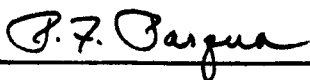


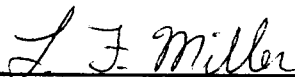
To the Graduate Council:

I am submitting herewith a thesis written by Amir Sassan Mobasheran entitled "Thermal Design and Heat Transfer Analysis of the OC-6 Graphite Irradiation-Induced Creep Test Capsule." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Nuclear Engineering.


Hall C. Roland, Major Professor

We have read this thesis
and recommend its acceptance:







Accepted for the Council:



Vice Chancellor
Graduate Studies and Research

THERMAL DESIGN AND HEAT TRANSFER ANALYSIS OF
THE OC-6 GRAPHITE IRRADIATION-INDUCED
CREEP TEST CAPSULE

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Amir Sassan Mobasheran
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greatefully aknowledged.

ABSTRACT

Graphite, due to its excellent nuclear, physical, and mechanical properties, is widely used in nuclear reactors; specially, it is utilized effectively, and in large quantities, as neutron moderator, reflector, and supporting structure in high-temperature gas-cooled reactors (HTGR's). This large application of graphite has justified extensive studies of its properties under simulated reactor core conditions.

One of the critical properties of nuclear graphite is its creep in a neutron-irradiation environment, referred to as "irradiation-induced creep". Knowledge of this creep and its dependence on neutron fluence, temperature, and stress is of paramount importance to the reactor designer to insure the structural integrity and dimensional stability of the graphite core. This knowledge can only be obtained by conducting rather complex and costly irradiation experiments.

It is the aim of this work to present the thermal design and analysis of a new graphite irradiation-induced creep test capsule, designated the OC-6 capsule. This capsule is cylindrical in shape and contains two cylindrical graphite specimen columns, one of which will be kept under constant compressive stress during the course of the irradiation experiment. The experiment is to be performed in the Oak Ridge Research Reactor (ORR), where the capsule will be placed at the E-5 position of the core for a total

period of several reactor power-cycles; the post-irradiation studies will be done after its removal from the core.

The main concern in the thermal design of the capsule is to make it capable of maintaining a constant temperature of 1200 C on the surface of the specimens, while not allowing that of the surrounding graphite block, at thermocouple locations, to exceed 950 C. Gamma heating will be the only heat source in the capsule. A modified version of the HEATING5 computer code was utilized to perform the heat transfer calculations for a computational model of the capsule in three-dimensional cylindrical coordinates.

In order to achieve the required high temperature, it was found that a thermal radiation reflector was required around the specimen columns. Tungsten was chosen for this reflector. Each tungsten sleeve is separated from the corresponding specimen column and the graphite block (surrounding both) by two annular gas gaps, referred to as the Inner Gap (IG) and Middle Gap (MG), respectively. A third annular gas gap, referred to as the Outer Gap (OG), separates the graphite block from the stainless-steel containment of the capsule which is in contact with the reactor coolant.

Because of the non-flat axial distribution of the gamma-heating rate, and due to the flat temperature distribution required for the specimens, the width of the MG and OG must be changed, stepwise, in the axial direction;

and a proper mixture of helium and neon must be used, as the sweep gas, to flow through the gaps. For a fixed power profile, the widths of the gaps and the conductivity of the gas mixture are the only two available tools in controlling the distribution and the level of the temperature within the specimens.

The main goal of the thermal design has been achieved by being able to maintain about half of the length of each specimen column (30 cm) at a rather flat temperature of 1200 C. The required gap widths, and their lengths, have been calculated. The overall level of temperature control has also been calculated for various He-Ne gas mixtures in the sweep gas.

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CHAPTER I

INTRODUCTION

1.1 Historical Background

Graphite, a solid phase of carbon, has been used in processes involving high temperatures at least since the fifteenth century, when crucibles for alloy melting were made from natural graphite. In 1896 E. G. Acheson discovered a method for manufacturing graphite (artificial graphite), which made it possible to produce forms with properties suitable for specific applications, mainly at high temperatures. As the result of this discovery, a variety of graphite grades, uniquely suited for use at high temperatures, have been developed.[1]

In addition to its high refractoriness, graphite has mechanical and physical properties (low elastic modulus, high thermal conductivity, and low coefficient of thermal expansion) which give it a high resistance to thermal shock. This feature is important in the design of structures to be used at elevated temperatures, from the viewpoints of dimensional stability and structural integrity.[2]

In 1942 graphite was used in the first nuclear reactor, CP-1, shown in Figure 1.1, as neutron moderator and reflector, because, at that time, it was the only suitable material readily available [4]. In the same year E. P. Wigner suggested that neutron-irradiation might affect the

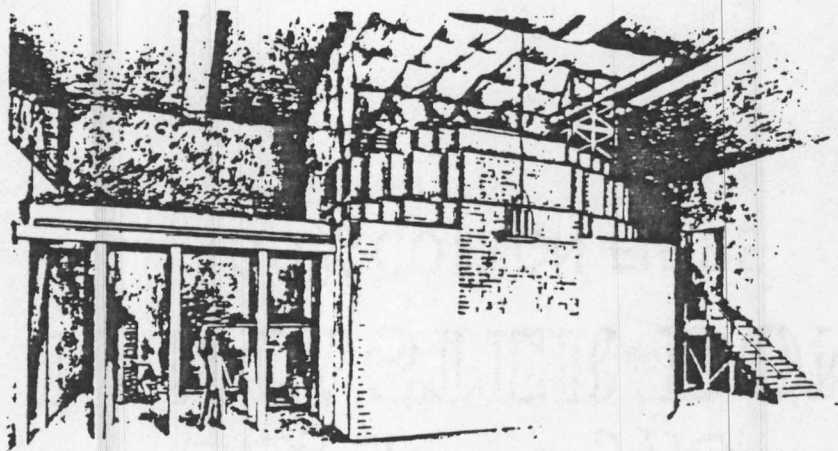


Figure 1.1. The first Nuclear Reactor, CP-1, constructed under the West Stands of Stagg Field, University of Chicago [3].

properties of moderator graphite by displacing carbon atoms from their normal positions and consequently producing lattice defects [5]. Early research and test reactors were constructed with little knowledge of radiation-induced effects on the properties of moderator graphite, such as dimensional changes or storage and release of energy. This lack of foreknowledge caused problems in the operation of some of those reactors [6]. Irradiation experiments soon confirmed Wigner's prediction and since then, the radiation-induced changes (Wigner effects) in graphite have been studied extensively.

1.2 OC-series Experiments at ORNL

Several years ago, a series of irradiation experiments, referred to as the OC-series, started at Oak Ridge National Laboratory (ORNL) under the supervision of the Metals And Ceramics Division with the joint effort of the Experimental Engineering Division. The main purpose of conducting these experiments, utilizing the experimental facilities of the Oak Ridge Research Reactor (ORR), has been the study of irradiation-induced creep in different grades of nuclear graphite at elevated temperatures up to 1200 C. The results of these studies will be used in the characterization and standardization of graphite for the High-Temperature Gas-Cooled Reactor (HTGR) program.

Some creep-data, for temperatures of 600 C and 900 C, different fluences, and two different compressive

stresses, have been obtained by conducting irradiation experiments in the OC-1 through OC-4 irradiation capsules. Experiments for 1200 C will be started after constructing the 1200 C irradiation-induced creep-test capsule (OC-6 capsule), whose thermal design is the subject of the current work.

1.3 Organization of the Thesis

The Introduction, Chapter I, provides a historical background about graphite, its important properties, its role in nuclear reactors, and the importance of studying its behavior in neutron irradiation environments; then, the OC-series capsules are briefly introduced. Finally, the organization of the materials covered in the current thesis is explained.

Chapter II introduces, in general, the creep and relaxation phenomena in materials and, in particular, the mechanism of graphite creep in a neutron irradiation environment. Some important features of the already-designed OC-series irradiation capsules are also covered in this chapter.

The basic design geometry of the OC-6 irradiation capsule, design restrictions, properties of the involved materials, and the gamma heating rate used in thermal analysis of the capsule are included in Chapter III.

Chapter IV contains a rather brief description of the HEATING5 computer code, emphasizing those features of the code which were utilized during the thermal analysis of the capsule.

Chapter V describes the physical and computational models of the capsule. Development of an input processing code, based on the geometry of the computational model, for HEATING5 code, the preliminary two-dimensional analysis, and the modification of the HEATING5 program are also covered in this chapter.

The three-dimensional thermal analysis and the axial shifting phenomenon in the gamma heating rate are contained in Chapter VI.

A summary and the results of the calculations are included in Chapter VII.

Appendix A discusses gamma heating in the nuclear reactor core environment and Appendices B through D contain the computer programs which were developed to facilitate the thermal design of the capsule.

CHAPTER II

GRAPHITE, CREEP, AND IRRADIATION EXPERIMENTS

After a brief description of graphite and its importance in HTGR's, this chapter explains the "creep" and "relaxation" phenomena in materials in general, and the mechanism of irradiation induced creep in graphite, in particular. Next, the related experiments are discussed. Finally, the already-designed OC-series irradiation capsules are introduced in this chapter.

2.1 Graphite and High temperature Gas Cooled Reactor

Due to its excellent moderating capability (having large values for logarithmic energy decrement, macroscopic slowing down power, and moderating ratio) and its adequate strength at temperatures up to and above 2000 C [7], graphite is widely used in nuclear reactors. Especially, it is utilized effectively, and in large amounts, as neutron moderator, reflector, and supporting structure in HTGR's, as well as being used as fuel and control-rod matrix material. As an example, the core of an 860-MWe HTGR, designed in the United States, contains about 1500 metric tons of high-purity nuclear-grade moderator blocks which fills a cylindrical volume 28 feet in diameter and 21 feet high. Figure 2.1 shows a typical HTGR; the reactor core and steam generators are depicted in Figure 2.2.[8]

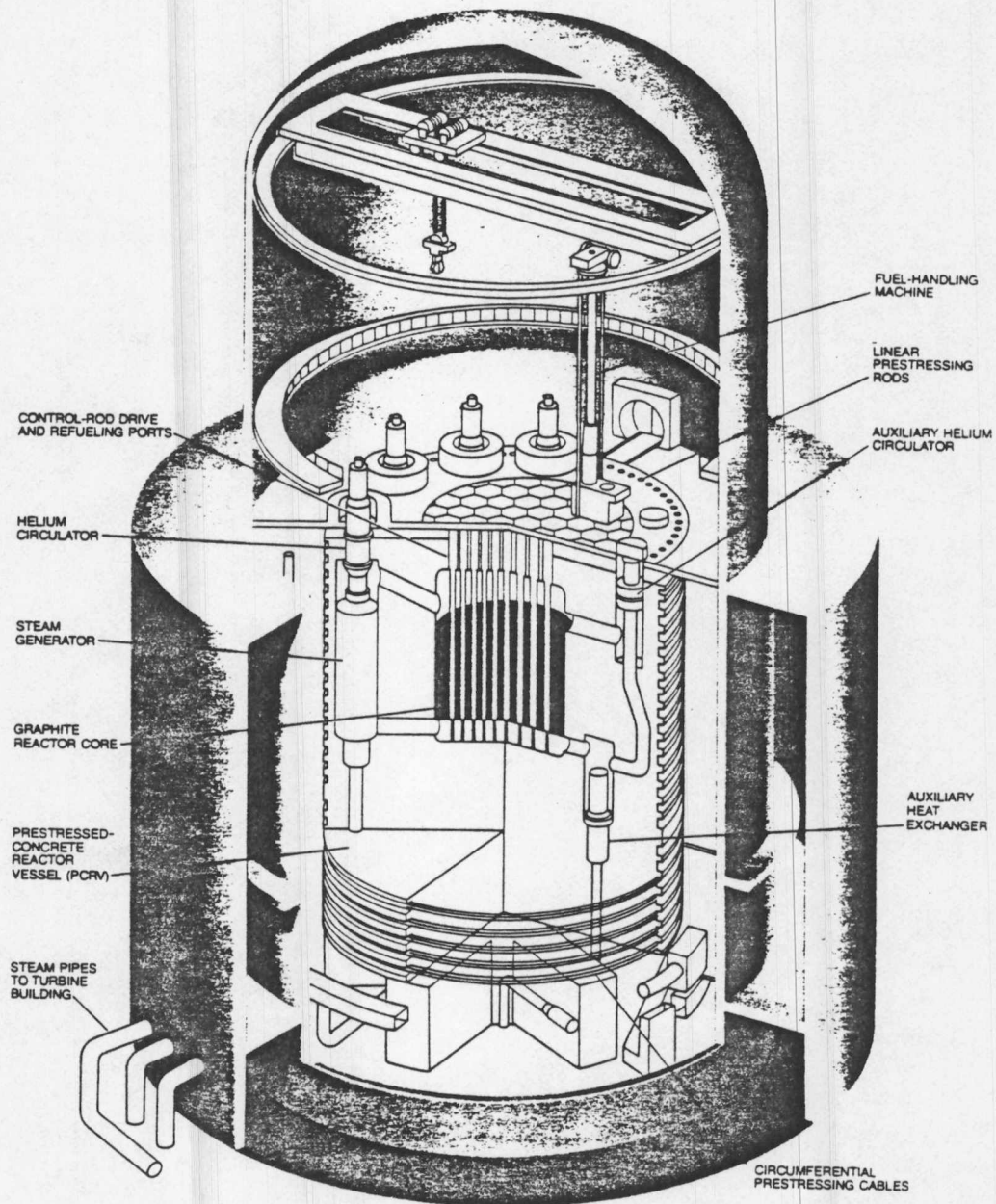


Figure 2.1. High-Temperature Gas-Cooled Reactor (HTGR).

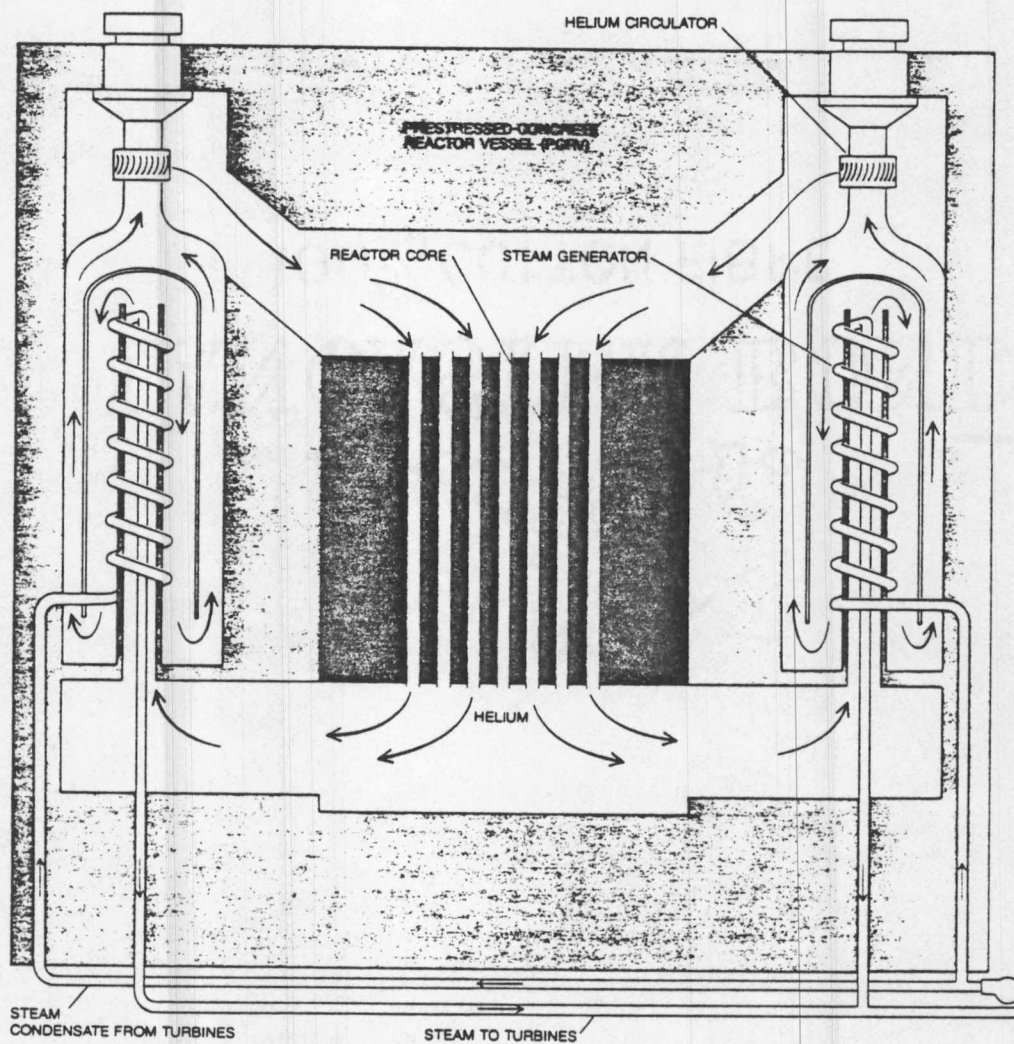


Figure 2.2. Reactor Core And Steam Generators Of The HTGR.

2.2 Creep and Relaxation in Materials

From the structural design standpoint, the elastic and plastic behavior of materials at high temperatures is extremely important, particularly the creep properties or the plastic deformation which occurs, as a function of time, under constant stress (tensile or compressive), and at a given temperature [9]. Creep is defined as the time-dependent plastic deformation (permanent strain) of a solid subject to constant stress and constant temperature. In other words, creep phenomenon in a solid is a function of time, stress, temperature and the material under consideration.

For most materials, creep behavior exhibits three stages, as shown in Figure 2.3. The constant slope in stage 2 is the minimum strain rate for the material and the creep test conditions. Figure 2.4 shows a family of actual creep curves for a constant temperature and three stress levels. In Figure 2.4(b), the time to rupture is plotted against stress for various temperatures; it should be noted that, in this figure, a separate creep test is required for each experimental point of each curve, whereas each curve in Figure 2.4(a) has been obtained by only one creep test.[10]

Another mechanical phenomenon, associated with creep and called "relaxation", occurs as a time-varying decrease in stress in a solid material that is held in a relatively fixed external configuration. In other words, relaxation is

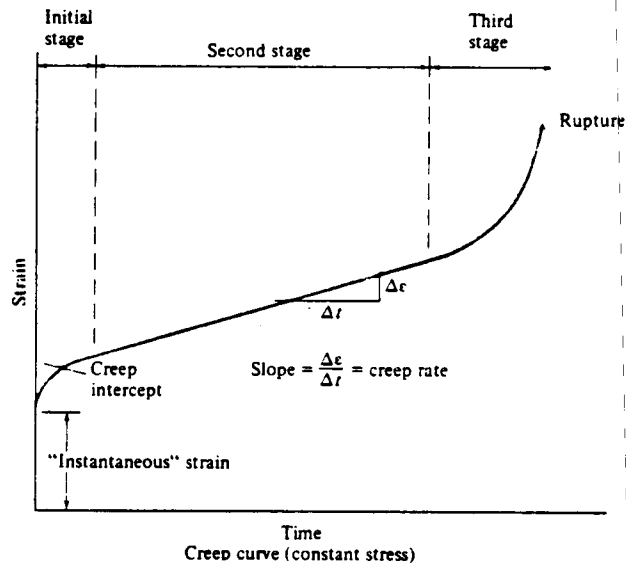
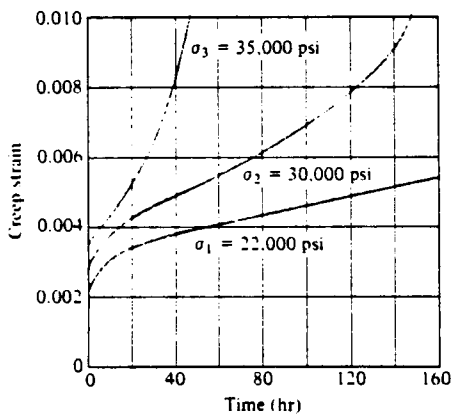
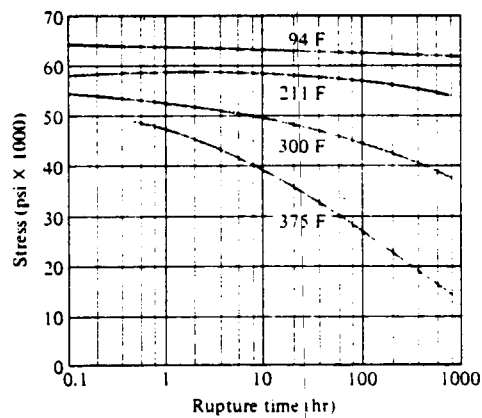


Figure 2.3. General Shape of Creep Curve (Constant Stress) for many Materials.



(a)



(b)

Figure 2.4. Creep Curves for Alclad 2024-T3 aluminum alloy sheet (a) at 400 F and (b) at a thickness of 0.040 in.

the relief of stress by internal creep. If a material is susceptible to creep, it is also susceptible to relaxation. A plot of the reduction of stress with time can be made to analyze this relaxation behavior for constant strain as in Figure 2.5. Relaxation, as with creep, is more common and occurs at a faster rate at high temperatures.[11]

2.3 Irradiation-induced Creep in Graphite

Knowledge of the creep behavior of graphite moderator, in the neutron-irradiation environment, is of paramount importance to the reactor designer in assuring the dimensional stability and structural integrity of the graphite core. In the radiation field, neutron fluence acts as the fourth variable upon which the creep is dependent (the other three, as mentioned in Section 2.2, are: stress, time, and temperature.)

Thermally-induced creep in graphite is not of significance at temperatures below 2000 C, but, irradiation-induced creep becomes an important phenomenon at temperatures as low as 300 C [12]. This is due to the stresses resulting from the time-varying differential growth, which, in itself, is caused by the neutron flux and the temperature gradients in the graphite-moderator blocks. Fortunately, graphite is able to creep under irradiation which allows the relaxation of stress intensity below critical levels for fracture [13]. The design of the graphite blocks is highly reliant upon the knowledge of

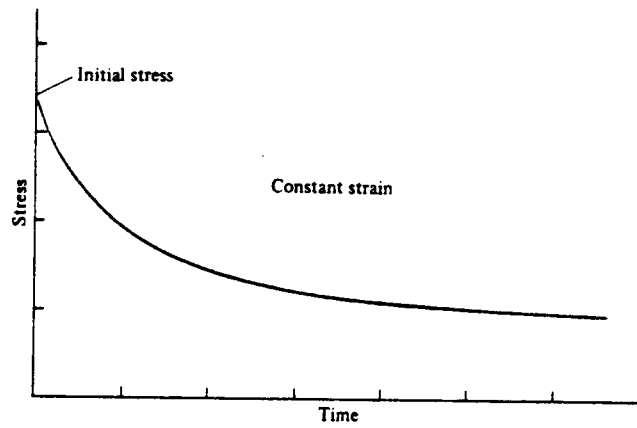


Figure 2.5. Reduction of Stress with time, due to Relaxation Phenomenon.

these effects in order to achieve a dimensionally stable core. This knowledge can be enhanced through performing elaborate irradiation experiments.

