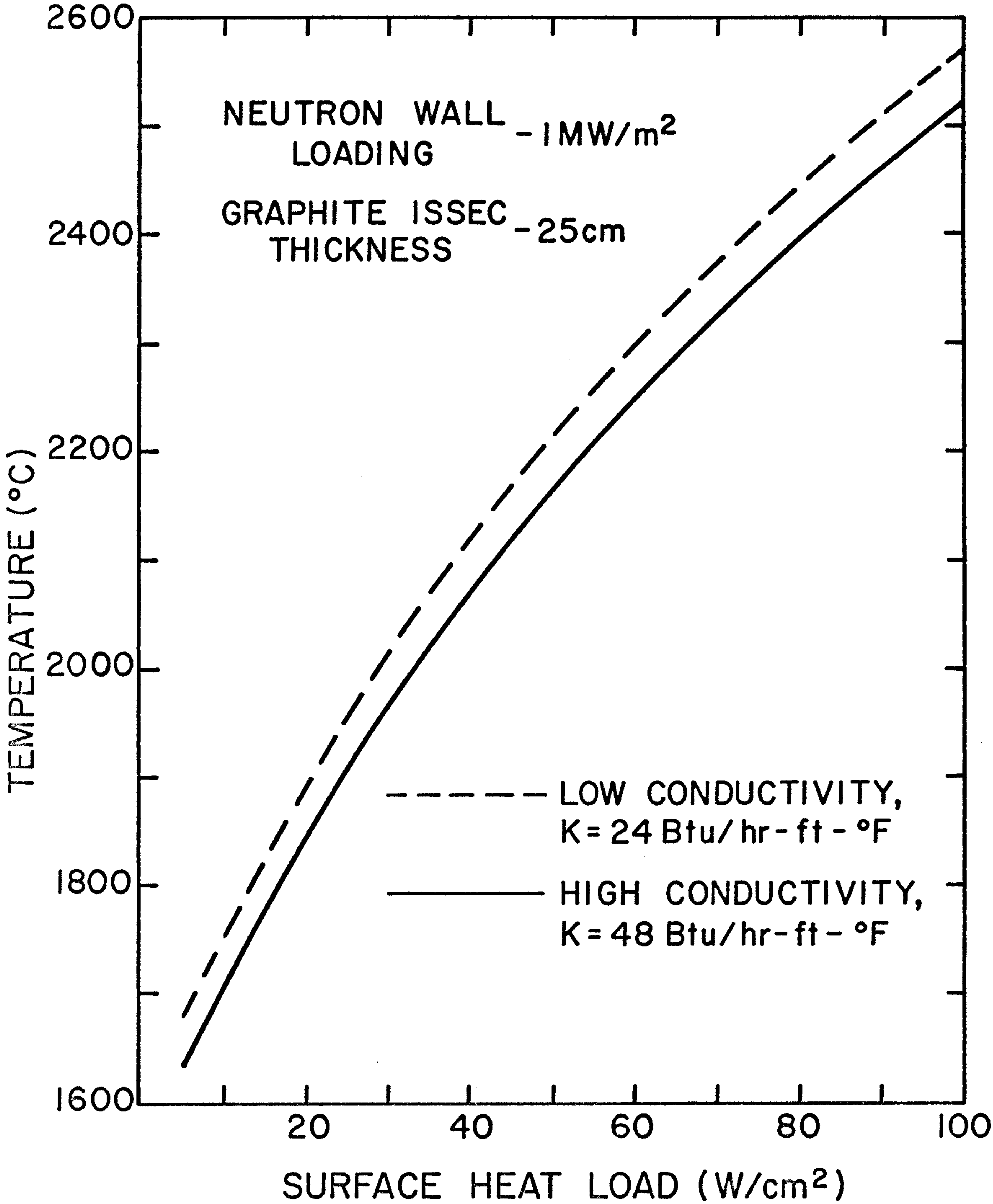


FIG. 12 TEMPERATURE OF PARTIAL ISSEC AS A FUNCTION OF SURFACE HEAT LOAD