Figure 2.6 depicts the characteristic creep behavior of graphite, consisting of a quasi-elastic transient (primary creep) component, which can be recovered if the stress is removed during irradiation, followed by a steady-state plastic (secondary creep) component, which is not recoverable. The primary (transient) and the secondary (steady-state) creep strains increase with increasing irradiation temperature in the range of 500 C to 1200 C; and are proportional to the applied stress and equal in magnitude for tensile or compressive stresses.[14]

2.4 Graphite-Creep Irradiation Experiment

Generally, there are three main steps involved in studying irradiation-induced defects in materials:

The first step requires the design and construction of a capsule which contains the specimen(s) under consideration and the necessary sensing and measuring devices. For creep testing, the designed capsule must be capable of maintaining the required constant temperature within and necessary constant stress on the specimen(s). The physical size and shape of the capsule are dictated by the specific experimental objectives and the physical limitations of the experimental hole of the reactor, where

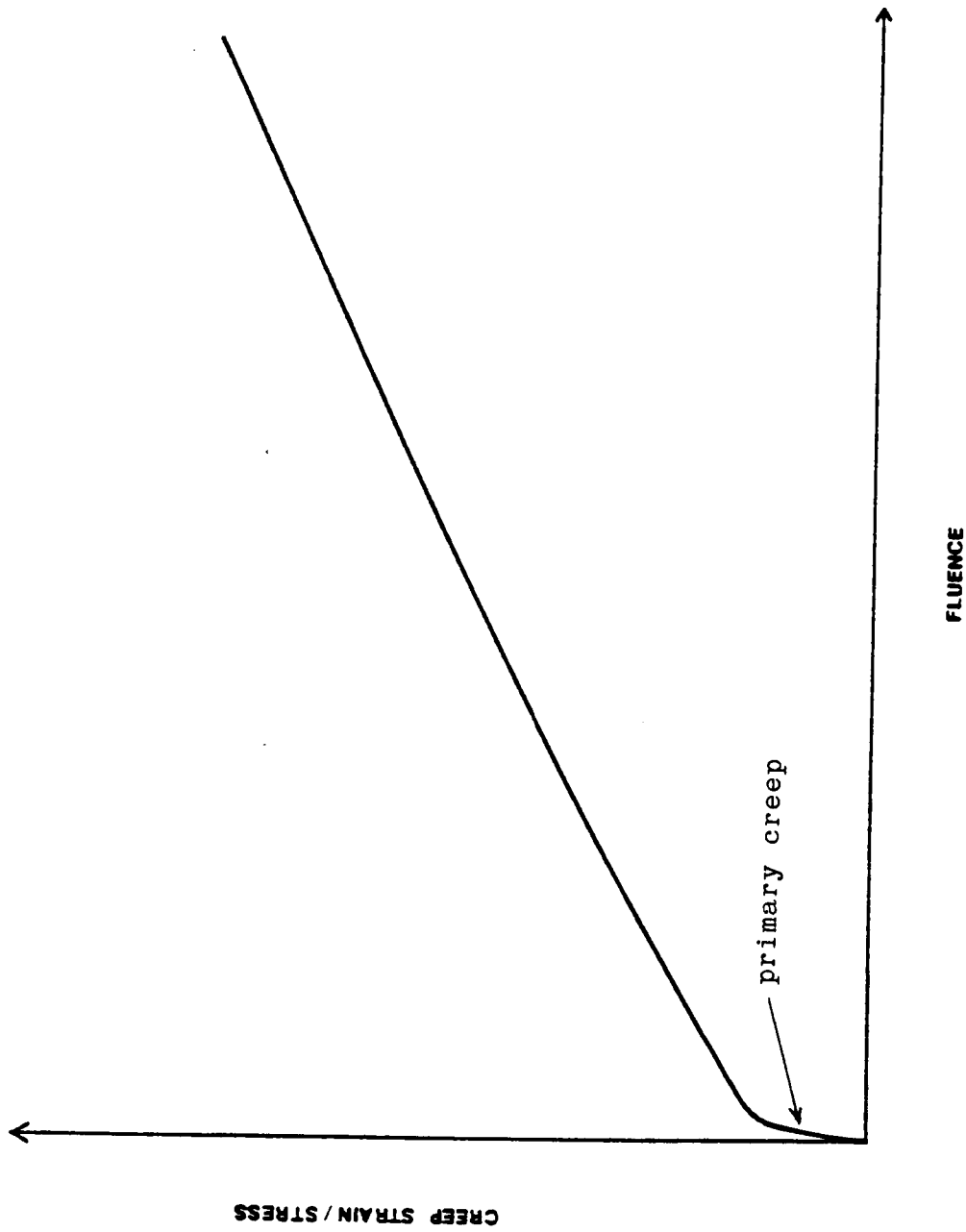


Figure 2.6. Characteristic Creep Behavior of Graphite.

the capsule is to be inserted and irradiated.

In the second step, the capsule is inserted, operated, and monitored in a predetermined experimental hole of the core. The total length of its residence at that location depends upon the test requirements.

Finally, in the third step, the post-irradiation studies of the specimen(s) are made after removing and disassembling the capsule. These studies include measuring the dimensional changes, Young's modulus of elasticity, electrical resistivity, sonic velocity, bulk density, and the coefficient of thermal expansion (CTE).

For irradiation-induced creep studies, monitoring the creep strain continuously, during the test and as a function of neutron fluence, is the best way to accurately determine the creep coefficients. Nevertheless, this method has the disadvantage of high cost and extreme experimental difficulties associated with the complications involved in the test design and the maintenance of the in-pile strain measuring devices or dilatometers.[15]

In the technique that has been employed in a series of graphite-creep irradiation experiments (OC-series) at the Oak Ridge National Laboratory (ORNL), specimen columns, composed of strings of graphite samples, have been used. In this technique the creep strain is measured after the removal and disassembly of the capsule; re-encapsulation and re-irradiation is required if further strain measurements are necessary.

2.5 OC-series Irradiation Experiments

The OC-series experiments were briefly introduced in Chapter I. This section provides a somewhat more detailed description.

The basic objective in performing these experiments, each employing an irradiation capsule, has been to study the fast-neutron-induced creep of graphite at elevated temperatures. The position E-5 of the ORR core is the source of fast neutrons (> 0.18 MeV) for the experiments. This position provides a 76 x 76 mm (3 x 3 in.) water-cooled facility, which accommodates an experiment of up to about 71 mm (2.8 in.) overall diameter. Both the primary and secondary creep coefficients are to be determined (the basic objective); as well as physical and other mechanical property data required to fully characterize the graphites employed in HTGR. These data can also be useful to other reactor designs such as the molten salt (breeder) and fusion reactors. The primary and secondary creep coefficients are to be determined as functions of fluence, temperature, stress, and Young's modulus of elasticity. To achieve this goal, specimens of graphites of interest are being irradiated at 600, 900, and 1250 C in a geometric progression of the fast fluence increments, while being under the constant compressive stresses of 13.8 and 20.7 MPa (2000 and 3000 psi) at each temperature. For one cycle of

the ORR, the accumulated increment of the fast fluence, at the E-5 position, is approximately 1.0×10^{21} n/cm². The irradiation capsules (OC capsules) which were designed and employed in the experiments for the temperatures of 600 and 900 C are of the same basic design shown in Figure 2.7. Each capsule contained four specimen columns; and each column was composed of a string of carefully-machined graphite samples. For example, capsule OC-1 was designed to irradiate twenty-eight 15.24-mm-diam by 25.4-mm-long (0.600-by 1.00-in.) specimens at 900 C to the first planned exposure level of 1×10^{21} n/cm² (>0.18 MeV) [15]. Figures 2.8, 2.9, and 2.10 show how the specimens, which have shallow holes at each end, are connected via the graphite pins, and centered by the spacers, to make a specimen column [17]. Two of these columns are under the constant compressive stresses (creep specimens or test specimens) and the other two are unstressed (control specimens). The unstressed control samples that match the stressed specimens are characterized before and after irradiation.

Basically, the dimensional differences between stressed specimens and their matching control specimens, after each cycle in the ORR, determine the total creep strains. Since the primary creep strain, provided the stress is removed, is recoverable under heating, it can be determined by re-heating selected stress-tested specimens to their test temperature and achieving the recovery.[16]

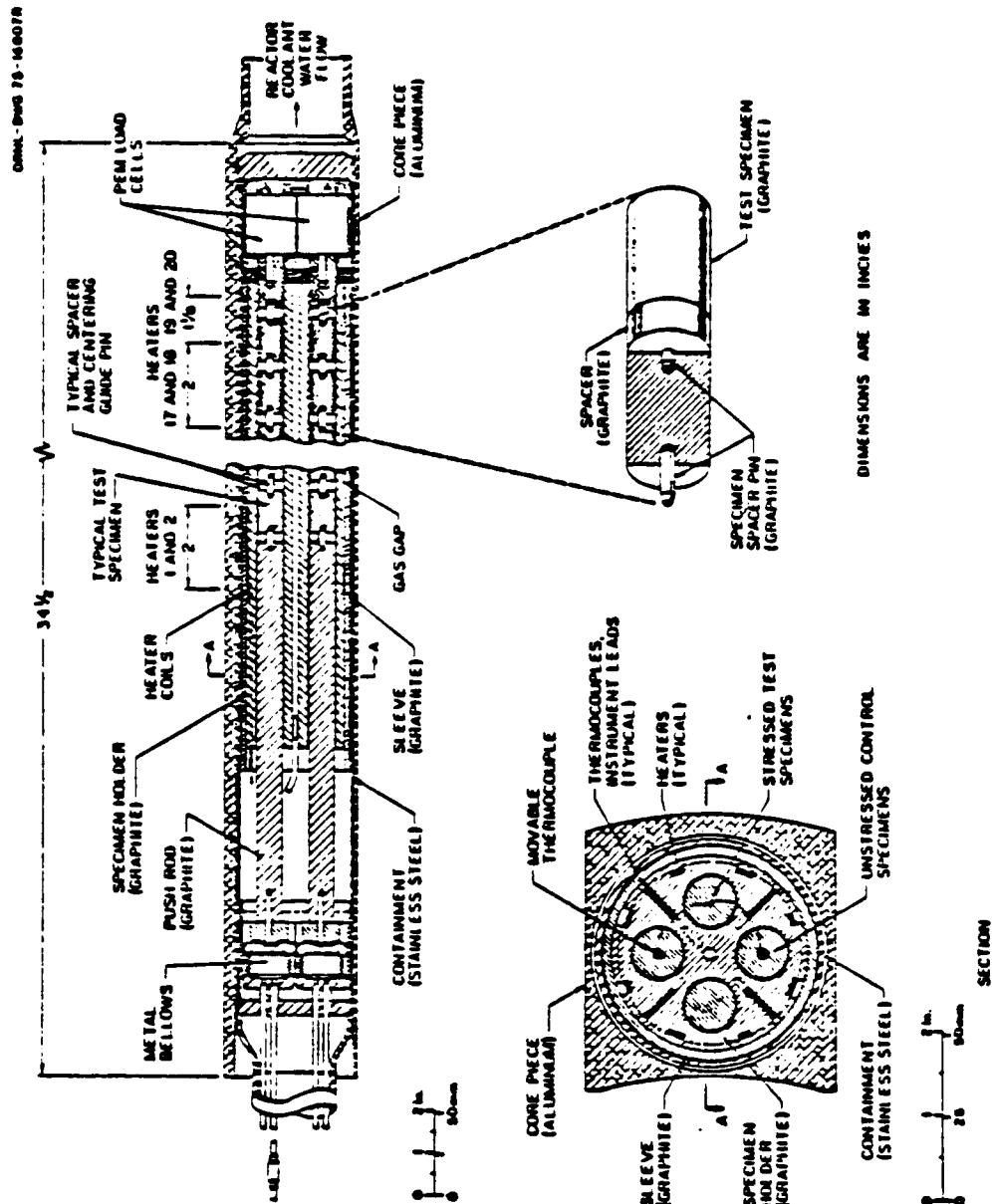


Figure 2.7. Radial and Axial Cross-Sections of the 900 C Irradiation Capsule (OC-1) showing Stressed and Un-stressed Specimen-Columns.

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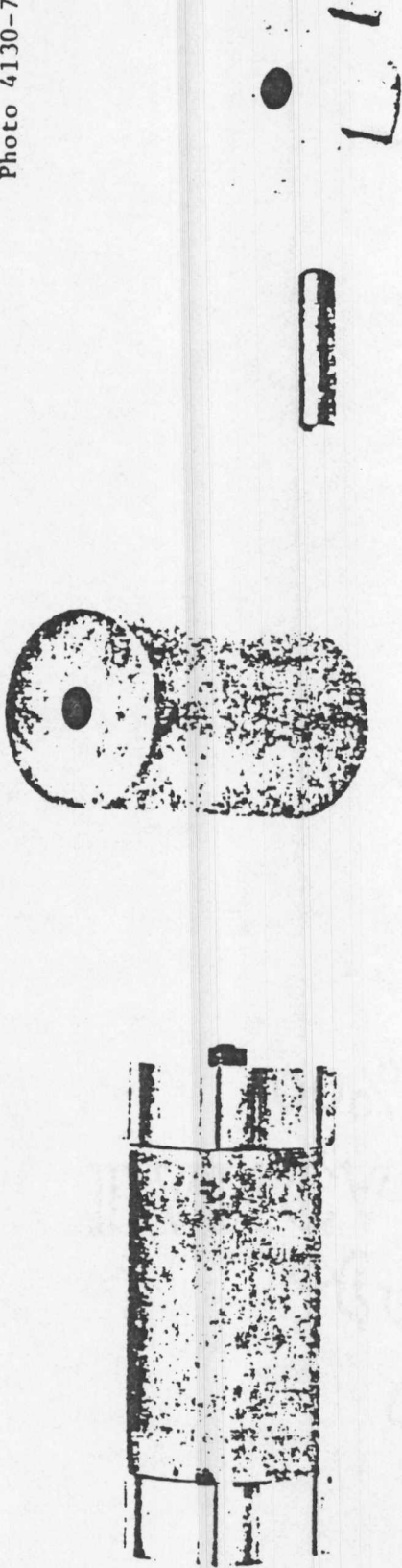


Figure 2.8. ORR CAPSULE OC-1 - Typical Stressed Specimen with Spacers and Centering Pins. 1.9x.

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Photo 4131-76

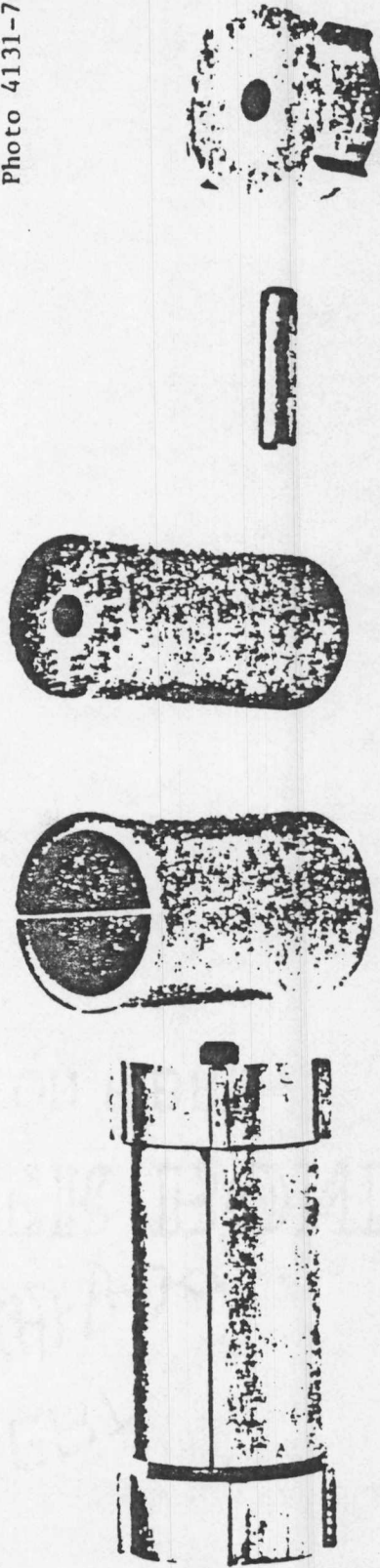


Figure 2.9. ORR Capsule OC-1 - Typical High-Stressed Specimen with Spacers, Centering Pins, and Split Sleeve. 1.9x.

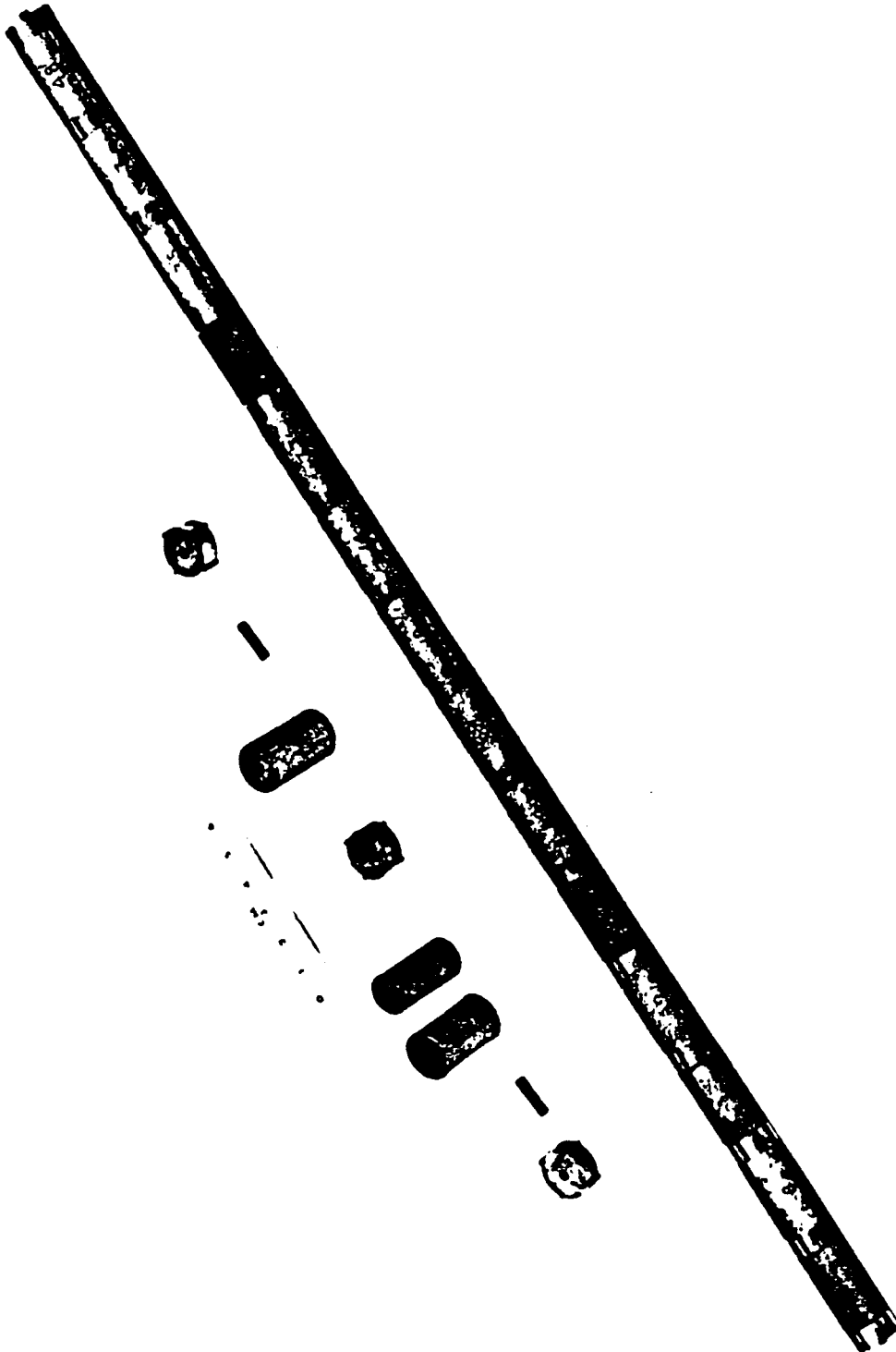


Figure 2.10. ORR Capsule OC-1 - Assembly of Stressed Column Before Insertion Into the Graphite Holder.

For each test temperature, an accumulated fluence of at least $8 \times 10^{21} \text{ n/cm}^2$ ($> 0.18 \text{ MeV}$), the full design fluence of HTGR, is required. A total irradiation time of 15 months is necessary for each set of specimens to attain the desired fluence.

A preliminary thermal design for the 1250 C irradiation-capsule (OC-5 capsule), based on the common basic design of the 600 and 900 C capsules (Figure 2.7) but with inclusion of a thermal radiation reflector around each specimen column, has been performed [14]. But, later, due to some considerations, it was decided to redesign a new capsule, for 1200 C, designated as the OC-6 capsule, whose thermal design is the purpose of this work and is discussed in the following chapters.

CHAPTER III

OC-6 IRRADIATION CREEP CAPSULE

The preliminary thermal design of the OC-5 capsule for 1250 C, mentioned in Section 2.5, considered the inclusion of a cylindrical tungsten sleeve around each specimen column (incorporating the basic design of the 600 and 900 C capsules) to achieve the required temperature within the specimens. The tungsten sleeve, whose interior surface is polished in order to have a low emissivity, acts as a thermal radiation reflector. A bench test [14] has been conducted to determine the emissivity of polished tungsten and check the constancy of this emissivity under some simulated capsule conditions.

Due to some experimental considerations, it was decided to make a new design, employing some features of the OC-5 capsule, for a 1200 C irradiation capsule, referred to as the OC-6 capsule. This chapter covers the description and the design requirements of the OC-6 capsule.

3.1 Basic Geometrical Configuration

The new design encapsulates two specimen columns, one of which will be kept under a constant axial compressive stress (stress specimen) and the other one (control specimen) will be unstressed during the experiment. The specimen columns, like those used in the other experiments (Figure 2.10), are composed of strings of graphite samples.

The stainless steel containment of the capsule has the same size as those incorporated in the previously designed capsules. Basically, the specimen columns are separated from the surrounding encapsulated graphite block by a gas gap (Inner Gap (IG)). The graphite blocks, themselves are separated from the containment by another gas gap (Outer Gap (OG)). These gas gaps are similar to those utilized in the previous relatively low-temperature capsules.

The preliminary design of the OC-5 capsule indicated that, to achieve the required high temperature within the specimens, a tungsten sleeve could be used as a thermal radiation reflector between the graphite blocks and each specimen column, in addition to the gas gap surrounding each column. Figure 3.1 depicts a cross section of the OC-6 capsule, incorporating the gas gaps used in the design of the OC-5 capsule but, having two specimen columns instead of four. It also has an additional gas gap between the tungsten sleeve and the main graphite block.

3.2 Initial Restrictions

The initial restrictions imposed on the design of the OC-6 capsule are the same as those for the design of the OC-5 capsule. These restrictions are:

1. The capsule was required to maintain a constant temperature of 1250 C on the surface of the each specimen columns by simply adjusting the gas gaps and the gas

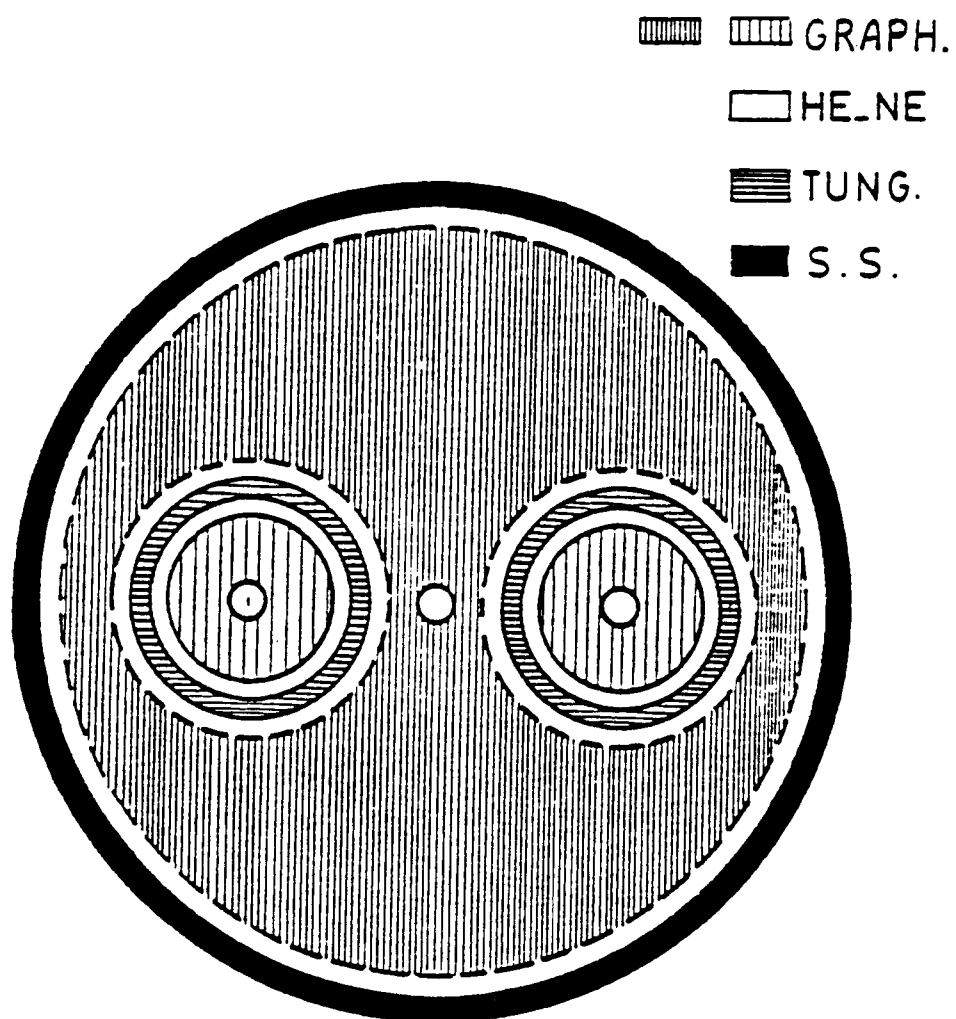


Figure 3.1. Radial Cross-Section of the Preliminary Model of the OC-6 Irradiation Capsule, incorporating the Gas Gaps used in the Preliminary Design of the OC-5 Capsule.

composition (a mixture of helium and neon).

2. The maximum temperature on the thermocouples to be located between the specimen columns, in the graphite blocks was not to exceed 950 C.

During the scoping step of the design, it was revealed that the first restriction had to be relieved in order to satisfy the second one; and, therefore, the chosen design temperature became 1200 C.

As it was pointed out before, during the course of the design of the OC-5 capsule, it became evident that, in order to achieve the required high temperature within the specimens, each specimen column had to be surrounded by a thermal radiation reflector with low emissivity. The material that was decided upon was tungsten. Therefore a tungsten sleeve was planned to be put around each specimen column. The inner surface of the tungsten sleeve was polished in order to obtain as low an emissivity for the surface as possible. Based on the results of the non-irradiated bench test, conducted for measuring the emissivity of the polished surface under OC-5 conditions, an emissivity of 0.45 was decided to be incorporated in the heat transfer analysis required for the OC-6 capsule.

Figure 3.2 shows the cross section of the OC-6 capsule for a typical axial position.

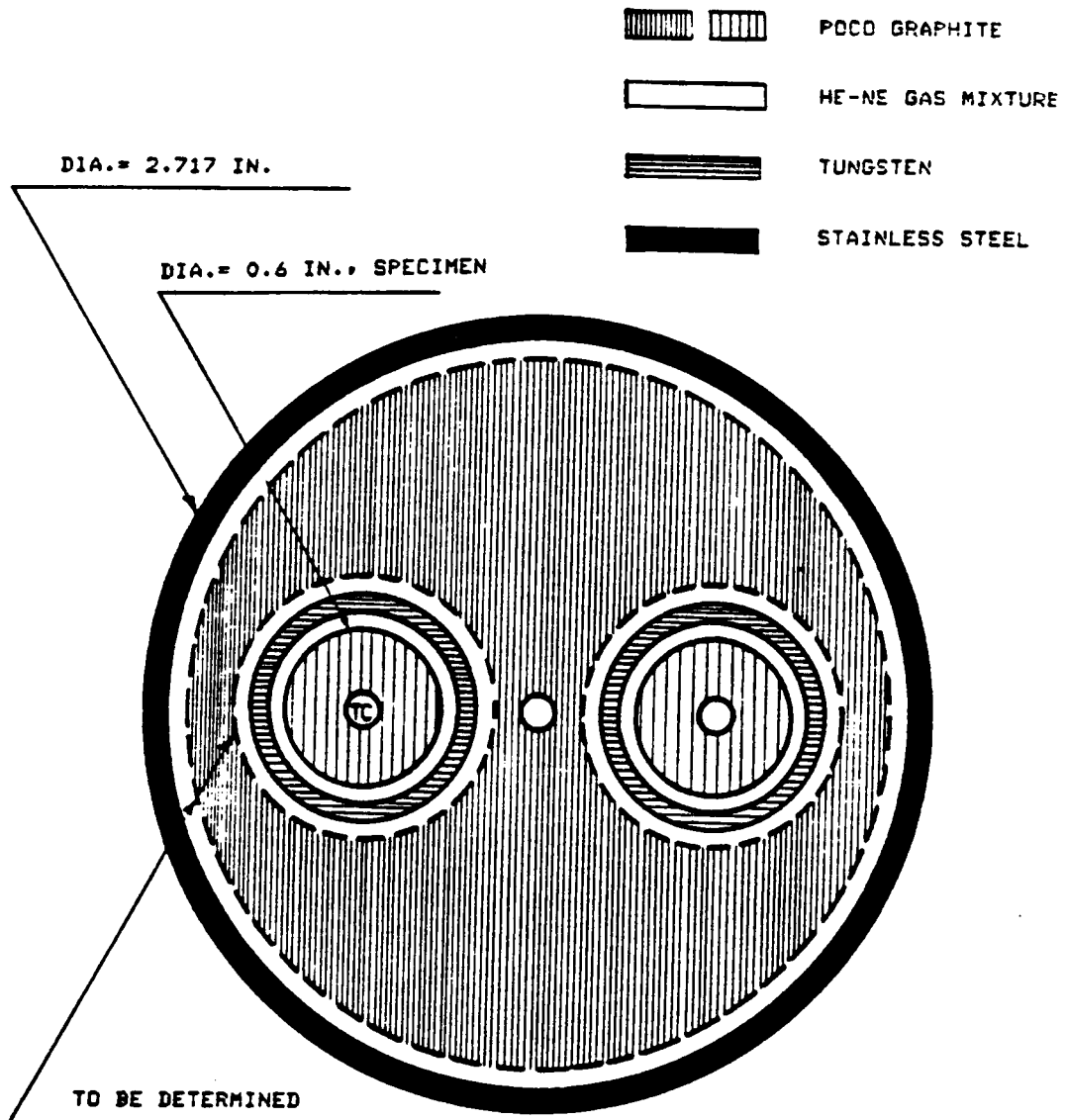


Figure 3.2. OC-6 Irradiation Creep Capsule Radial Cross-Section.

3.3 Gamma Heating

Gamma heating is the only heat generation source for the planned high-temperature creep experiment. The capsule is to be inserted at the position E-5 of the Oak Ridge Research Reactor (ORR), where it is subject to gamma heating. A brief description of sources of gammas leading to gamma-heat generation in reactor experiments is included in Appendix A.

Figure 3.3 shows the approximate gamma heating rate at position E-5 of the ORR core. This curve was used, as the internal heat generation source, for the thermal analysis of the OC-6 capsule. A typical core configuration, for ORR, is depicted in Figure 3.4.

During a power cycle, as the reactor fuel is burned up and the control rods are withdrawn, the reactor flux peak shifts toward the top of the experiment. This shifting, which changes the gamma heating rate, must be taken into consideration during the conduction of the experiment. The way that this shifting can be taken into account is discussed in Chapter VI.

3.4 Materials and their Properties

As it was described before (Figure 3.2), the stainless steel containment of the capsule contains: two graphite specimen columns, graphite block, two tungsten sleeves, and the gas-gaps (IG, MG, and OG). The outer surface of the containment will be exposed to water at a temperature of 118 F (42.2 C).

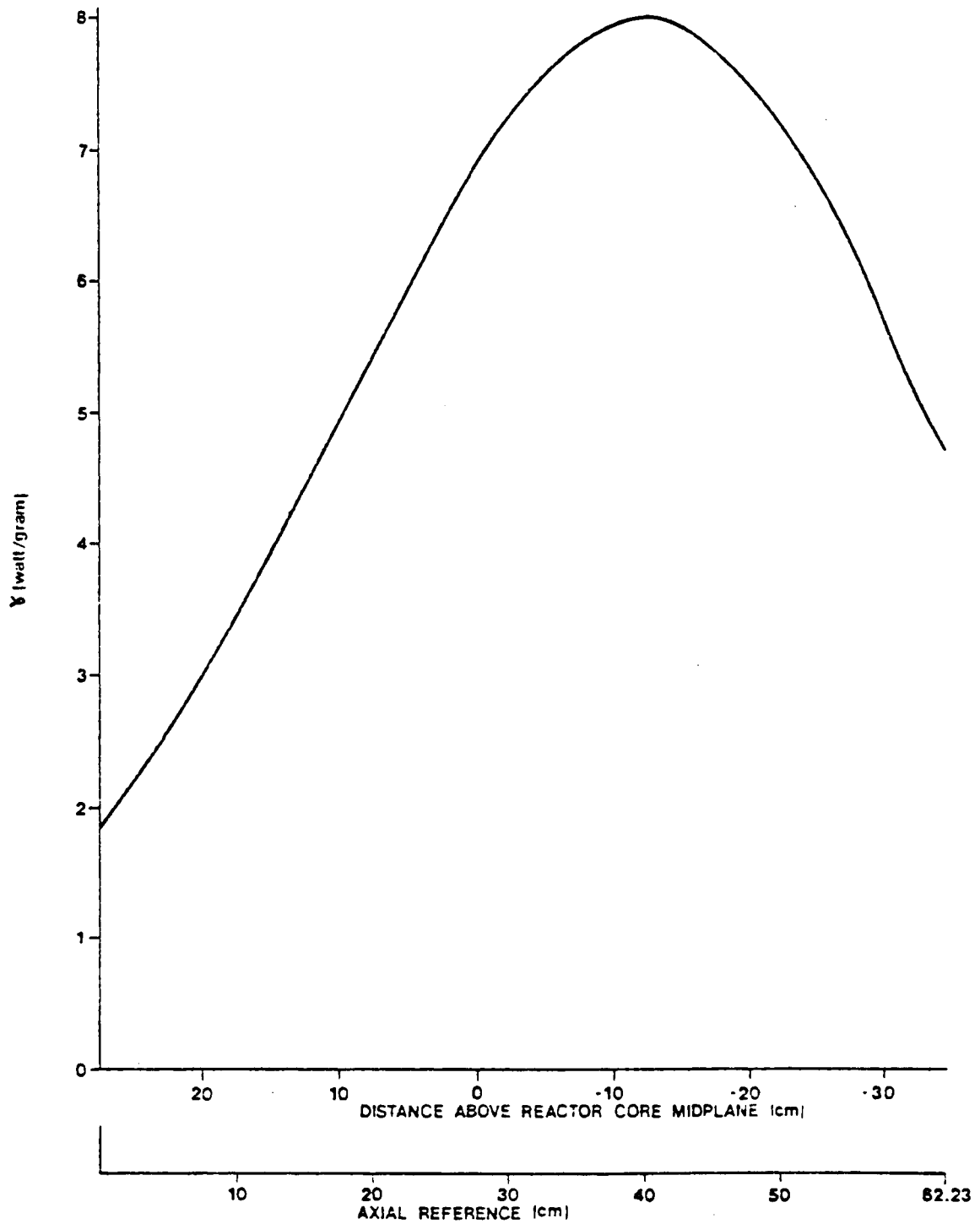


Figure 3.3. Gamma Heating Rate. Position E-5 of the ORR Reactor [14].

Be - Beryllium element
 Fuel - Fuel element
 SR - Shim rod
 Exp. - Experiment or
 experimental facility

POOL
 W

A-1 Be	A-2 Be	A-3 Fuel	A-4 Fuel	A-5 Fuel	A-6 Fuel	A-7 Be	A-8 Be	A-9 Be
B-1 Be	B-2 Be	B-3 Fuel	B-4 SR	B-5 Fuel	B-6 SR	B-7 Fuel	B-8 Be	B-9 Be
C-1 Be	C-2 Fuel	C-3 Fuel	C-4 Fuel	C-5 Fuel	C-6 Fuel	C-7 Fuel	C-8 Exp.	C-9 Be
D-1 Be	D-2 Fuel	D-3 Fuel	D-4 SR	D-5 Fuel	D-6 SR	D-7 Fuel	D-8 Exp.	D-9 Be
E-1 Be	E-2 Fuel	E-3 Exp.	E-4 Fuel	E-5 Fuel	E-6 Fuel	E-7 Fuel	E-8 Exp.	E-9 Be
F-1 Be	F-2 Fuel	F-3 Fuel	F-4 SR	F-5 Fuel	F-6 SR	F-7 Exp	F-8 Be	F-9 Be
G-1 Be	G-2 Be	G-3 Be	G-4 Be	G-5 Be	G-6 Be	G-7 Be	G-8 Be	G-9 Be

E

Figure 3.4. Typical ORR Core Configuration [27].

The nuclear-grade graphite under investigation is POCO graphite (grade AXF-5Q). This artificial graphite is an isotropic material with high purity and its thermal conductivity is not direction-dependent.

The materials and their properties, used for the thermal analysis of the capsule, are listed in Tables 3.1 and 3.2.

TABLE 3.1
MATERIAL PROPERTIES USED IN THE THERMAL ANALYSIS
OF THE OC-5 IRRADIATION CAPSULE

Material	Density (gr/cm)	Radiant Emissivity	Conductivity (BTU/min-in- F)	Conductivity Temperature (F)
Stainless Steel	7.85	0.7	0.01111	32
			0.01306	212
			0.01514	572
			0.02478	2240
Graphite	1.79	0.9	0.025 (see also Figs. 3.5 and 3.6)	constant
Tungsten	19.3	0.7	0.1139	500
			0.1028	1000
			0.09305	1700
			0.09004	2061
			0.08917	2400
Sweep Gas	0.0	0.0	Figure 3.7	

TABLE 3.2
PROPERTIES OF THE COOLANT USED IN THE THERMAL ANALYSIS

Coolant	Temperature (F)	Coefficient of Forced Convection (BTU/min-in ² - F)
Water	118	0.6181

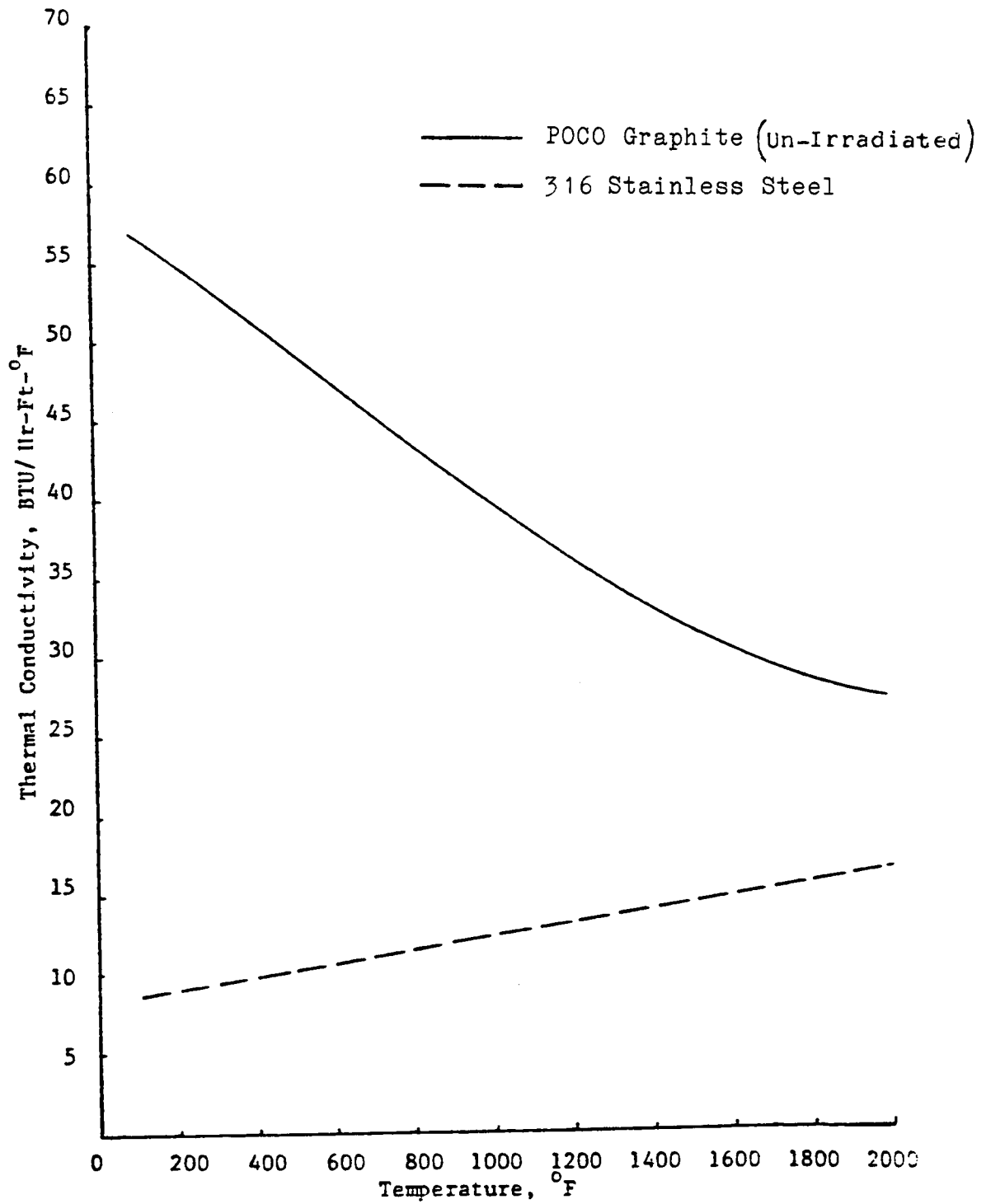


Figure 3.5. Thermal Conductivity of POCO Graphite and Stainless Steel[26].

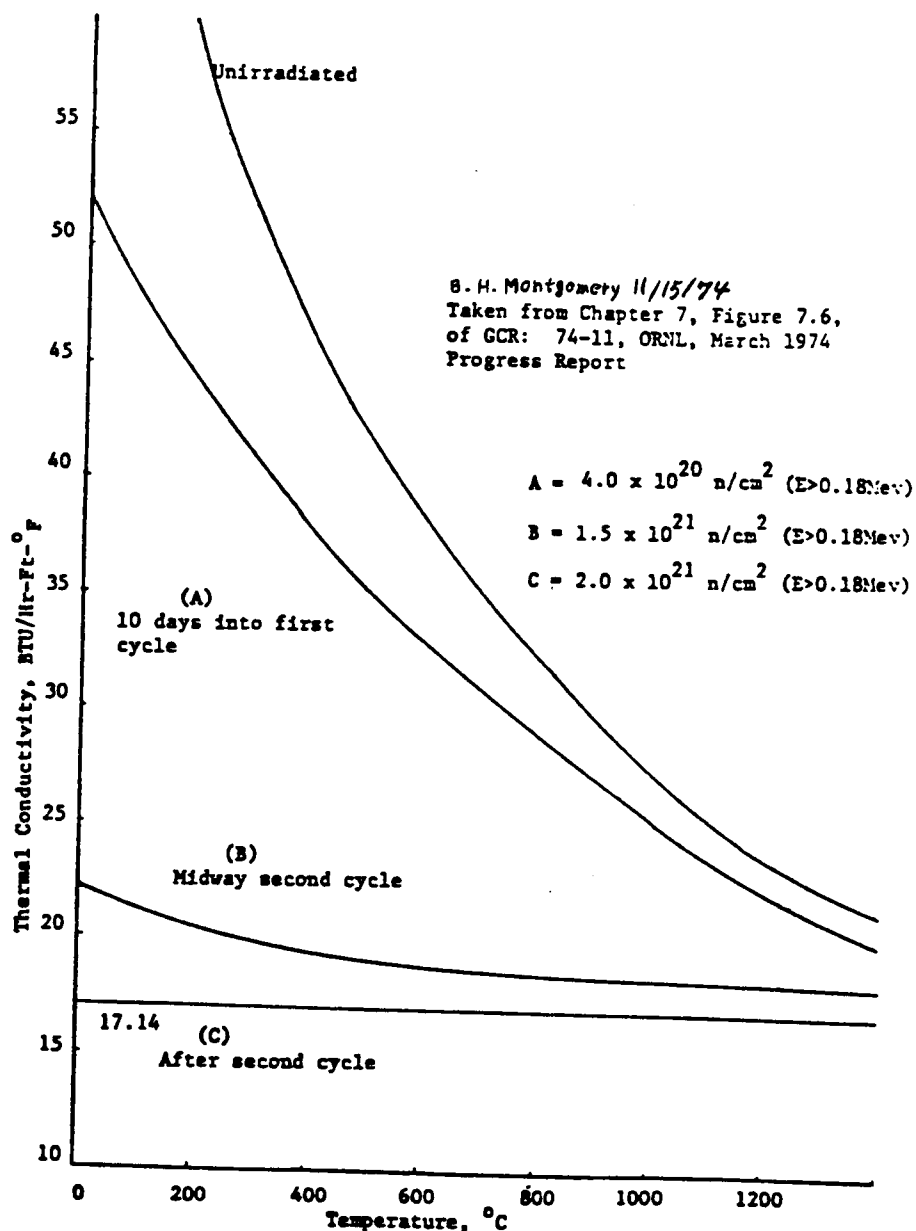


Figure 3.6. The Thermal Conductivity vs Temperature of POCC Graphite grade AXF-5Q Unirradiated and at Three Fluence Levels.

HELIUM-NEON GAS MIXTURE

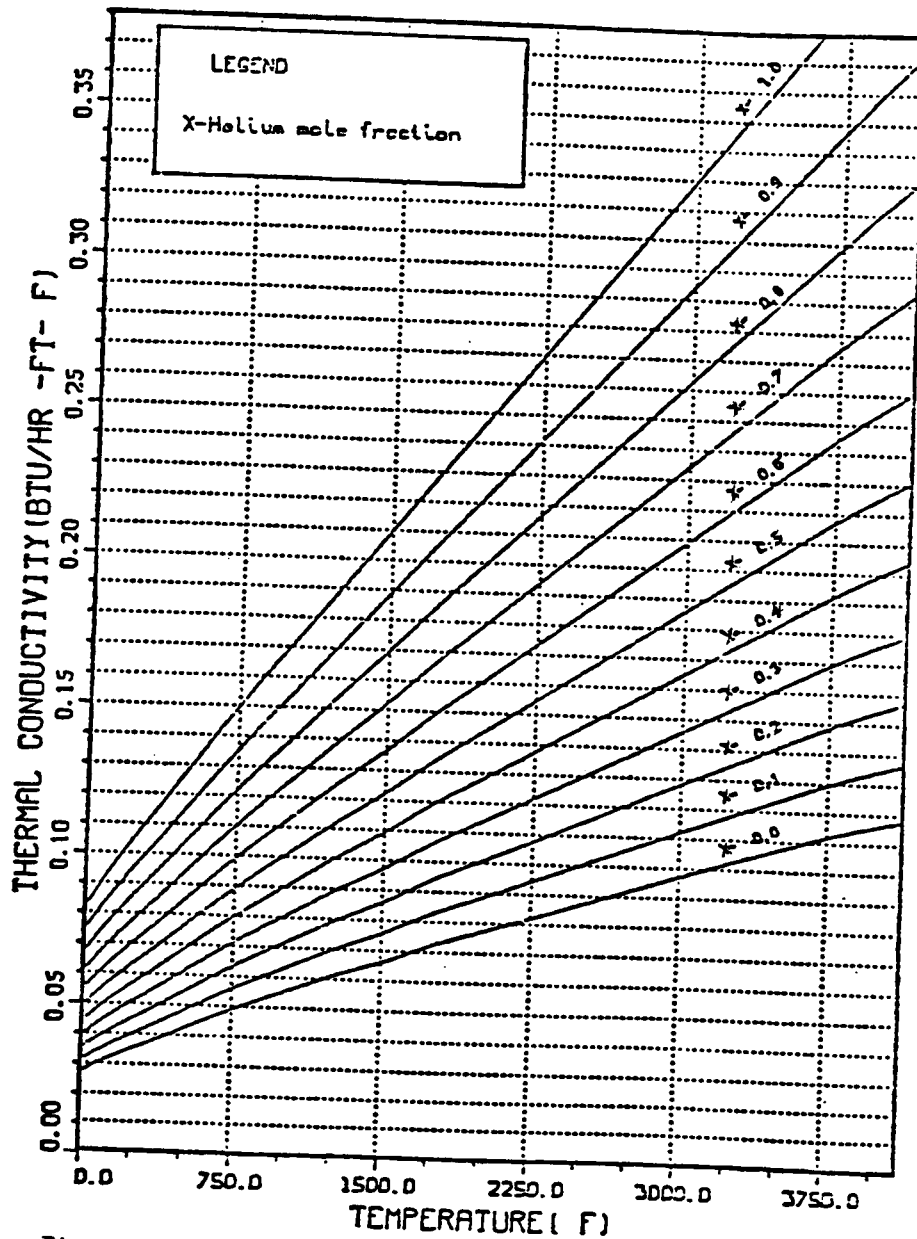


Figure 3.7. Thermal Conductivity Of Helium-Neon Gas Mixture [26].