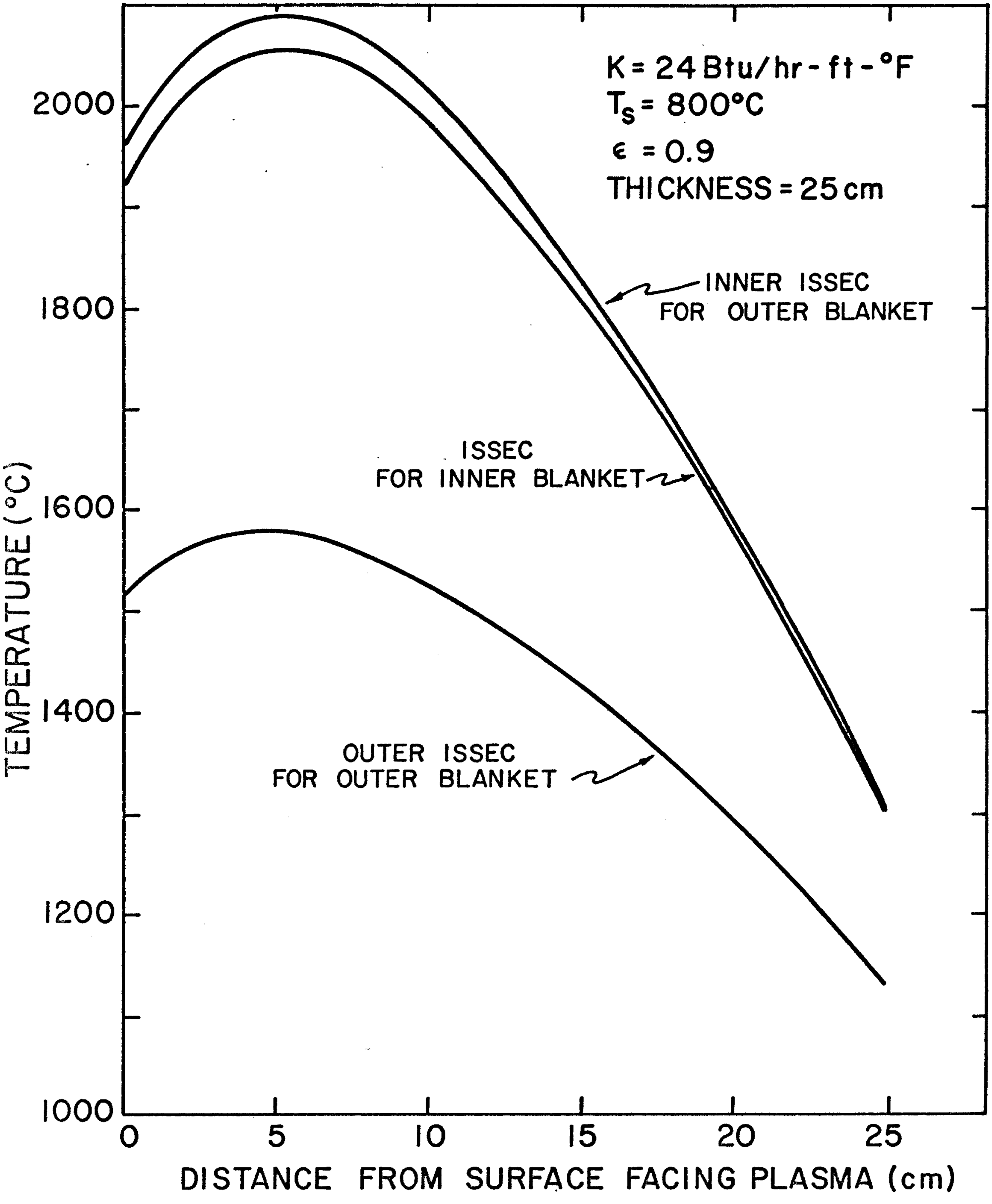


FIG. 13 TEMPERATURE WITHIN THREE DIFFERENT ZONE OF MODIFIED ISSEC