CHAPTER IV

METHOD OF ANALYSIS

Only heat transfer problems with very simple geometries and boundary conditions can be solved by analytical methods. Finite differences (approximating derivatives by differences) is a feasible method of attack for more complex problems.

In problems involving nonlinearities, such as fourth-power radiation law, free convection, melting or solidification, and ablation, where analytical methods rarely work, finite difference methods are also quite useful. Problems which deal with variable properties must often be handled numerically [18, 19].

In the design problem under consideration, the variable widths of the middle gap and outer gap (discussed later in Chapter V and which are to be determined), the temperature dependence of the thermal properties of the involved materials, the axially dependent gamma-heating rate and its shifting due to the core aging, and the involved linear and nonlinear (radiative) boundary conditions give rise to a complex heat transfer problem which makes the use of numerical methods and consequently that of a digital computer indispensable and inevitable.

This chapter provides a rather brief description of the HEATING5 computer code and the way that it handles a

heat transfer problem. This code was used extensively during the course of the thermal design. Reference [20] has been consulted for developing the contents of this chapter except Section 4.6.

4.1 HEATING5 Computer Code

The general-purpose heat-transfer computer-code HEATING5 (an acronym for Heat Engineering And Transfer In Nine Geometries, 5th version) was utilized as the main tool in thermal analysis of the capsule. It seemed appropriate to describe, briefly, the underlying requirements, restrictions, and those features of the code which resulted in the development of the computational model of the capsule (Chapter V). This necessity is justified by the fact that being familiar with the numerical method(s) based on which the HEATING5 code has been written, and therefore, not treating that as a black box, leads to an efficient use of the code. In other words, this familiarity is very useful in developing accurate and efficient (requiring minimum computer time and storage) computational models for physical problems of complex geometries.

HEATING5 is a multi-dimensional general-purpose heat-conduction computer program with temperature-dependent thermal properties, non-linear and surface-to-surface boundary conditions and change-of-phase capabilities. A detailed description of the different features of the code, including the numerical techniques for steady-state and

transient calculations, are covered in reference [20].

Generally, in order to find the steady-state or transient temperature-distributions for a physical problem, using HEATING5 computer code, the following steps should be taken:

1. A computational model, for the physical problem under investigation, must be developed. This model is an approximation when the geometrical configuration of the problem does not fit any of the standard coordinate-systems which can be handled by the code. This approximation (modeling) is based on the coordinate system which best suits the involved geometry.

2. The developed model is, in turn, approximated by a nodal network, where each node is associated with a small volume. This system of nodes is generated by superimposing a system of orthogonal planes on the problem. Each generated region must be composed of one material, bounded by the orthogonal surfaces of the coordinate-system used.

As it was mentioned before, only those capabilities or features of the code which were invoked in developing the computational model and in performing the computer runs are briefly introduced.

4.2 Regions, Grid Lines, and Nodes

By way of illustration, six adjacent nodes, for a three-dimensional problem in cartesian coordinates, are

shown in Figure 4.1. As this figure indicates, in HEATING5, a typical internal node (lattice point), i.e., node 0, which is connected to its six neighboring nodes, may be composed of as many as eight different materials for three-dimensional problems. HEATING5 calculates temperatures at the intersection of grid lines (orthogonal surfaces), where all the materials within the node join.

The total number of nodes generated for a model depends upon the number of the grid lines, which, in turn, is dependent upon the number of different materials and the geometrical complexity of the computational model.

4.3 Basic Equations and Numerical Technique

For the general unsteady-state three-dimensional case of heat conduction, with internal heat generation, using standard vector operator notation, the equation is :

$$\vec{\nabla} \cdot K \vec{\nabla} T + P = \rho c \frac{\partial T}{\partial t} \quad (4.1)$$

where

$$\vec{\nabla} = \frac{\partial}{\partial x} \vec{i} + \frac{\partial}{\partial y} \vec{j} + \frac{\partial}{\partial z} \vec{k}$$

K = thermal conductivity,

T = temperature,

P = heat generation rate per unit volume,

ρ = density,

c = specific heat,

t = time.

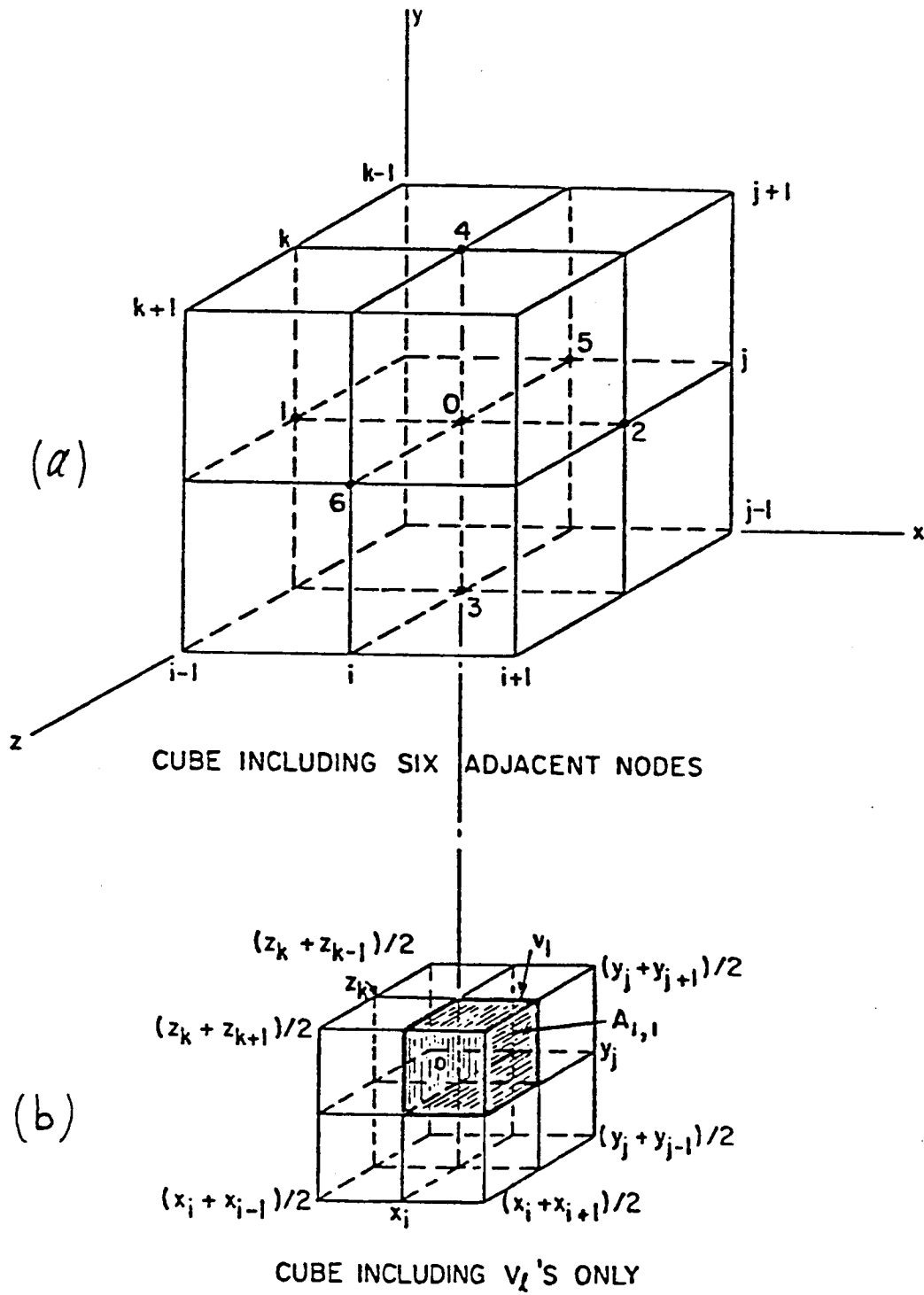


Figure 4.1. HEATING5 Nodal Description for Three-Dimensional Problem.

For steady-state heat conduction problems, equation (4.1) reduces to:

$$\vec{\nabla} \cdot K \vec{\nabla} \cdot T + P = 0 \quad (4.2)$$

As it was mentioned in the previous section, the computational model of the heat transfer problem is approximated by a system of nodes. Using the thermal resistance approach, each node is connected by thermal resistances to its adjoining neighbors. For steady-state conditions, the net energy transfer into a node plus the thermal energy generated in nodal volume is zero. Invoking the Fourier's law of heat conduction and using the thermal-conductance formulation, the finite-difference heat-balance equation for node 0 in Figure 4.1, for steady-state condition is:

$$\sum_{m=1}^6 oK_m (T_m - T_o) + P_o = 0 \quad (4.3)$$

where

oK_m = thermal conductance between nodes o and m,

T_m = temperature of the mth node adjacent to node o,

T_o = temperature of node o,

P_o = heat generation rate in the material associated with node o.

As the figure 4.1(a) indicates, for a three-dimensional

Problem, one P and six K's will be associated with each internal node. These parameters are calculated by the following formulas for node 0:

$${}_0K_m = \frac{1}{L_m} \sum_{\gamma=1}^4 k_{m\gamma} A_{m\gamma} \quad (4.4)$$

$$P_0 = \sum_{l=1}^8 Q_l V_l \quad (4.5)$$

where

L_m = distance between node 0 and adjacent node m,

$k_{m\gamma}$ = thermal conductivity for region γ between nodes 0 and m,

$A_{m\gamma}$ = cross-sectional area, normal to heat flow path, of region γ between nodes 0 and m,

Q_l = rate of heat generation per unit volume in region l,

V_l = volume of region l.

By referring to Figure 4.1(b), the V_l 's and $A_{m\gamma}$'s are further defined, by way of examples, as follows:

$$V_1 = \frac{x_{i+1} - x_i}{2} \frac{y_{j+1} - y_j}{2} \frac{z_{k+1} - z_k}{2} \quad (4.6)$$

$$A_{11} = \frac{y_{j+1} - y_j}{2} \frac{z_{k+1} - z_k}{2} \quad (4.7)$$

Depending on the location of the node and the number of dimensions in the coordinate system being used, the number of neighbors for nodes are different. Therefore, the heat balance equation for node i being connected to M_i

neighbors is written as:

$$\sum_{m=1}^{M_i} K_m (T_m - T_i) + P_i = 0 \quad (4.8)$$

where m is the m th neighbor of the i th node.

By performing the above finite-difference heat-balance about each node, a system of N linear simultaneous equations with N unknowns, for a problem modeled by N nodes, is derived. The solution of these equations is the steady-state temperature distribution.

4.4 Effective Conductance and Effective Heat Transfer Coefficient

The concept of effective thermal conductance has been utilized in order to maintain the generality of Eq. 4.8, while dealing with different boundary conditions such as surface-to-boundary (convective) and surface-to-surface (radiative) boundary conditions. In these equations the leakage term is calculated as:

$${}_i K_m (T_m - T_i) = {}_i K_b (T_b - T_i) \quad (4.9)$$

where ${}_i K_b$ is the effective thermal conductance between surface node i and boundary node b or the opposing surface node b , and T_b is the temperature of node b . This concept, in turn, employs another one, which is that of the effective heat transfer coefficient h , and ${}_i K_b$ is calculated as:

$${}_i K_b = hA \quad (4.10)$$

where A is the surface area, perpendicular to the direction of heat flow, of node i corresponding to the boundary condition.

For problems involving only forced convection and radiation boundary conditions, the effective heat transfer coefficient is defined as:

$$h = h_c + h_r [T_i^2 + T_b^2][T_i + T_b] \quad (4.11)$$

where

h_c = heat transfer coefficient for forced convection,

h_r = radiative heat transfer coefficient.

Calculation of h_r , as the product of graybody shape-factor and Stefan-Boltzmann constant, is discussed in Section 5.4.

4.5 Iteration Process and Convergence Criterion

The system of equations mentioned in Section 4.3 can be solved by employing an iterative procedure and invoking a digital computer. Basically, the following iterative process can be used for Equation 4.8:

$$T_i^{(n+1)} = \frac{P_i + \sum_{m=1}^{M_i} \epsilon_i K_m T_m^{(n)}}{\sum_{m=1}^{M_i} \epsilon_i K_m} \quad (4.12)$$

where superscript (n) implies the nth iteration. The actual iterative process incorporated in HEATING5 code is discussed, in detail, in reference [20].

In solving the system of equations, by the iteration process, HEATING5 continues the successive iterations until

$$\left| \frac{T_i^{(n)} - T_i^{(n+1)}}{T_i^{(n+1)}} \right|_{\text{Max}} \leq e \quad (4.13)$$

where e is the specified convergence criterion.

Having defined the grid lines and the convergence criterion, it seemed important, in view of the evaluation of the results of each run, to directly quote the following paragraph from the introduction of reference [20].

The user is cautioned that this code is not a black box which digests the input data and automatically yields the correct solution to the physical problem. Care must be exercised in correctly simulating the physical problem as well as in interpreting the results from the code. For steady-state problems, one must experiment with the mesh spacing in order to gain confidence in the numerical solution to a model of a physical problem. For instance, numerical solutions must be obtained for several different mesh spacings, then these solutions must be compared and the differences that are noted at points of interest must be acceptable. In addition, one must also experiment with the convergence criterion. When the criterion is satisfied, it only guarantees that the temperatures did not change more than a specified amount over the previous iteration. This is sufficient for many problems, but it is possible to have a problem which is converging so slowly that the convergence criterion is satisfied even though the last iterate is a very poor estimate of the true solution to the model. Again one must make several calculations with different convergence criteria and compare the results before obtaining confidence in the solution.

4.6 Utilization of Computers

The PDP-10 time sharing systems at the University of Tennessee and ORNL, together with the IBM 360/191 and 370/3033 computers and the computer plotting facilities at ORNL were utilized to perform the thermal analysis of the OC-6 irradiation capsule. The preparation and formatting of the input data for the HEATING5 code were conducted on the PDP-10 machine and then, passed, through an interface, to the IBM machine for execution. The important parts of each run were required to either be saved on magnetic tapes or be routed back to PDP-10 to be stored on disks. These segments of the output could be utilized in subsequent runs or plottings.

When possible and applicable, as was the case for most runs, the final temperature distribution of one run was incorporated in the input of its following run, as the initial temperature distribution for that run. This considerably reduced the number of iterations necessary to satisfy the specified convergence criterion of each case.

CHAPTER V

PHYSICAL AND COMPUTATIONAL MODELS

Based on the requirements and restrictions imposed by the HEATING5 code, a computational model and an input processing program were developed. They are discussed in this chapter. Preliminary two-dimensional thermal analysis is also included in this chapter.

5.1 Physical Model of the Capsule

A horizontal cross-section of the capsule is depicted, in some detail, in Figure 5.1. The dashed circles in this figure indicate that the widths of the corresponding gas-gaps (two middle-gaps and one outer-gap) are to be determined. Should the design requirements necessitate, the width of each middle gap, in addition to that of the outer gap, can be varied in the axial direction, due to the behavior of the axial profile of the gamma heating rate (Figure 3.3 (page 28)).

The temperatures at different locations in the capsule are monitored by movable and fixed thermocouples (MTC and FTC). The cylindrical hole (circular in cross section) at the center of the unstressed specimen column serves as a guide for a MTC, which will monitor the temperatures along that column. A set of fixed thermocouples (FTC's), for measuring the temperature of the graphite block, will be placed in the graphite block at a

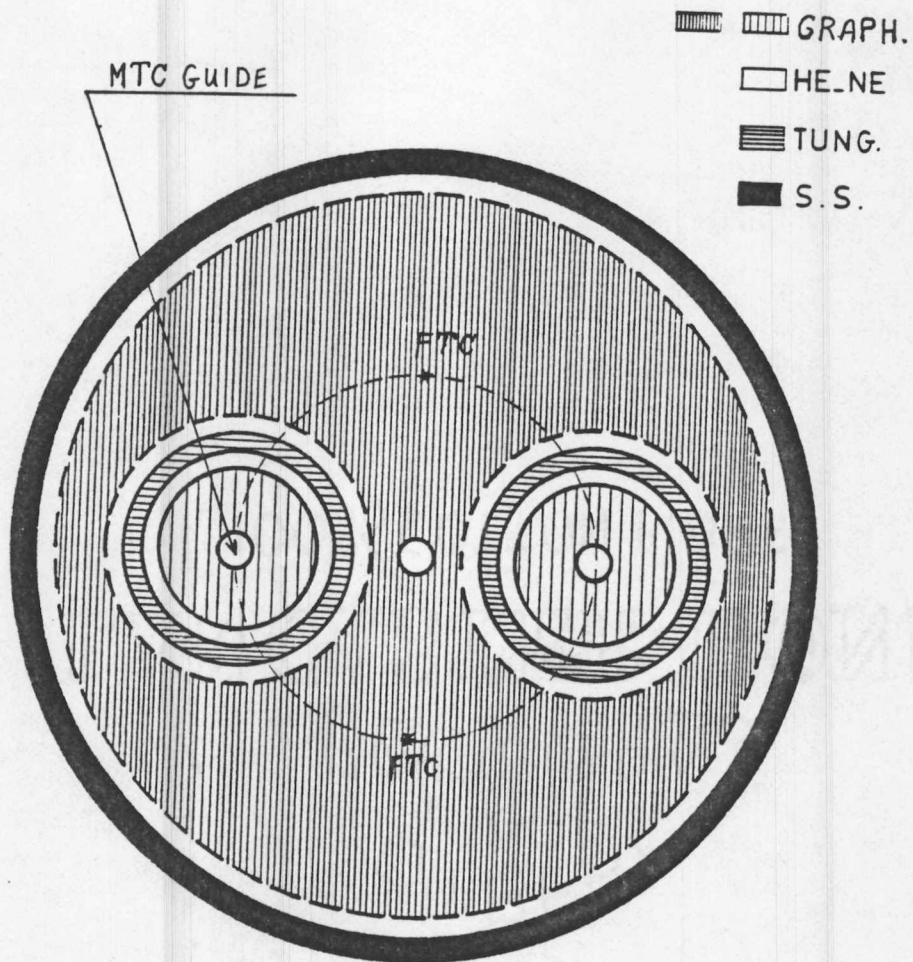


Figure 5.1. Radial Cross-Section of the Capsule showing the locations of Movable and Fixed Thermocouples (MTC and FTC).

radius equal to that of the specimen centers. Typical locations for FTC's are shown in Figure 5.1. The temperatures of the graphite block at these locations, as mentioned before (Section 3.2), are not to exceed 950 C. The MTC's employed in the 900 C irradiation capsule (OC-1 capsule) were two (due to having two unstressed columns) 3.2-mm-diam (1/8-in.) stainless-steel-sheathed Chromel vs Alumel TC's. The FTC's (twenty five), used in that capsule, were 1.6-mm-diam (1/16-in.) stainless-steel-sheathed MgO-insulated Chromel vs Alumel TC's [21]. The exact number of FTC's for the current design (OC-6 capsule) is yet to be determined.

Figure 5.2 shows a schematic axial cross-section of the OC-6 capsule, for a segment of the capsule where the gap widths remain unchanged.

Using the same cutting plane as Figure 5.2, Figure 5.3 illustrates a typical set of different gap widths for a section of the capsule, which is subject to varying heating rates. The minimum gaps are at the maximum heating rate. Since the gas gaps are the chief thermal resistances to heat flow, the width of a variable gap increases stepwise, and axially, as the gamma heating rate decreases in axial direction. This figure indicates the case in which variation of the middle gap is necessary, in addition to that of the outer gap. It is noted that the annular gas gaps (pathways for a sweep-gas mixture) must be small enough

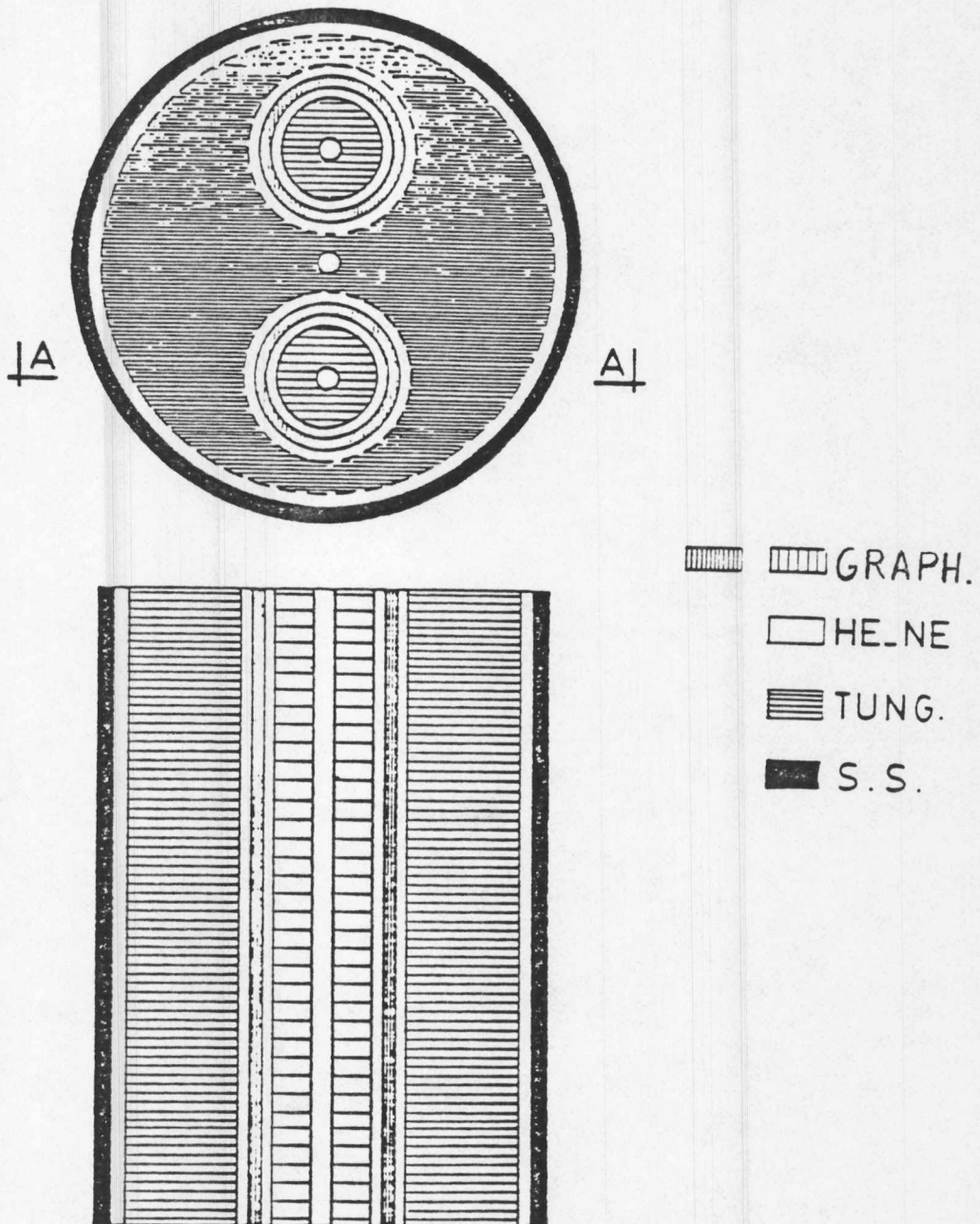


Figure 5.2. Radial and Axial Cross-Sections of the Capsule;
all Gaps are fixed.

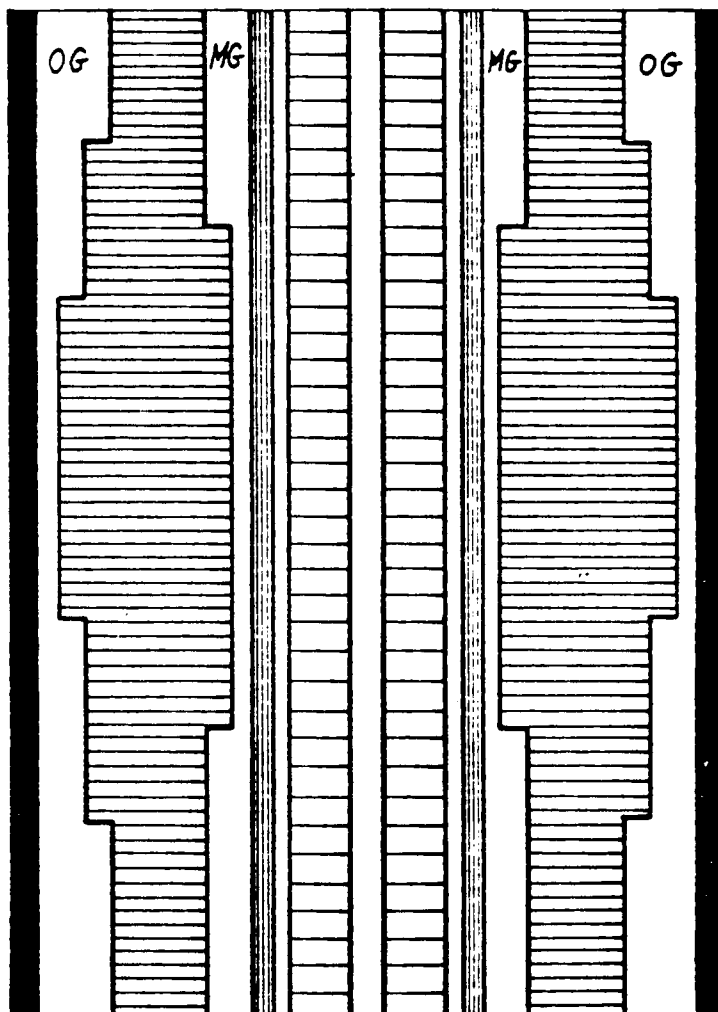


Figure 5.3. The Axial Cross-Section of a Section of the Capsule where the Widths of the Middle Gap and Outer Gap vary, stepwise, in Axial Direction.

and the flow rate low enough to inhibit convection phenomenon and thus make the heat transfer model simply conduction and radiation across the gaps. However, they should be large enough to prevent large errors due to machining limitations.

5.2 Simplifying Assumptions

Generally, in engineering analysis, one uses a simplified model (ideal model) of the physical problem, for which he wants to perform the analysis. Otherwise, this task would be too complicated or too costly to carry on. However, the simplification of the physical problem should be conducted in a manner which results in a solution with sufficient accuracy, from an engineering standpoint. The thermal analysis of the capsule is not an exception to this rule.

Several simplifying assumptions were made in developing a computational model for the capsule, in order to reduce the required computer storage, computation time, and consequently, the cost of analysis.

Each specimen column, composed of string of samples, is assumed to be a continuous solid cylindrical sample. This is a fair assumption because the specimens and spacers are of approximately the same material.

Due to the thermal insulation and greatly reduced gamma heating at the ends of the capsule and their distance

from the specimen region of interest, end effects were neglected, i.e., the ends were assumed to be adiabatic planes.

The sweep gas in the capsule was assumed to be stagnant, due to the very low flow rate of a few cubic centimeters per minute.

Because of their comparatively small volumes and masses the thermocouples were neglected.

Shielding effect of the tungsten sleeve was ignored. Because, despite its large gamma absorption, this effect was expected to be small [14].

The capsule was assumed to have two adiabatic radial-planes of symmetry, perpendicular to each other. This was a reasonable assumption because of the symmetrical arrangement of the capsule (Figure 5.1) and its insertion at the position E-5 of the ORR.

The computational model which was developed, based on the above simplifying assumptions, is discussed in the next section.

5.3 Development of Computational Model

Having defined the physical model, a suitable computational model must be developed. This section is devoted to the evolutionary procedure which led to the creation of such a model.

In problems which involve complex geometries, it is of interest to limit the calculations to the smallest

possible region by making use of symmetry. Moreover, with regard to coordinate systems used in calculations, the geometry can be symplified, considerably, by replacing complex shapes with simpler shapes of equivalent volume and resistance to heat flow. These two general steps, i.e., use of symmetry and shape simplification, were incorporated in the development of a computational model for the capsule.

The two-fold symmetry of the capsule (one of the assumptions in previous section), shown in Figure 5.4, enabled the problem to be attacked by considering just one-fourth of the capsule. The horizontal cross-section of this segment is shown, as a quadrant, in Figure 5.5; the same quadrant, magnified and with numbered regions, is seen in Figure 5.6. As the latter Figure illustrates, the interior and exterior boundaries of regions 1, 2, 3, and 4 are concentric half-cylinders, whose common cylindrical axis is the centerline of the specimen column. It is also seen, in this figure, that those boundaries for regions 6 and 7 and the corner boundary for region 5 are coaxial quarter-cylinders, whose common cylindrical axis is the centerline of the capsule. The non-cylindrical (non-circular in cross-section) boundaries of all regions are parts of the two adiabatic radial-planes (straight lines in cross-section), across which there will be no transfer of heat.

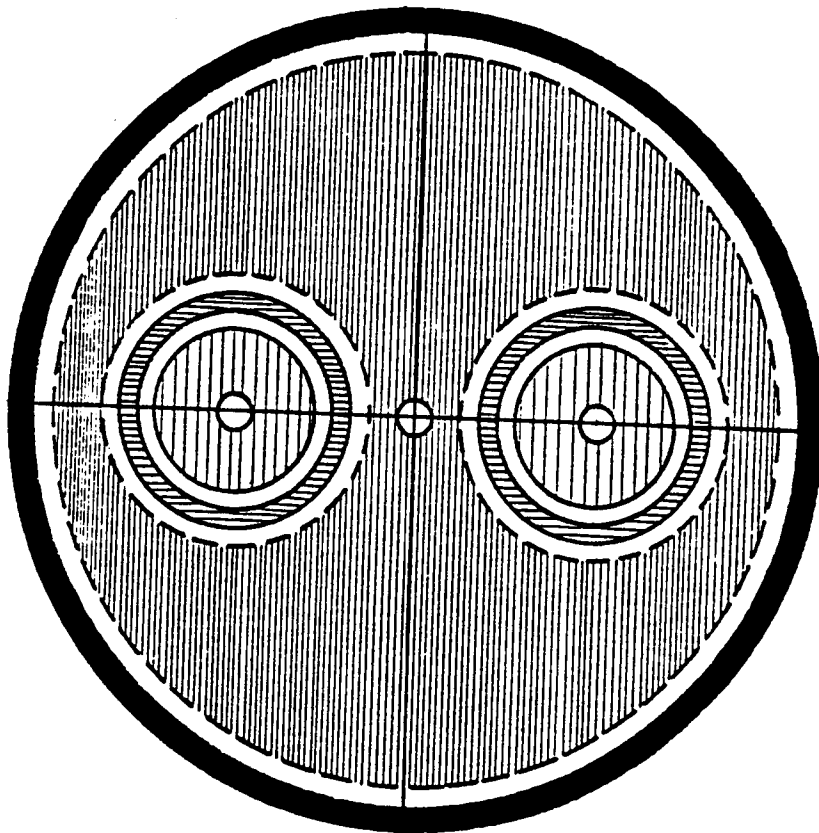


Figure 5.4. A Horizontal Cross-Section of the OC-6 Capsule showing the involved Two-Fold Symmetry.

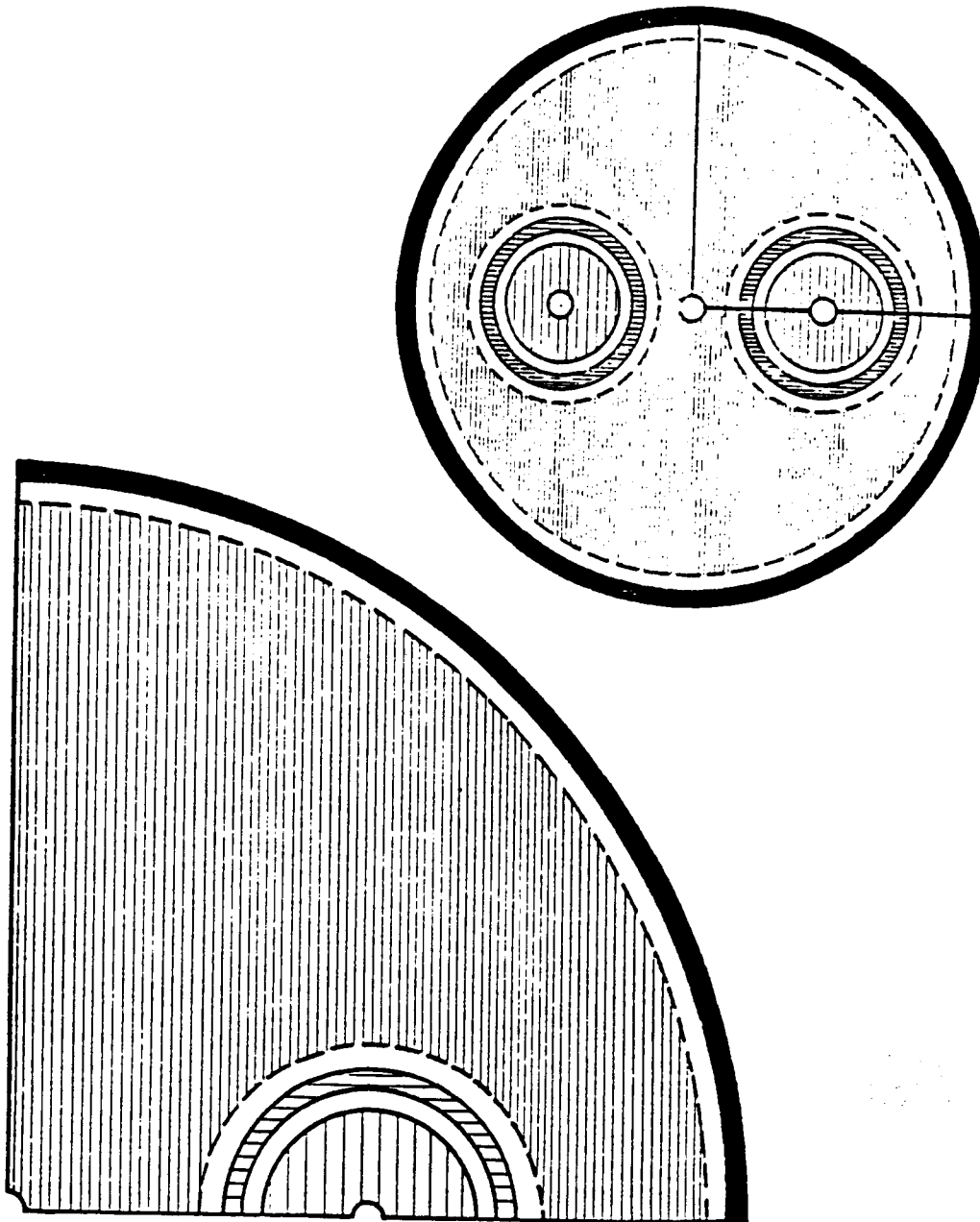


Figure 5.5. The Section of the Capsule which was used for developing the Computational Model.

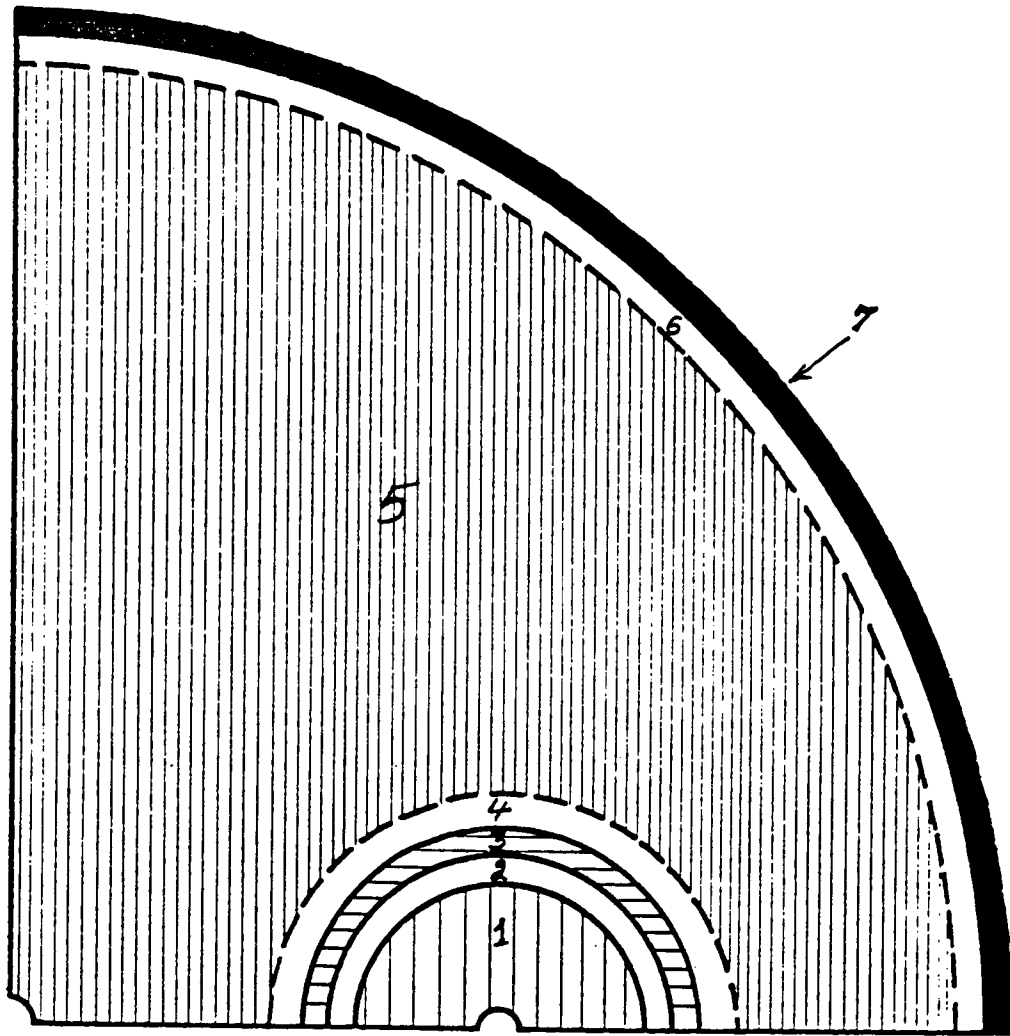


Figure 5.6. The Radial Cross-Section of one Quarter of the Physical Model with Numbered Regions.

The geometrical configuration of the problem indicates that the system of coordinates that best suit it is that of the three-dimensional cylindrical coordinates. Therefore, logically, one of the two cylindrical axes should be chosen, i.e., either the centerline of the specimen column or that of the capsule. But, with regard to the HEATING5 requirement for region definition (Section 4.2), those regions which are not "compatible" with the cylindrical axis to be chosen, cannot be defined properly, without performing region approximation. In other words, a shape simplification is needed for "non-compatible" regions. The three-dimensional cylindrical coordinate system and a typical region in this system are shown in Figures 5.7 and 5.8, respectively.

The cylindrical axis was chosen at the center of the test column for two good reasons:

First, by this choice, only three regions require shape approximation, i.e., regions 5, 6, and 7; whereas, by choosing the other cylindrical axis (centerline of the capsule), five regions, i.e., regions 1, 2, 3, 4, and 5, have to be approximated for compatibility with cylindrical coordinates. Consequently, more nodes will be involved, by the latter choice, necessitating higher computer core size and CPU time and, as the result, higher cost.

The second and, in fact, more important reason for this choice, comes from the fact that radiation heat transfer is a significant factor around the test column and

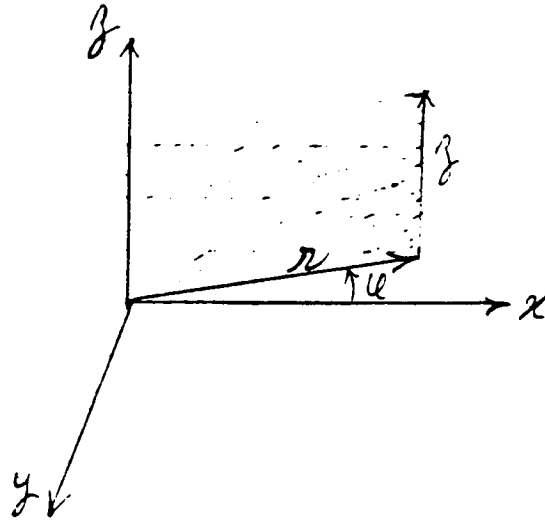


Figure 5.7. Cylindrical Coordinate System.

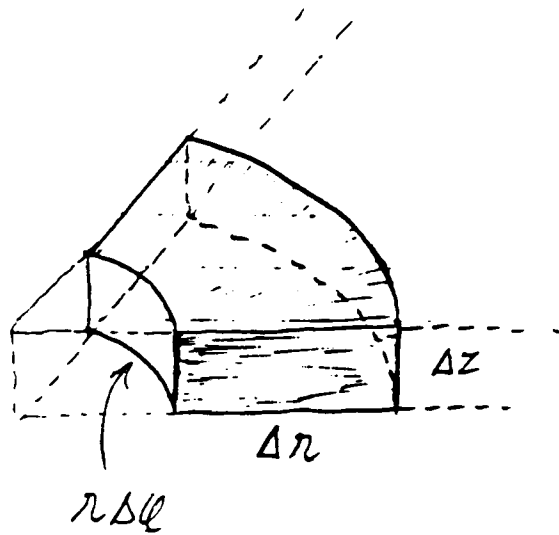


Figure 5.8. Small Volume in Cylindrical Coordinate System.

requires a good geometric description for the involved regions to accurately apply the radiation shape factor capability of the HEATING5 code (discussed in the next section).

As expected, while choosing the cylindrical axis greatly simplified the modeling of regions 1, 2, 3, and 4, it required the approximation of the outer boundary in cylindrical steps, which, in turn, necessitated shape approximation for the involved regions (regions 5, 6, and 7).

In performing the required modeling, two restrictions are dictated by heat transfer considerations:

First, the area (directly proportional to perimeter) of the outer boundary of region 7, which is subject to a forced convection boundary condition, must be as close to the corresponding area, in the physical model, as possible. This correctly models the magnitude of thermal resistance to transfer of heat from the capsule to its surrounding, which acts as a heat sink. It should be noted that this restriction is not imposed upon the vertical boundary of the graphite block, because, this boundary is subject to an adiabatic boundary condition.

The second restriction implies that the volumes (areas in the horizontal cross-section) of the approximated regions must be as close to the areas of corresponding regions, in the physical model, as possible in order to have a sufficiently-accurate internal heat-generation rate.

Using two-dimensional polar-coordinate system and keeping the above mentioned restrictions in mind, a computer program was written to calculate the outer-boundary perimeter for heat transfer, and cross-sectional areas of the modeled components, for comparison with the true values. This allowed variation of the stepping of the outer boundaries (stainless steel and graphite block) so these values could be kept very close to the true values. The preliminary computational model which was developed is seen in Figure 5.9.

In order to prevent erroneous coupling of the stainless steel and the outer gap, in the circumferential direction, to the graphite block, very small gaps, referred to as circumferencial gaps (CG), were incorporated in the final model, as seen in Figure 5.10.

Figure 5.11 facilitates the comparison of the horizontal cross-sections of the physical and computational model of the quadrant of the capsule for which the thermal analysis was conducted.

Figure 5.12 shows the number and material associated with each region in the computational model.

5.4 Thermal Radiation Coefficient

As it was indicated in Section 4.4, h_r , the coefficient for radiation heat transfer, is one of the factors involved in the definition of effective conductance

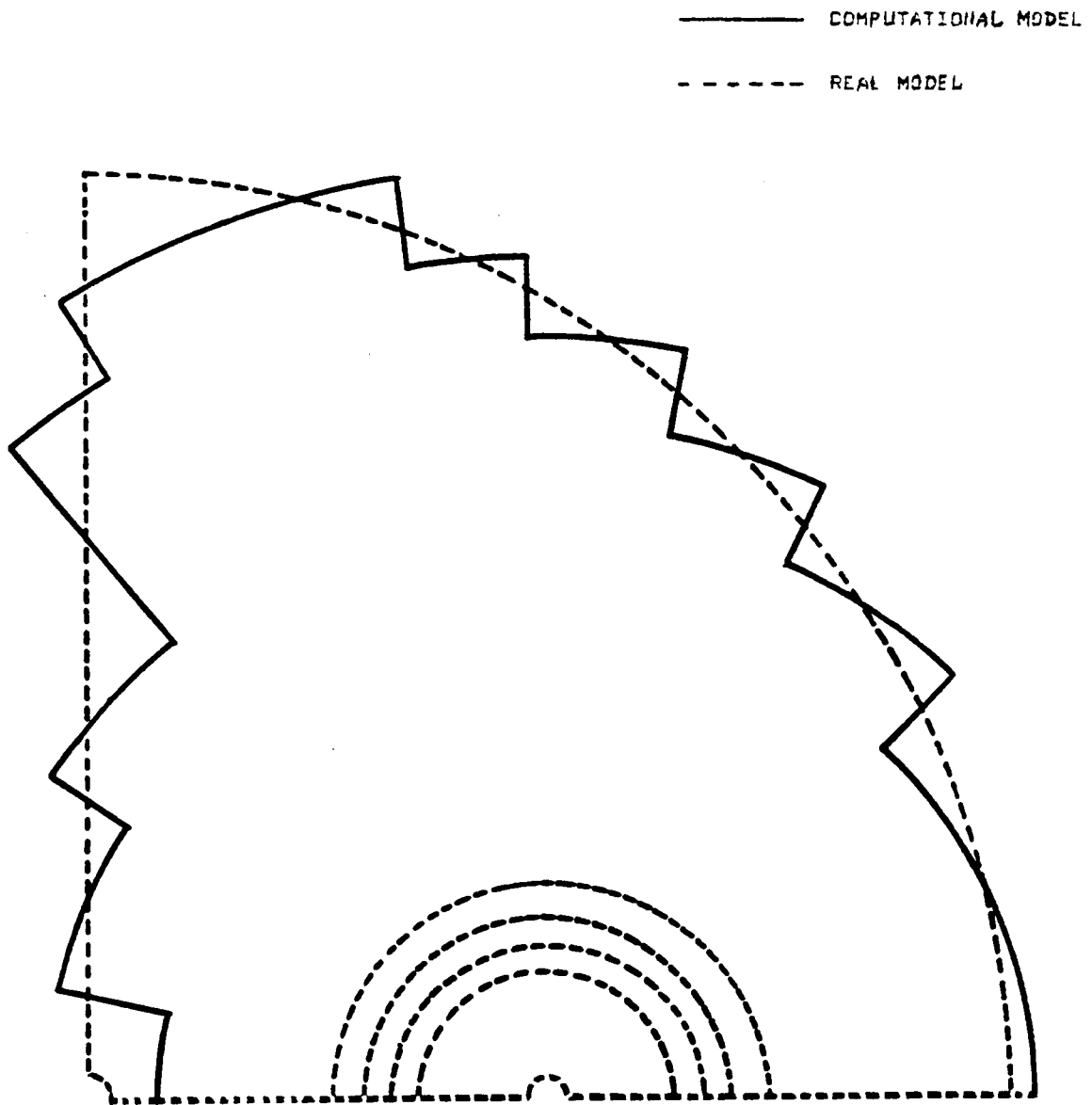


Figure 5.9. The Real and Approximated Boundaries of the Selected Section of the Capsule for Modling.

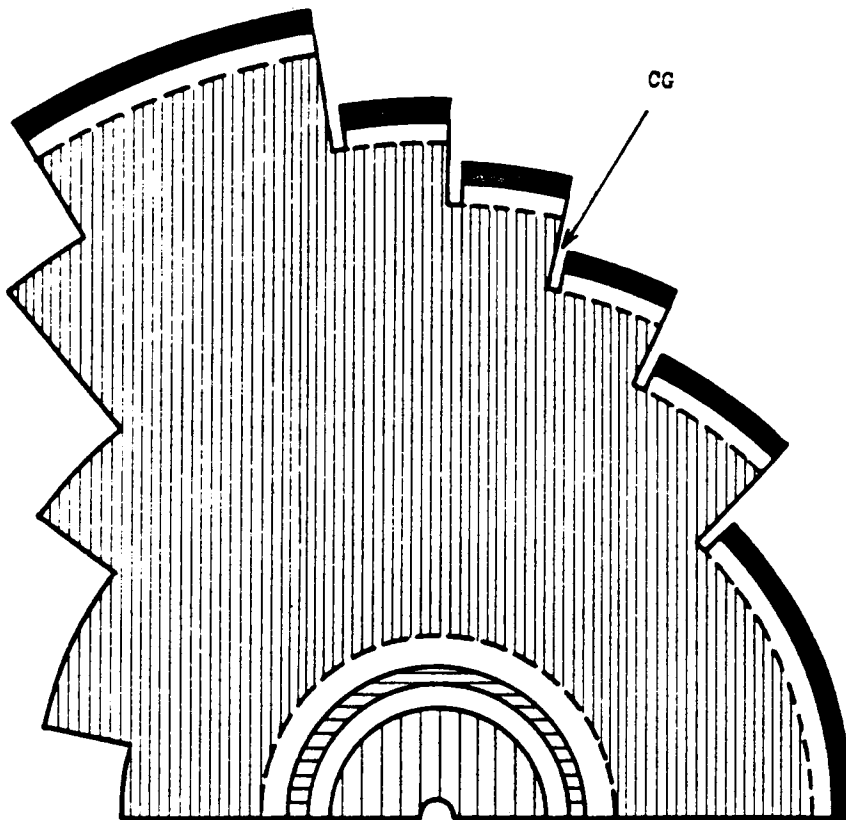


Figure 5.10. The developed Computational Model after incorporation of the decoupling Circumferential Gaps (CG).

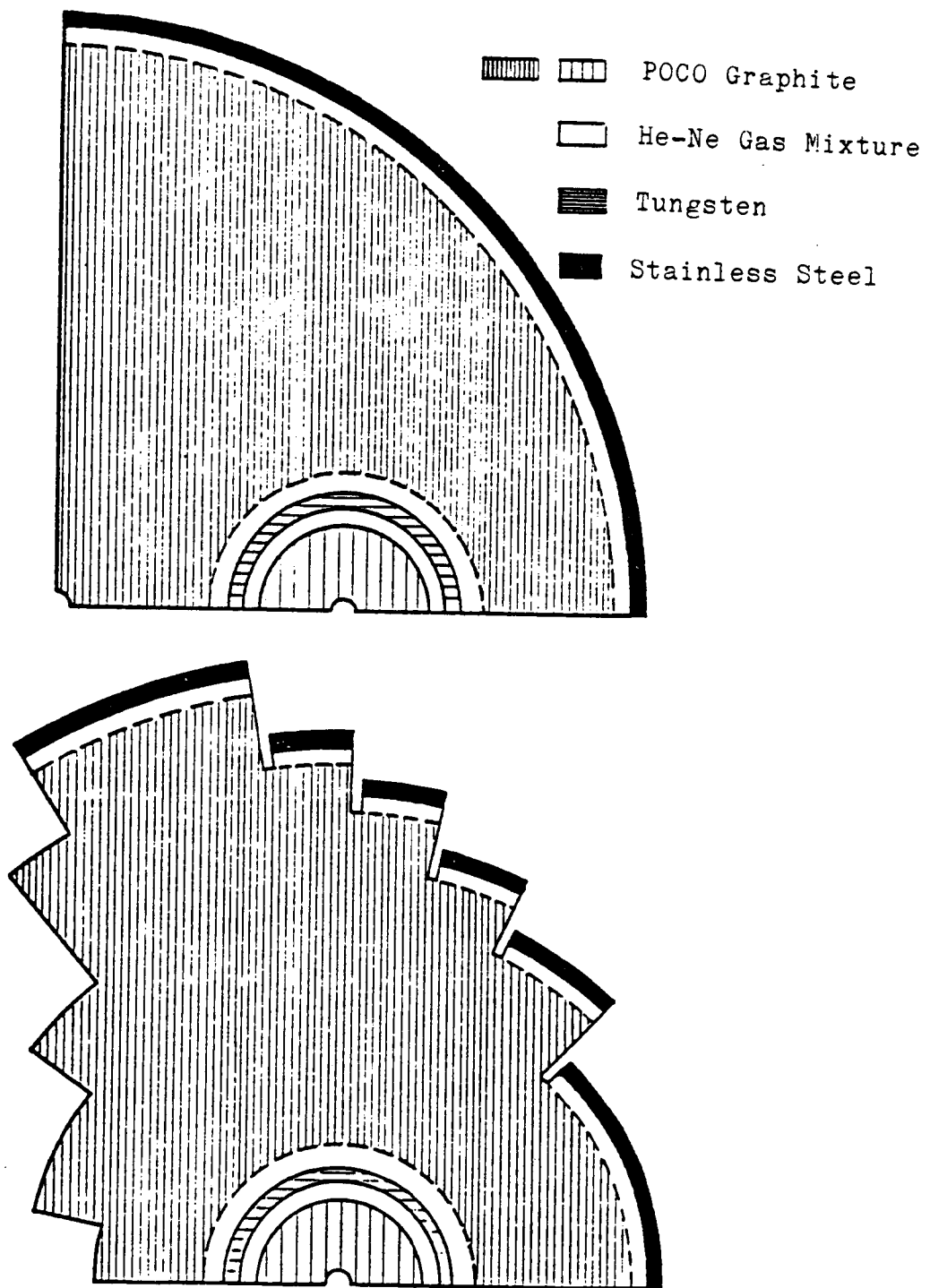


Figure 5.11. The selected Section of the Capsule (a) and its Approximation (b).

REGION NO.	MATERIAL
1,5,8,11,14,17,20,23,24,25,26	POCO Graphite
2,4,6,9,12,15,18,21	He-Ne Gas Mixture
3	Tungsten
7,10,13,16,19,22	Stainless Steel

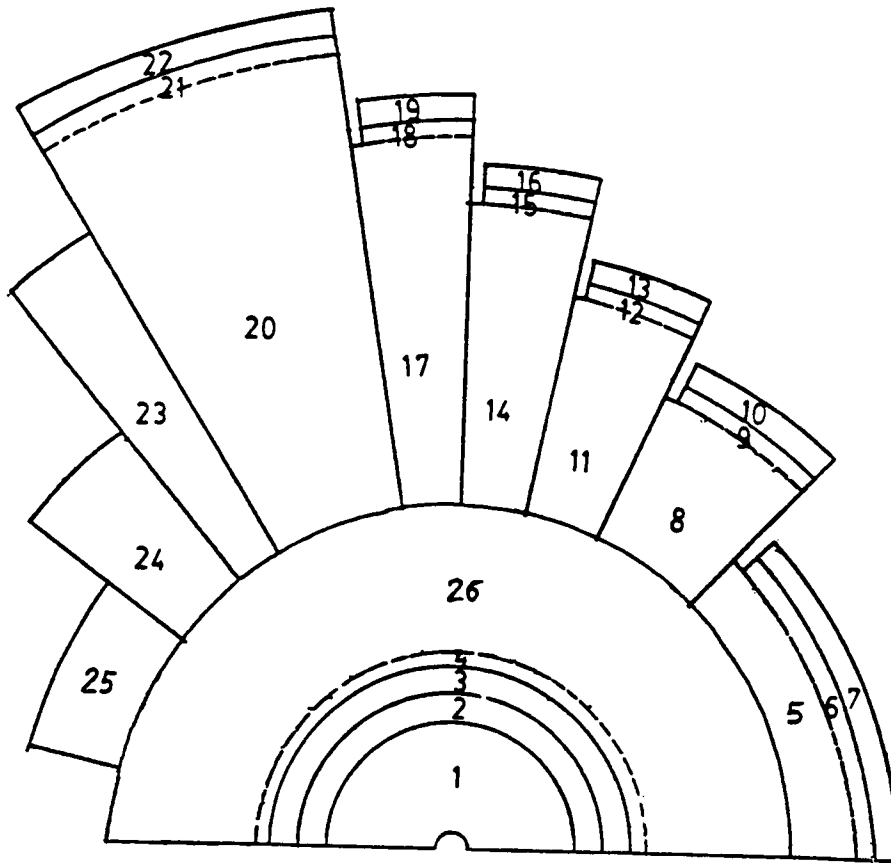


Figure 5.12. The Computational Model and its Regions in Polar Coordinates.

incorporated in the HEATING5 code. This coefficient is the product of graybody shape-factor for the involved surfaces, numbered 1 and 2, (F_{12}), and Stefan-Boltzmann constant (σ), where the former is generally a function of view factor (f_{12}), areas (A_1 and A_2), and the emissivities of the involved surfaces (e_1 and e_2) as follows:

$$h_r = F_{12} \sigma \quad (5.1)$$

where

$$\begin{aligned} F_{12} &= 1/[(1/f_{12}) + (1-e_1)/e_1 + \\ &\quad (A_1/A_2)(1-e_2)/e_2] \quad (\text{unitless}) \quad (5.2) \\ \sigma &= 5.669 \times 10^{-8} \text{ W/m}^2/\text{K}^4 \\ &= 0.1714 \times 10^{-8} \text{ BTU/h/Ft}^2/\text{F}^4 \end{aligned}$$

Since the direct input of the various radiant emissivities is not provided by the HEATING5 code, the thermal radiation coefficients must be calculated and then input into the code. The calculations, for the gap regions in the model, were performed by utilizing the following simplified form of Eq. 5.1, obtained for two long concentric cylinders:

$$h_r = F_{io} \sigma \quad (5.3)$$

where

$$\begin{aligned} F_{io} &= 1/[1/E_i + (R_i/R_o)(1-E_o)/E_o] \quad (5.4) \\ &\quad (\text{unitless graybody shape-factor}) \end{aligned}$$

i and o refer to the inner surface and outer surface
of each gas gap, respectively,

e is the radiant emissivity,

r is the radius of the surface,

$$\sigma = 0.1984 \times 10^{-12} \text{ BTU/min./in}^2/\text{F}^4$$

The above value of σ was chosen with regard to the system of units introduced to the computer code. The unit system used was in.-min.- $^{\circ}$ F-radian-lb.-BTU.

5.5 Volumetric Heat Generation Rate

The gamma heating rate for the ORR at position E-5, which is the only heat source in the thermal analysis of the OC-6 capsule, was initially given in units of watt/gram (joule/gram/sec), while the HEATING5 code requires the volumetric heating rate in BTU/in³/min. A tabular function, representing the variation of gamma heating rate with z, based on Figure 3.2 (page 26), was constructed and a different multiplication constant was assigned to each material, in order to input consistent data for the heating rate. This constant was obtained as follows:

$$\begin{aligned} &\text{material density (gram/cm}^3\text{)} \times \\ &(16.387 \text{ cm}^3/\text{in}^3) \times \\ &(\text{BTU}/1055 \text{ J}) \times (60 \text{ sec/min}) = \\ &\text{density} \times 0.932 \text{ (gram-BTU/in}^3\text{-min-watt)} = \text{Const.} \end{aligned}$$

By multiplying this constant, for each material, by the gamma heating rate, gamma heating rate with consistent units is obtained.

5.6 The Input Processing Code HINT

Calculating and formatting the input data for HEATING5 code, with regard to the geometrical configuration of the computational model (Figure 5.12), is very cumbersome. Even for a two-dimensional case (r, θ) , variations of middle gap, outer gap, and circumferential gap result in some changes in the boundary (or boundaries) of the majority of regions, which must be taken into account for each new computer run. In other words, for each new set of design variables, the amount and format of the necessary input data requires a major effort for data compilation and transformation.

In order to avoid the above mentioned difficulty, a computer program, referred to as HINT, was written for the geometry of the calculational model, which translates basic design information into the proper HEATING5 input format. The HINT code for two-dimensional case has been included in Appendix B.

The HINT input for the two-dimensional cylindrical geometry (r, θ) consists basically of the following:

1. expected required cpu time,
2. width of the circumferential gap,

3. width of the outer gap,
4. width of the middle gap,
5. case number and date.

The non-varying input-data, such as types of boundary conditions and temperature-dependent thermal properties, have been incorporated into the HINT. Those input data of HEATING5 code, which are dependent upon the inputs of HINT code, such as lattice lines in R and θ directions, are generated by HINT and then mixed with or concatenated to constant data, leading to production of clean-cut, formatted input data for HEATING5 code.

5.7 Preliminary Two-dimensional Calculations

In order to broadly specify the required gaps at various gamma-heating rates, several computer runs were performed in two-dimensional (r and θ) coordinates. In these calculations, He-Ne gas mixture, with 0.3 mole fraction helium, was chosen as the sweep gas. A convergence criterion (discussed in Section 4.5) of 10^{-6} appeared to be sufficient, as a means for terminating the steady-state iterations; because, going from 10^{-6} to 10^{-7} , as the magnitude of the steady-state convergence criterion, resulted in insignificant changes in the already-obtained steady-state temperature-distribution.

The preliminary two-dimensional calculations revealed that to hold the main support graphite block

temperature down to 950 C or less, with a gamma heating rate of 5 W/g, it was necessary to increase the gap around the tungsten thermal radiation shield above that used at the maximum gamma heating rate of 8 W/g. Based on the obtained results from the two-dimensional case, it was decided to decrease the initial temperature requirement for the specimens, from 1250 C to 1200 C.

The required axial variation of the middle gap, which became evident from the preliminary calculations, in addition to the necessary axial variation for the outer gap, further complicates the design and assembly and the three-dimensional heat transfer calculations. Due to this complexity, the HINT and HEATING5 codes had to be modified in order to be able to perform the three-dimensional thermal analysis.

5.8 Modification of the HINT Code

The capability of the input processing code HINT, introduced in Section 5.6, in generating and formatting input data for HEATING5 code, was enhanced, through considerable modifications, in order to perform its task for three-dimensional cases. In other words, the final version of HINT, included in Appendix C, has evolved out of the need for an input generator for the complex three-dimensional heat-transfer problem under consideration.

The input for the final version of HINT consists basically of the following:

1. number of dimensions (2 or 3),
(if 2 is given as the first answer,
the code proceeds by requiring the pieces
of information for two-dimensional
case, as discussed in Section 5.6)
2. value of circumferential gaps,
3. number of steps (different widths), in
z (axial) direction, for the outer gap,
4. values of lower height, upper height,
and width associated with each step
in the outer gap,
5. number of steps, in z direction,
for the middle gap,
6. values of lower height, upper height,
and width associated with each step in the
middle gap,
7. case number and date.

After processing and preparing some typical sets of input data for HEATING5 code, using the general (modified) version of the HINT code, the computer program REGPLOT [22] was used to graphically check the generated input data. A typical set of input data for three-dimensional case is included in Appendix D.

5.9 Modification to the HEATING5 Computer Code

Development of the three-dimensional computational model of the capsule resulted in a large number of regions and, consequently, a great number of gross grid lines. This caused some problem size limits of the HEATING5 code to be exceeded, therefore a modification of the code turned out to be necessary.

Because of the incapability of the existing HEATING5 computer code to handle more than 100 regions, 50 gross lattice lines along an axis, and 100 fine lattice lines along an axis, a modification was made to the code [23] and these limits changed to 200, 100, and 200 respectively. In other words, as far as the numbers of regions, gross grid lines along an axis, and fine grid lines along an axis are concerned, the capability of the code has been doubled.

Table 5.1 depicts the problem size limits for the original HEATING5 code. The numbers included in parentheses indicate the maximum numbers of corresponding items in the modified version of the code. The limit imposed on the maximum number of lattice points (nodes) can be varied by including the involved number of nodes in the main routine [20].

The amount of computer core in k bytes required by the new version is given roughly by the equation:

$$M = 300 + 0.208 N$$

where N is the maximum number of nodes as supplied in the main routine [23].

TABLE 5.1

PROBLEM SIZE LIMITS FOR THE HEATING5 CODE

Item	Maximum Number*
Analytical Functions	25
Boundary Conditions	50
Fine Lattice Lines Along Any axis	100 (200)
Gross Lattice Lines Along Any Axis	50 (100)
Heat Generation Functions	20
Initial Temperature Functions	25
Lattice Points	1400
Materials	50
Materials with Change-of-Phase Capabilities	5
Number of Nodes in Special Temperature Table	20
Points Per Tabular Function	25
Printout Times	100
Regions	100 (200)
Surface-to-Surface Connectors	2000
Tabular Functions	25

* Numbers included in parentheses indicate the maximum numbers of corresponding items in the modified version of the code.

CHAPTER VI

THERMAL ANALYSIS IN THREE DIMENSIONS AND CONSIDERATION
OF SHIFTING PHENOMENON IN GAMMA
HEATING CURVE

6.1 Three-Dimensional Thermal Analysis

Having prepared the main tools of the thermal analysis, i.e., the HINT code and the HEATING5 code, the three-dimensional heat-transfer problem under consideration was attacked.

In order to keep the number of nodes and cosequently the required amount of CPU time and computer core down, during the determination and adjustment of necessary steps in the outer and middle gaps, for the three-dimensional case, the computational model of the capsule was split into two separate parts. This separation was performed along the axial lattice line which coincides with the maximum value of the gamma heating rate. This particular lattice position was chosen because of the very nearly adiabatic condition along it. The other end of each part was also considered to be subject to adiabatic boundary condition; because, in the actual design it can be insulated.

While treating the above mentioned two separate segments of the computational model as two independent heat transfer problems, enough care was taken, in modeling the gas gaps around the axial positions corresponding to the

high values of the mamma heating rate to have only a small discontinuity in temperatures at the location where the two sections of the computational model of the capsule join together.

The thermal conductivity of helium-neon gas mixture (0.3 mole fraction helium) and that of a slightly irradiated graphite were employed in the computations in order to maintain a flat temperature distribution in the graphite specimen with a magnitude of 1200 C. This was done for both parts of the model by introducing different steps in the outer gap and middle gap while trying not to allow the temperature of the graphite block, at the positions of thermocouples, to exceed 950 C. The obtained flat temperature regions sum up to about 30 cm in the axial direction, as depicted in Figure 6.1.

In order to see whether the flatness of temperature distribution for that portion of the specimen will be maintained as the irradiation damage to the graphite increases (thermal conductivity decreases), the thermal conductivity of the graphite with saturated damage (constant minimum thermal conductivity) was used as an extreme case (the gas composition was kept as before). It was revealed that the flat region in the "temperature versus z" curve which had been obtained from the previous case (slightly irradiated POCO graphite) maintained its flatness, but the temperature was about 25 C higher than that of the former

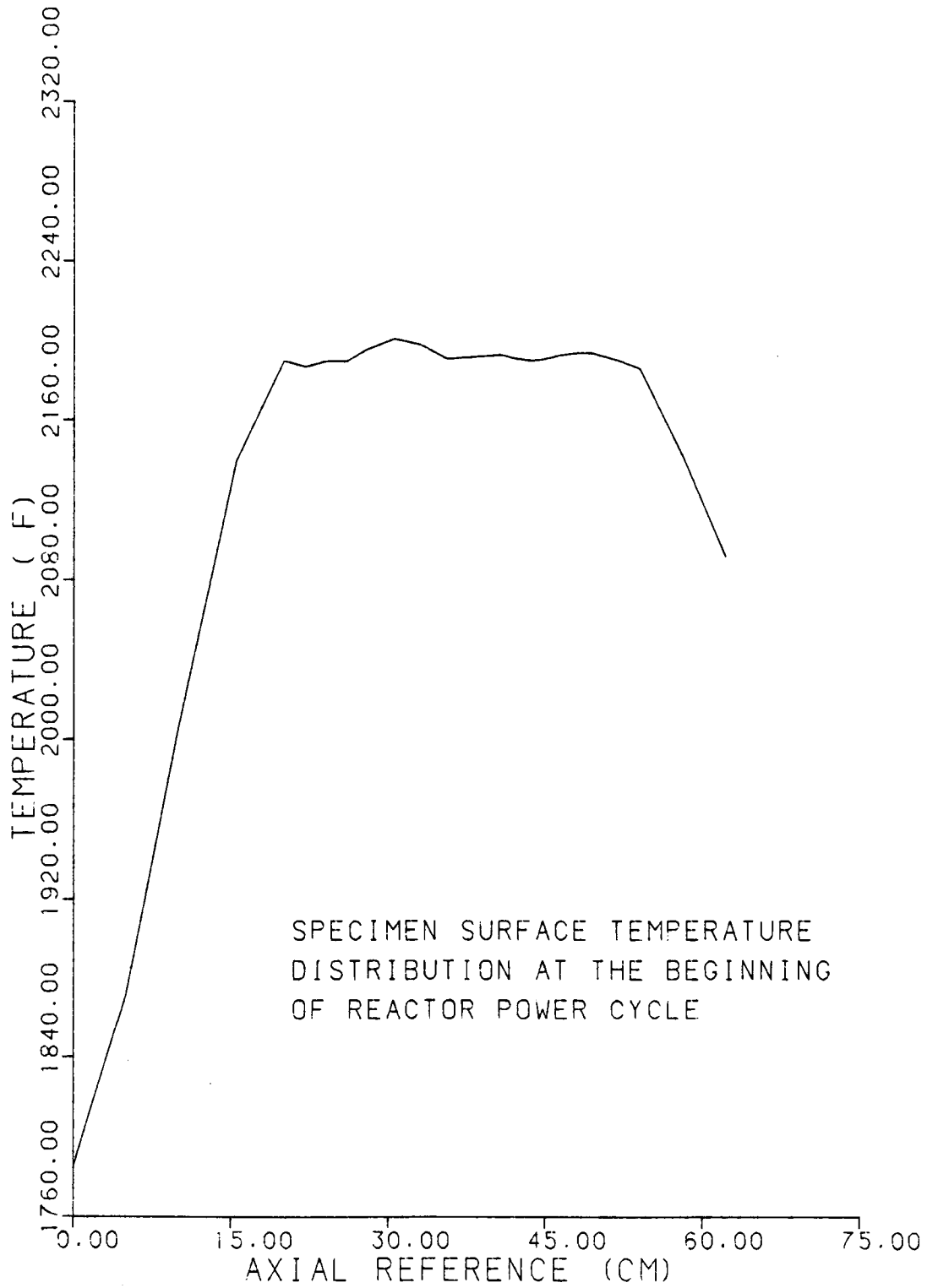


Figure 6.1. Axial Temperature Distribution of the Graphite Specimen.

case, as shown in Figure 6.1. This increase in the temperature was expected because of the lower thermal conductivity of the graphite.

With a constant gap set up, the only tool which can be used to control the temperatures inside the capsule is the gas composition. Pure helium (highest conductivity compared to that of the gas mixture) was tried as an extreme case. The examination of the results revealed that the temperature was decreased substantially and the flat region was maintained.

The results obtained from different runs indicate that varying the mole fraction of helium in the helium-neon gas mixture is a reliable tool in controlling the temperature of the specimen.

6.2 Shifting Phenomenon In Gamma Heating Curve

As pointed out in Section 3.3, due to core aging, the gamma heating rate experiences an upward shift in the axial direction, as shown in Figure 6.2. If the capsule is maintained at its original position, with the same set of gap widths, the rather flat temperature distribution which has been obtained at the beginning of reactor power cycle can not be maintained unless somehow the capsule position is shifted to match the gamma heating rate. A computer run was made to study whether the flatness of the temperature distribution can be maintained by shifting the capsule in the same axial direction as the gamma heating rate shifts.

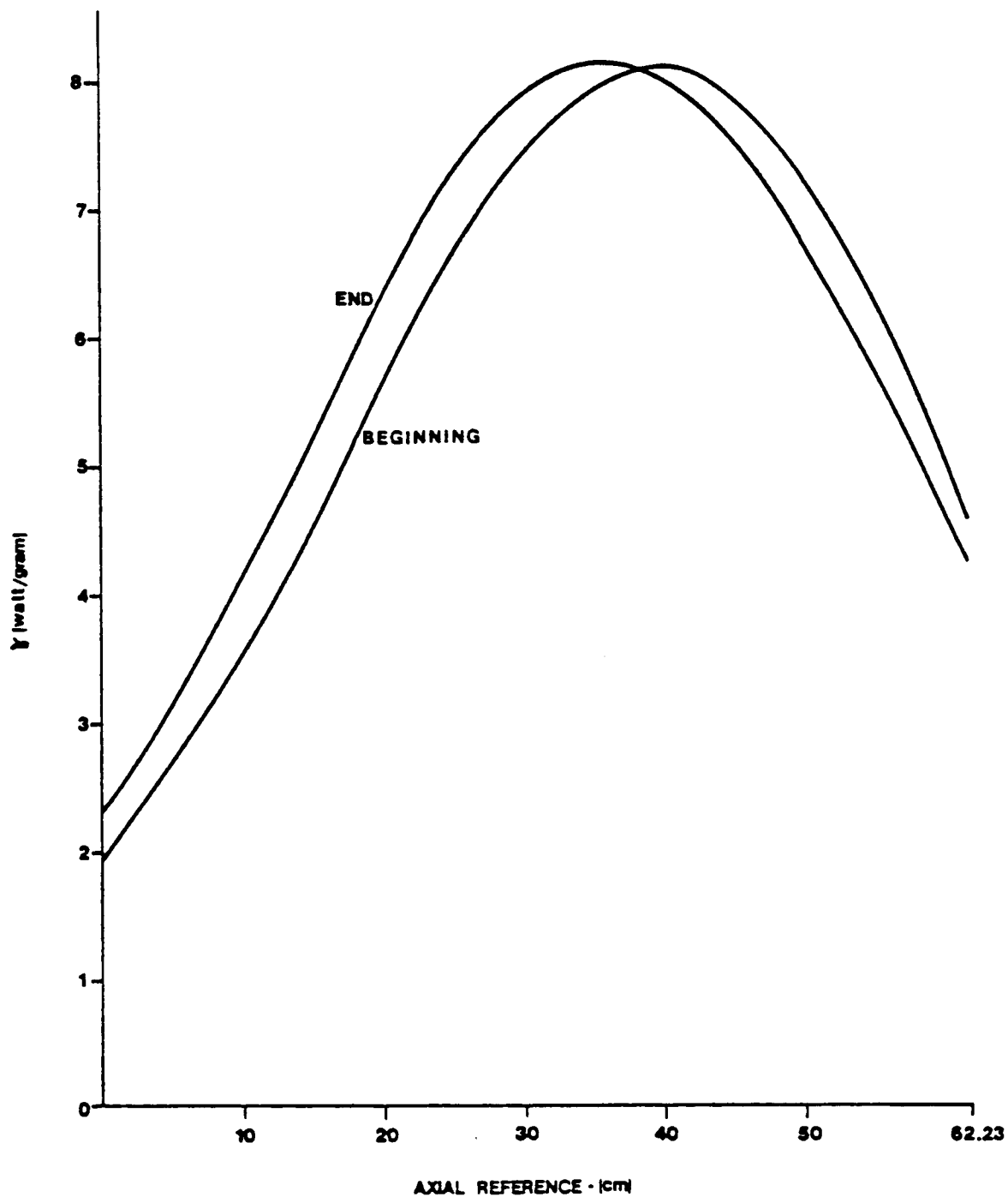


Figure 6.2. Gamma Heating Rate at Beginning and End of 14 Day Reactor Power Cycle [14].

The tabular functions which were incorporated in this run were obtained based on the comparison of the gamma heating rates at the beginning and the end of the 14-day reactor power cycle (Figure 6.2). The results for a 4.92 cm shift indicated an over-shifting, as shown in Figure 6.3, and therefore a smaller shift should be used. This figure indicates that the flatness of the temperature distribution along the same segment of the specimen column (about 30 cm.) can be maintained by conducting a proper shift. The control of new temperature level can be performed by varying the gas mixture.

6.3 Change Of Gamma Heating in Tungsten And New Results

It was at this stage of the calculations, when it was understood that the specific heat generation rate in tungsten, by gamma heating, is about 1.5 times as much as that in graphite [24]. This change was incorporated into the input-data processing code HINT, simply by multiplying the density of the tungsten sleeve by 1.5 (see Section 5.5). In other words the tabular function defining the heat generation rate in tungsten as a function of z (distance from the bottom of the ORR core), was modified based on the new information. Then, again, it was necessary to determine with what fraction of helium in He-Ne gas mixture, with the previously determined gap setups, the design requirements could be met and to what extent control can be imposed on

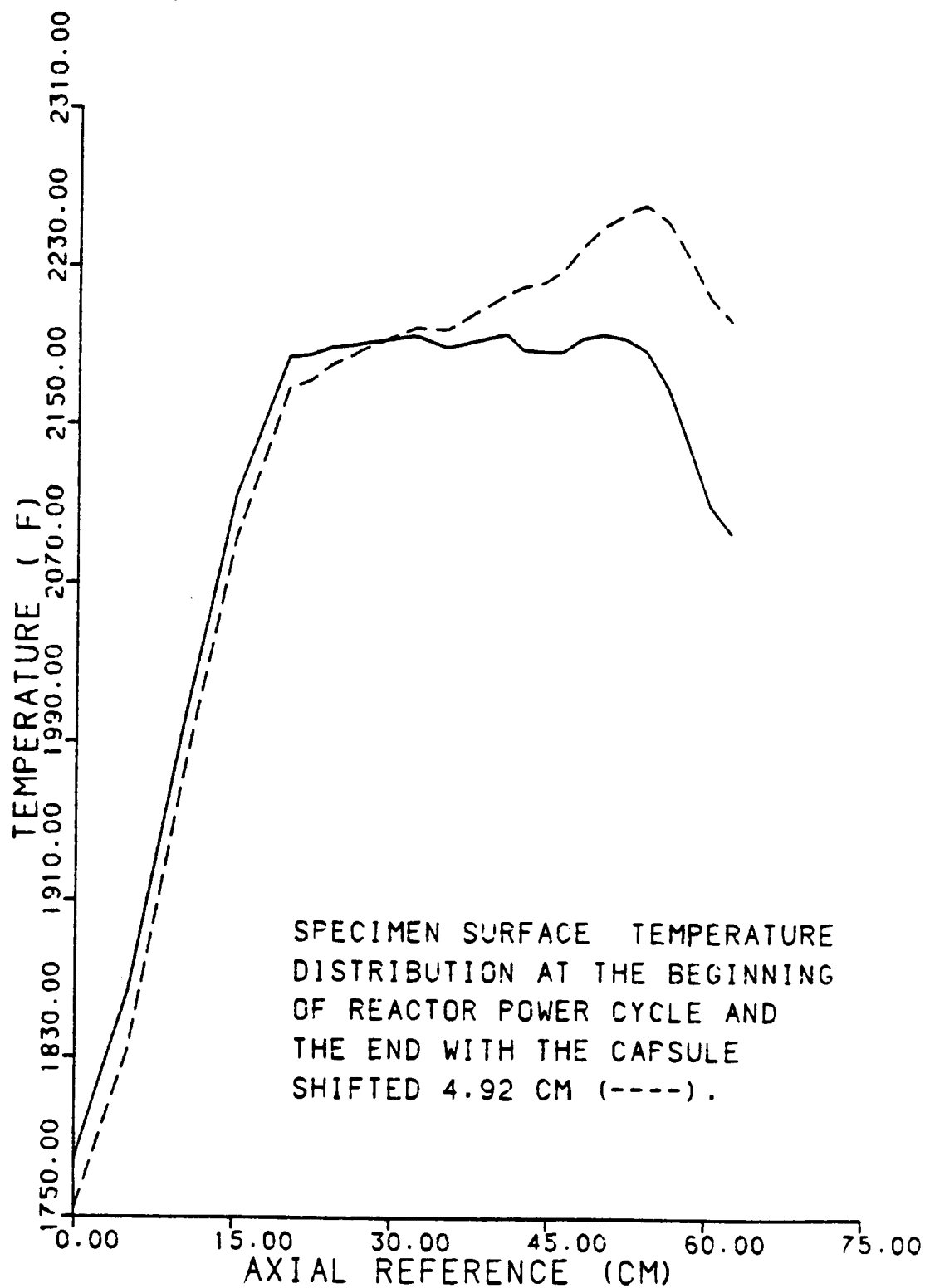


Figure 6.3. Temperature Distribution of the Specimen before and after Shifting the Capsule.

the temperature level. Having determined the rather final "setups" for the middle and outer gaps, it was decided to perform the computer runs just for the upper segment of the computational model, because the number of nodes involved in this shorter segment is less than that in the larger one. The two segments of the computational model of the capsule have been discussed in Section 6.1. This attempt, along with utilization of standby rate, brought the computing cost down considerably. It should be noted that as long as the once determined gap "setups" are not changed and as far as the level of the specimen temperature (flat part) and the block temperature are concerned, the results obtained from the analysis of the shorter segment are very close to those of the longer one.

Some computer runs were performed to predict the maximum and minimum temperature levels that can be achieved in the specimen and block by using pure neon and pure helium, respectively, as sweep gas. In these runs, which were performed for the upper segment of the capsule, the thermal conductivity of POCO graphite with saturated damage was used. Table 6.1 summarizes the results.

6.4 Final "Setups" of the Variable Gaps

Figure 6.4 shows the final axial variation of the middle gap. The numbers on the horizontal axis indicate the radii with respect to the centerline of the specimen column. The axial reference on the vertical axis is the same as the

TABLE 6.1
RESULTS FOR POCO GRAPHITE WITH SATURATED DAMAGE

Sweep Gas	Graphite Specimen Temp. [Deg. F (Deg. C)]		Graphite Block Temp. at the Location of T.C. [Deg. F (Deg. C)]
	Inner Surface	Outer Surface	
Pure Ne	2794 (1534)	2784 (1529)	2145 (1174)
Pure He	2018 (1103)	2010 (1099)	1379 (748)
50% He	2401 (1316)	2392 (1311)	1734 (946)

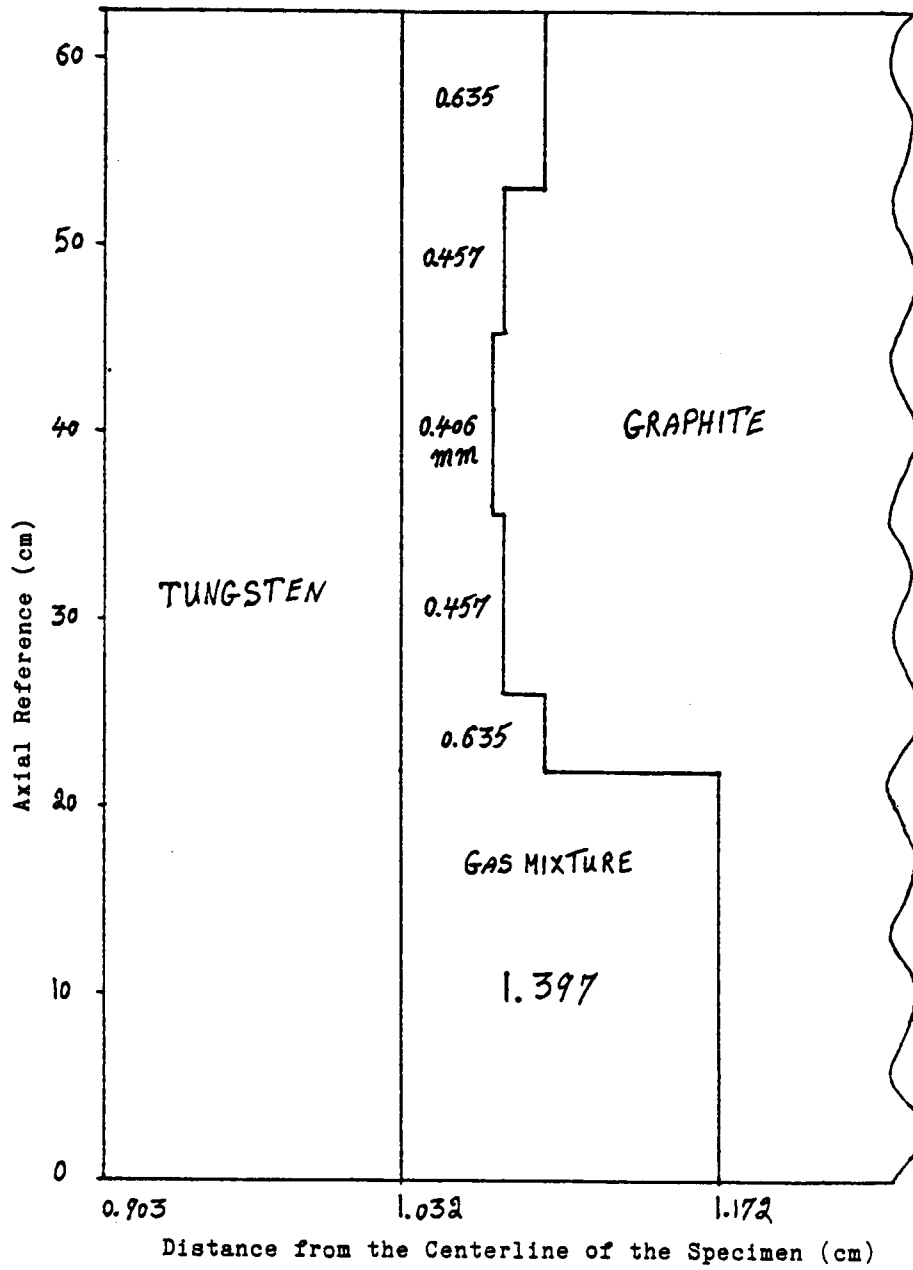


Figure 6.4. Final Axial Variation of the Middle Gap.

one used in Figure 3.3 (page 28).

Figure 6.5 depicts the final axial variation of the outer gap. the numbers on the horizontal axis indicate the radii with respect to the centerline of the capsule. The axial reference on the vertical axis is the same as the one used in Figure 3.3 (page 28).

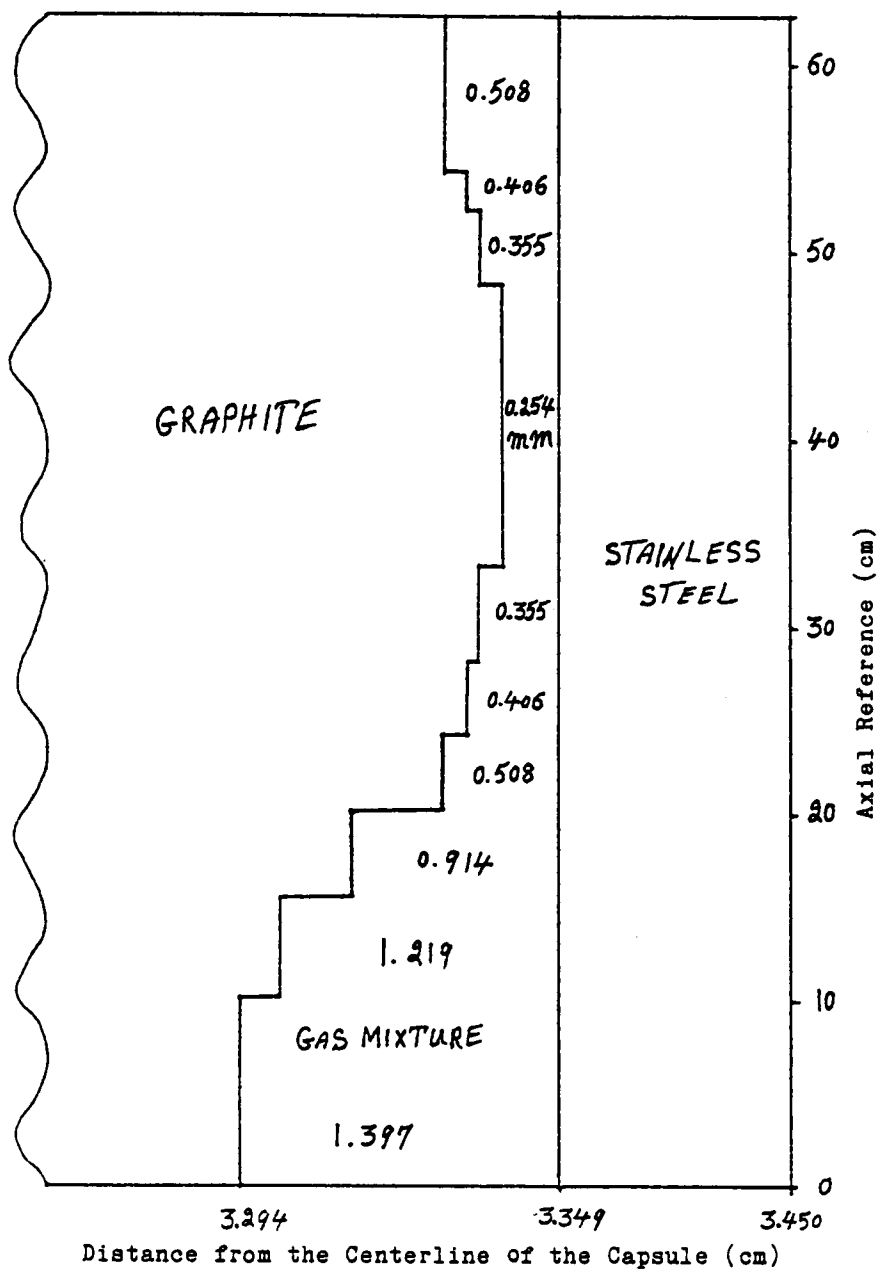


Figure 6.5. Final Axial Variation of the Outer Gap

CHAPTER VII

SUMMARY AND CONCLUSIONS

The thermal design of the OC-6 irradiation-induced creep test capsule (Figure 3.2 (page 26)) was performed; the following features have been incorporated into this design:

1. The dimensions of the stainless-steel containment of the capsule and those of the two encapsulated graphite specimen columns are the same as those used in the other OC-series capsules.
2. Gamma heating is the only internal heat generation source in this capsule.
3. The shifting of the gamma heating rate over a reactor operating cycle is accounted for by an upward shift of the capsule. Calculations showed that the temperature distribution of each specimen column maintained its flatness, along the same length of the unshifted specimen column, after conducting the shift. This requires that the capsule be shifted about 5 cm. (2 in.) upward to match the gamma heat shift. The exact amount of shift can be determined experimentally by monitoring the moveable thermocouple.
4. The gas gap (Inner Gap) surrounding each specimen column has a constant thickness of 0.141 cm (0.055 in.).

5. A 0.129 cm (0.051 in.) thick tungsten tube with the inner surface polished (with an emissivity of 0.45) and an inner diameter of 1.806 cm (0.711 in.), surrounds each specimen column.
6. Each tungsten tube is surrounded by an axially-varying gas gap (Middle Gap) whose variation is shown in Figure 6.3.
7. The outer gas gap which surrounds the graphite block varies axially and its variation is depicted in Figure 6.3.
8. The sweep gas is a mixture of neon and helium. The temperature level of the specimens can be controlled by varying the He-Ne sweep gas mixture; this was shown in Table 6.1. It is expected that the required mixture will contain about 80% mole fraction helium. However, some more computer runs can be performed, should the determination of the exact combination of the mixture be necessary.

The final axial variations of the middle gap and the outer gap (Figures 6.4 and 6.5) have been summarized in Tables 7.1 and 7.2, respectively.

The input processing program HINT, included in Appendix C) can be used with the HEATING5 code, should more heat transfer calculations be necessary during the course of the irradiation experiment.

TABLE 7.1

STEPWISE VARIATION OF THE MIDDLE GAP (MG)

Axial Range* (cm (in.))	Gap Width (cm (in.))
0.000 - 22.000 (0.000 - 8.661)	0.140 (0.055)
22.000 - 26.000 (8.661 - 10.236)	0.063 (0.025)
26.000 - 35.500 (10.236 - 13.976)	0.046 (0.018)
35.000 - 45.000 (13.976 - 17.717)	0.041 (0.016)
45.000 - 53.000 (17.717 - 20.866)	0.046 (0.018)
53.000 - 62.230 (20.866 - 24.500)	0.063 (0.025)

* Using the axial reference of Figure 3.3 (page 28).

TABLE 7.2

STEPWISE VARIATION OF THE OUTER GAP (OG)

Axial Range* (cm (in.))	Gap Width (cm (in.))
0.000 - 10.000 (0.000 - 3.937)	0.140 (0.055)
10.000 - 15.500 (3.937 - 6.102)	0.122 (0.048)
15.500 - 20.000 (6.102 - 7.874)	0.091 (0.036)
20.000 - 24.000 (7.874 - 9.449)	0.051 (0.020)
24.000 - 28.000 (9.449 - 11.024)	0.041 (0.016)
28.000 - 33.000 (11.024 - 12.992)	0.035 (0.014)
33.000 - 48.000 (12.992 - 18.898)	0.025 (0.010)
48.000 - 52.000 (18.898 - 20.472)	0.035 (0.014)
52.000 - 54.000 (20.472 - 21.260)	0.041 (0.016)
54.000 - 62.230 (21.260 - 24.500)	0.051 (0.020)

*Using the axial reference of Figure 3.3 (page 28).

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APPENDICES

APPENDIX A

GAMMA HEATING IN REACTOR EXPERIMENTS [25]

Gamma-heat generation in in-pile experiments is due to primary and secondary gammas. Figure A.1 shows the important sources of gamma heating in a material placed in or near the reactor core.

Primary Gammas. Fission gammas and fission-product decay gammas, each, constitutes about one third of the gammas released in the core. Resonance and thermal absorption of neutrons in core materials and neutron inelastic scattering causes the remainder of core gammas. Figure A.2 shows the effect of the neutron spectrum on the total core gamma sources.

All of these gammas, which have different initial energies, are absorbed to produce thermal energy or escape the reactor, after being scattered and degraded in energy by multiple collision with core materials. This source of energy is called primary gamma heating and is the major source of heating in any material placed in or near the reactor core. The source strength is expressed as an energy release rate per unit volume of core, $\text{MeV/cm}^3/\text{sec}$.

Secondary Gammas. Another group of gammas, which are due to resonance and thermal absorption of neutrons and inelastic scattering in the experimental material, are called

secondary gammas. The absorption of these gammas constitute another cause of energy deposition in experimental material. This can be of importance if the material is large and has a high density.

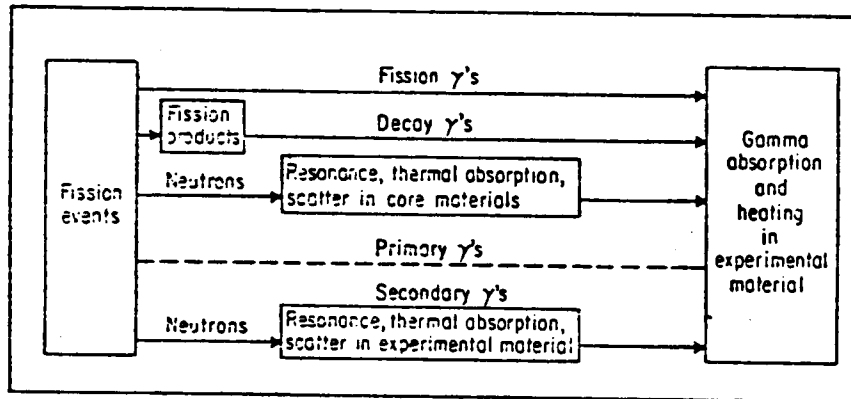


Figure A.1. Sources of Gammas leading to Gamma-Heat Generation in Reactor Experiments.

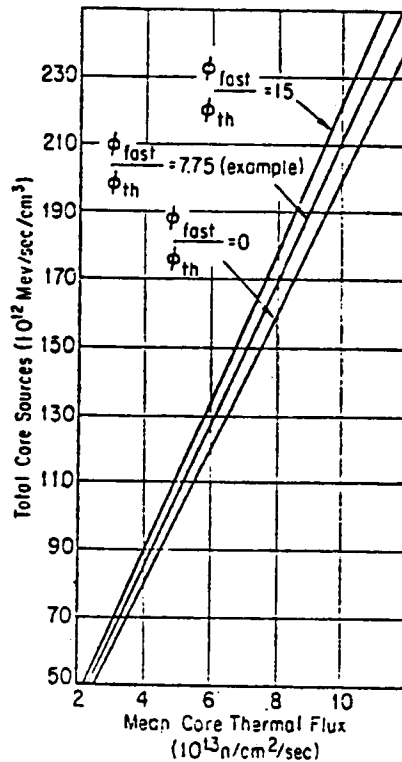


Figure A.2. Effect of Neutron Spectrum on Total Core Gamma Sources.

APPENDIX B

2-D HINT CODE AND TYPICAL OUTPUTS

The preliminary two-dimensional HINT code and its typical outputs are included in this appendix. This code, when run, generates two different output files: FOR21.DAT and FOR22.DAT.

The first file (FOR21.DAT) shown on pages 104-105, contains some pieces of information related to the physical problem under consideration and its computational model.

The second file (FOR22.DAT), shown on pages 102-103, contains the required formatted input data for the HEATING5 code.

The 2-D HINT code was later extended to the three-dimensional case (included in Appendix C).

```

      DIMENSION N(40),R(40,5),T(40,5),HR(10)
      REAL MIDGAP, OUTGAP
C-----
C      THE FOLLOWING FUNCTION CALCULATES THE EMISSIVITY FUNCTION
C      (FE) FOR RADIATION EXCHANGE BETWEEN TWO CONCENTRIC CYLINDRICAL
C      SURFACES (CAN BE A PART OF CYLINDER) WITH EMISSIVITIES E1 AND E2
C      AND RADII R1 AND R2
C
      FE(E1,E2,R1,R2)=1/((1/E1 + (R1/R2)*(1/E2 -1))
C-----
      WRITE(5,10)
10     FORMAT(2X,'WHAT IS THE VALUE OF MIDDLE GAS GAP (IN INCH) ?')
      READ(5,*) MIDGAP
C
      WRITE(5,20)
20     FORMAT(2X,'WHAT IS THE VALUE OF OUTER GAS GAP (IN INCH) ?')
      READ(5,*) OUTGAP
C
      WRITE(5,30)
30     FORMAT(2X,'WHAT IS THE VALUE OF ANGULAR GAP (IN INCH) ?')
      READ(5,*) ANGGAP
C
      WRITE(5,35)
35     FORMAT(2X,'WHAT IS THE VALUE OF GAMMA HEATING RATE (GHR) IN WATT
          1/GR. ')
      READ(5,*) GHR
C-----
      C=2.54
      THICK=.040
C-----
      DATA (N(I),I=1,4) /1,2,3,2/, (N(I),I=7,22,3) /6*5/
      DATA (N(I),I=6,21,3) /6*2/, (N(I),I=5,20,3) /6*4/
      DATA (N(I),I=23,26)/4*4/
C
      R(1,1)=0.0000
      R(1,2)=0.7620/C
      R(2,1)=R(1,2)
      R(2,2)=0.8992/C
      R(3,1)=R(2,2)
      R(3,2)=1.0363/C
      R(4,1)=R(3,2)
      R(4,2)=R(4,1) + MIDGAP
C
      DO 36 I=5,23,3
36     R(I,1)=R(4,2)
C
      DO 38 I=24,26
38     R(I,1)=R(4,2)
C
      R(5,2)=1.86150/C - OUTGAP
      R(6,1)=R(5,2)
      R(6,2)=1.86150/C
      R(7,1)=R(6,2)
      R(7,2)=R(7,1) + THICK
      R(8,2)=2.20499/C - OUTGAP
      R(9,1)=R(8,2)
      R(9,2)=2.20499/C
      R(10,1)=R(9,2)
      R(10,2)=2.20499/C + THICK
      R(11,2)=2.52536/C - OUTGAP
      R(12,1)=R(11,2)
      R(12,2)=2.52536/C

```

```

R(13,1)=2.52534/C
R(13,2)=R(13,1) + THICK
R(14,2)=2.82930/C - OUTGAP
R(15,1)=R(14,2)
R(15,2)=2.82930/C
R(16,1)=2.82930/C
R(16,2)=R(16,1) + THICK
R(17,2)=3.12655/C - OUTGAP
R(18,1)=R(17,2)
R(18,2)=3.12655/C
R(19,1)=3.12655/C
R(19,2)=R(19,1) + THICK
R(20,2)=3.43135/C - OUTGAP
R(21,1)=R(20,2)
R(21,2)=3.43135/C
R(22,1)=3.43135/C
R(22,2)=R(22,1) + THICK
R(23,2)=2.82930/C
R(24,2)=2.20499/C
R(25,2)=1.67591/C
R(26,2)=1.33462/C
C-----
DATA (T(I,1),I=1,7) /7*0.0/, (T(I,2),I=1,4) /4*3.14159/
C
T(5,2)=0.82339
T(6,2)=T(5,2) - ANGGAP/R(6,2)
T(7,2)=T(6,2)
DATA (T(I,1),I=8,10) /3*0.82339/
C
T(8,2)=1.15922
T(9,2)=1.15922 - ANGGAP/R(9,2)
T(10,2)=T(9,2)
DATA (T(I,1),I=11,13) /3*1.15922/
C
T(11,2)=1.39576
T(12,2)=T(11,2) - ANGGAP/R(12,2)
T(13,2)=T(12,2)
DATA (T(I,1),I=14,16) /3*1.39576/
C
T(14,2)=1.59192
T(15,2)=T(14,2) - ANGGAP/R(15,2)
T(16,2)=T(15,2)
DATA (T(I,1),I=17,19) /3*1.59192/
C
T(17,2)=1.76764
T(18,2)=T(17,2) - ANGGAP/R(18,2)
T(19,2)=T(18,2)
DATA (T(I,1),I=20,22) /3*1.76764/
DATA (T(I,2),I=20,22) /3*2.16081/, T(23,1) /2.16081/
DATA T(23,2) /2.25058/, T(24,1) /2.25058/
DATA T(24,2) /2.59213/, T(25,1) /2.59213/
DATA T(25,2) /2.98748/, T(26,1) /2.98748/
C
T(24,2)=T(24,2) - (2.* 0.01678)/(R(24,2)**2 - R(24,1)**2)
T(25,1)=T(24,2)
T(26,2)=3.14159
C-----
WRITE(21,40) MIDGAP, OUTGAP, ANGGAP
40  FORMAT(/,5X,'MIDGAP=',F7.5,' IN.',15X,'OUTGAP=',F7.5,' IN.',15X,
1'ANGGAP=',F7.5,' IN.')
C
WRITE(21,50)

```

```

50  FORMAT(/,2X,'REG. NO.',5X,'MAT. NO.',10X,'R1 (IN.)',10X,
    1'R2 (IN.)',10X,'T1 (RAD)',10X,'T2 (RAD)')
C
    WRITE(21,55)
55  FORMAT(2X,'-----'
    1'-----')
C
    DO 60 I=1,26
        WRITE(21,70) I,N(I),R(I,1),R(I,2),T(I,1),T(I,2)
70  FORMAT(2X,I2,15X,I1,4(11X,F8.5))
        WRITE(21,80)
80  FORMAT(2X,'-----'
    1'-----')
60  CONTINUE
C-----
C  FINDING THE RADIATION HEAT TRANSFER COEFFICIENTS FOR BOUNDARY
C  CONDITIONS 1 THROUGH 8 (RADIATION AND CONDUCTION)
C  STEFAN-BOLTZMAN CONSTANT: 0.1714 X 10**-8 BTU/HR-FT**2-R**4
C  OR 5.6697 X 10**-8 W/M**2-K**4
C  THE ABOVE CONSTANT IN UNIT OF BTU/MIN-IN**2-R**4 WILL BE :
C
    STBOLT=0.1714E-8/(60.*144.)
C-----
    WRITE(21,90) STBOLT
90  FORMAT(/,5X,'STEFAN-BOLTZMAN CONSTANT =',E9.4,' BTU/MIN-IN.**2
    1-R**4')
C
C  ESPEC=E OF GRAPH. SPEC., EPOL=E OF POLISHED TUNG., ENONPO=E OF
C  NONPOLISHED TUNG., EBLOCK=E OF GRAPH. BLOCK, ESS=E OF S.S.
C
    ESPEC=0.9
    EPOL=0.45
    ENONPO=0.9
    EBLOCK=0.9
    ESS=0.7
C
    HR(1)=STBOLT * FE(ESPEC,EPOL,R(1,2),R(3,1))
    HR(2)=STBOLT * FE(ENONPO,EBLOCK,R(3,2),R(5,1))
    HR(3)=STBOLT * FE(EBLOCK,ESS,R(5,2),R(7,1))
    HR(4)=STBOLT * FE(EBLOCK,ESS,R(8,2),R(10,1))
    HR(5)=STBOLT * FE(EBLOCK,ESS,R(11,2),R(13,1))
    HR(6)=STBOLT * FE(EBLOCK,ESS,R(14,2),R(16,1))
    HR(7)=STBOLT * FE(EBLOCK,ESS,R(17,2),R(19,1))
    HR(8)=STBOLT * FE(EBLOCK,ESS,R(20,2),R(22,1))
C
    WRITE(21,100) ESPEC,EPOL,ENONPO,EBLOCK,ESS
100 FORMAT(/,6X,'THE EMISSIVITIES OF THE MATERIALS :',/,2X
    1'E OF SPEC.=',F3.1,3X,'E OF POL.TUNG.=',F4.2,3X,'E OF NONPOL.
    2TUNG.=',F3.1,3X,'E OF G.BLOCK=',F3.1,3X,'E OF S.S.=',F3.1)
C
    WRITE(21,110)
110 FORMAT(/,3X,'B.C.#',10X,'H.T. COEFF. HR FOR RADIATION',/,
    121X,'(BTU/MIN.-IN.**2-R**4)')
C
    DO 120 K=1,8
120  WRITE(21,130) K, HR(K)
130  FORMAT(5X,I1,20X,E9.4)
C  THE COEFFICIENT OF FORCED CONVECTION (BTU/MIN-IN**2-F) FOR B.C.9
C
    HC=0.6181
C
    WRITE(21,140) HC

```

```

140   FORMAT(/,5X,'THE COEFF. OF FORCED CONVEC. =',F6.4,2X,'BTU/MIN.-
      1IN.**2-F')
C
C ----- BOUNDARY TEMP.: COOLANT(WATER) TEMP. = BT IN DEG. F -----
C
      BT = 118.0
      WRITE(21,150) BT
150   FORMAT(/,5X,'BOUNDARY TEMP. (FOR B.C. #9) = ',F6.2,' DEG. F')
C
C ----- FINDING THE VOLUMETRIC HEATING RATE (VHR) FOR EACH MATERIAL ---
C ----- VHR [ BTU/IN.**3-MIN ] = DENSITY * 0.932 [ GR-BTU/IN.**3-MIN-
C       WATT ] * GAMMA HEATING RATE (GHR) [ WATT/GR ]
C --- NOTE THE VALUE OF DENSITY IS THAT IN THE UNIT OF : GR/CM.**3
C
      VHRSPN = 1.79 * 0.932 * GHR
      VHRTUN = 19.3 * 0.932 * GHR
      VHRGBC = 1.79 * 0.932 * GHR
      VHRSS = 7.85 * 0.932 * GHR
C
      WRITE(21,160) GHR
160   FORMAT(/,5X,'GAMMA HEATING RATE (GHR) = ',F5.3,' WATT/GR.')
C
      WRITE(21,170) VHRSPN, VHRTUN, VHRGBC, VHRSS
170   FORMAT(/,5X,'VHRSPN =',F8.4,' BTU/IN.**3-MIN.'
      1/,5X,'VHRTUN =',F8.4,' BTU/IN.**3-MIN.'
      2/,5X,'VHRGBC =',F8.4,' BTU/IN.**3-MIN.'
      3/,5X,'VHRSS =',F8.4,' BTU/IN.**3-MIN.')
C-----
C ----- FINDING THE AREA OF THE GR. BLOCK IN THE CAPSULE -----
C
      PI=3.14159
      SSINR=3.3490/C
      GBREAL=(( SSINR - OUTGAP)**2)*PI/4. - (( R(4,2)**2)*PI/2. )
      RHOLE = 0.3175/C
      GBREAL = GBREAL - (RHOLE **2)*PI/4.
C
C -----FINDING THE AREA OF THE S.S. IN THE CAPSULE -----
      SSREAL = ((3.4506/C)**2 - (3.3490/C)**2)*PI/4.
C----- FINDING THE INNER & OUTER PERIMETERS OF S.S. IN THE CAPSULE --
C
      RSSIN = (3.3490/C) * PI/2.
      RSSOUT = (3.4506/C) * PI/2.
C ----- FINDING THE AREA OF THE GR. BLOCK IN THE COMPUTER MODEL ----
C----- ALSO, FINDING THE AREA OF THE S.S. IN THE COMPUTER MODEL -----
C----- AND CALCULATING THE INNER AND OUTER PERIMETER OF THE S.S.-----
C----- IN THE COMPUTER MODEL . -----
      GBMODL = 0.
      SSMODL = 0.
      SSINM = 0.
      SSOUTM = 0.
      AREAM = 0.
C
      DO 180 I=5,20,3
          GBMODL = GBMODL + (R(I,2)**2 - R(4,2)**2)*(T(I,2)-T(I,1))/2.
          K=I+2
          SSMODL = SSMODL + (R(K,2)**2 - R(K,1)**2)*(T(K,2)-T(K,1))/2.
          SSINM = SSINM + R(K,1) * (T(K,2) - T(K,1))
          SSOUTM = SSOUTM + R(K,2) * (T(K,2) - T(K,1))
          AREAM=AREAM+(R(K,1)**2-R(4,2)**2)*(T(I,2)-T(I,1))/2.
180   CONTINUE
C----- ADDING THE AREA OF REGIONS 21-24 TO THE PREVIOUS GBMODL--
C

```

```

DO 190 J=23,24
  GBMODL = GBMODL + (R(J,2)**2 - R(4,2)**2)*(T(J,2)-T(J,1))/2.
  AREAM=AREAM+(R(J,2)**2-R(4,2)**2)*(T(J,2)-T(J,1))/2.
190 CONTINUE
C
  DIFFGB= GBREAL - GBMODL
  PCTGB = DIFFGB/GBREAL*100.
  DIFFSS= SSREAL - SSMODL
  PCTSS = DIFFSS/SSREAL*100.
  DIFIN = RSSIN - SSINM
  PCTIN = DIFIN/RSSIN * 100.
  DIFOUT = RSSOUT - SSOUTM
  PCTOUT = DIFOUT/RSSOUT * 100.
C
  WRITE(21,200) GBREAL, GBMODL, DIFFGB, PCTGB, SSREAL, SSMODL
1, DIFFSS, PCTSS
200 FORMAT(//,2X,'CONSIDERING THE GRAPHITE BLOCK :',
1//,5X,'AREA OF THE GR. BLOCK IN THE CAPSULE =',F10.5,/
2,5X,'AREA OF THE GR. BLOCK IN THE COMPUTER MODEL =',F10.5,/
3,5X,'REAL GR. BLOCK AREA - COMPUTER MODEL AREA =',F10.7,
4,5X,'% ERROR IN GR. BLOCK AREA =',F9.4,
5//,2X,'CONSIDERING THE STAINLESS STEEL :',
6//,5X,'AREA OF THE S.S. IN THE CAPSULE =',F10.5,
7//,5X,'AREA OF THE S.S. IN THE COMPUTER MODEL =',F10.5,
8,5X,'REAL S.S. AREA - COMPUTER MODEL AREA =',F10.5,
9,5X,'% ERROR IN S.S. AREA =',F9.4)
C
C----- PRINTING THE RESULTS CONCERNING THE INNER & OUTER PERIMETERS
C----- OF THE S.S. SLEEVE IN THE CAPSUL AND THE COMPUTER MODEL -----
C
  WRITE(21,210) RSSIN, SSINM, PCTIN, RSSOUT, SSOUTM, PCTOUT
210 FORMAT(//,2X,'CONSIDERING THE INNER AND OUTER PERIMETERS OF THE
1 S.S. SLEEVE IN BOTH THE CAPSULE AND THE COMPUTER MODEL :',
2//,5X,'INNER PERIMETER OF S.S. IN THE CAPSULE =',F10.5
3//,5X,'INNER PERIMETER OF S.S. IN THE COMPUTER MODEL =',F10.5
4//,5X,'% ERROR IN THE INNER PERIMETER =',F10.5
5//,5X,'OUTER PERIMETER OF S.S. IN THE CAPSUL =',F10.5
6//,5X,'OUTER PERIMETER OF S.S. IN THE COMPUTER MODEL =',F10.5
7//,5X,'% ERROR IN THE OUTER PERIMETER =',F10.4)
C ----- CONSIDERING THE AREA OF THE GR. BLOCK BOUNDED BY S.S.
C ----- AND THE MIDDLE GAS GAP -----
  AREAC = ((3.1490/C)**2)*PI/4. - ((R(4,2)**2)*PI/2.)
  AREAC = AREAC - (RHOLE **2)*PI/4.
  DIFFFF = AREAC - AREAM
  PCTTTT = DIFFFF/AREAC*100.
  WRITE(21,220) AREAC, AREAM, PCTTTT
220 FORMAT(//,2X,'CONSIDERING THE GR. BLOCK WITH NO OUTER GAP'
1//,5X,'THE AREA OF GR. BLOCK IN THE CAPSULE =',F10.5
2//,5X,'THE AREA OF THE GR. BLOCK IN THE COMPUTER MODEL =',
3,F10.5//,5X,'% ERROR IN THE AREA =',F10.5)
  STOP
  END

```

2D CYL COOR(R,T);GHR=6.00,SG=.3HE,MG=.035,AG=.012,OG=.030,C# 2, 3/ 1/81 CARD1 1
 50 2 26 5 4 4 4 CARD2 2
 25 16 0 4 0 0 10 CARD3 3
 50 5 7 CARD4 4
 CARD5 5

1	1500	1.0E-6							
1	1	0.06500	0.30000	0.00000	3.14159	0.000	0.000	R1	6
1	1	0	0	0				R2	7
2	2	0.30000	0.35402	0.00000	3.14159	0.000	0.000	R1	8
1	0	1	1					R2	9
3	3	0.35402	0.40799	0.00000	3.14159	0.000	0.000	R1	10
1	2	0	0					R2	11
4	2	0.40799	0.44299	0.00000	3.14159	0.000	0.000	R1	12
1	0	2	2					R2	13
5	4	0.52544	0.70287	0.00000	0.82339	0.000	0.000	R1	14
2	3	0	0					R2	15
6	2	0.70287	0.73287	0.00000	0.80702	0.000	0.000	R1	16
3	0	3	3					R2	17
7	5	0.73287	0.77287	0.00000	0.80702	0.000	0.000	R1	18
4	4	0	4					R2	19
8	4	0.52544	0.83811	0.82339	1.15922	0.000	0.000	R1	20
2	3	0	0					R2	21
9	2	0.83811	0.86811	0.82339	1.14540	0.000	0.000	R1	22
3	0	3	3					R2	23
10	5	0.86811	0.90811	0.82339	1.14540	0.000	0.000	R1	24
4	4	0	4					R2	25
11	4	0.52544	0.96424	1.15922	1.39576	0.000	0.000	R1	26
2	3	0	0					R2	27
12	2	0.96424	0.99424	1.15922	1.38369	0.000	0.000	R1	28
3	0	3	3					R2	29
13	5	0.99424	1.03424	1.15922	1.38369	0.000	0.000	R1	30
4	4	0	4					R2	31
14	4	0.52544	1.08390	1.39576	1.59192	0.000	0.000	R1	32
2	3	0	0					R2	33
15	2	1.08390	1.11390	1.39576	1.58115	0.000	0.000	R1	34
3	0	3	3					R2	35
16	5	1.11390	1.15390	1.39576	1.58115	0.000	0.000	R1	36
4	4	0	4					R2	37
17	4	0.52544	1.20093	1.59192	1.76764	0.000	0.000	R1	38
2	3	0	0					R2	39
18	2	1.20093	1.23093	1.59192	1.75789	0.000	0.000	R1	40
3	0	3	3					R2	41
19	5	1.23093	1.27093	1.59192	1.75789	0.000	0.000	R1	42
4	4	0	4					R2	43
20	4	0.52544	1.32093	1.76764	2.16081	0.000	0.000	R1	44
2	3	0	0					R2	45
21	2	1.32093	1.35093	1.76764	2.16081	0.000	0.000	R1	46
3	0	3	3					R2	47
22	5	1.35093	1.39093	1.76764	2.16081	0.000	0.000	R1	48
4	4	0	4					R2	49
23	4	0.52544	1.11390	2.16081	2.25058	0.000	0.000	R1	50
2	3	0	0					R2	51
24	4	0.52544	0.86811	2.25058	2.48975	0.000	0.000	R1	52
2	3	0	0					R2	53
25	4	0.52544	0.65981	2.48975	2.98748	0.000	0.000	R1	54
2	3	0	0					R2	55
26	4	0.44299	0.52544	0.00000	3.14159	0.000	0.000	R1	56
2	3	0	0					R2	57
1	SPECHN				-1			M	58
2	GAS				-2			M	59

	W	-3	M	60				
3		-1	M	61				
4	GR	-4	M	62				
5	SS		G	63				
1	10.0097		G	64				
2	107.9256		G	65				
3	10.0097		G	66				
4	43.8972		I	67				
1	2100.00		I	68				
2	1400.00		I	69				
3	600.00		I	70				
4	140.00		B1	71				
1	.9241D-13		B2	72				
2	.1635D-12		B1	73				
3	.1299D-12		B2	74				
4	118.00		B1	75				
0.6181			B2	76				
0.06500	0.30000	0.35402	L1	77				
0.73287	0.77287	0.83811	L1	78				
1.08390	1.11390	1.15390	L1					
1.39093			N1					
1	1	1	1	1 N1				
1	1	1	1	1 N1				
1	1	1	1	1 N1				
0.00000	0.80702	0.82339	1.14540	1.15922	1.38369	1.39576	1.58115	L2
1.59192	1.75789	1.76764	2.16081	2.25058	2.48975	2.98748	3.14159	L2
2	1	1	1	1	1	1	1	N2
1	1	2	1	2	2	1		T1
1	11							T1
400.0	0.07132	600.0	0.06571	800.0	0.06036	1000.0	0.05513	T1
1200.0	0.05021	1400.0	0.04551	1600.0	0.04219	1800.0	0.03926	T1
2000.0	0.03767	2200.0	0.03660	2400.0	0.03579			T1
2	5							T2
0.0	5.56D-5	750.0	9.9D-5	1500.0	1.353D-4	2250.0	1.701D-4	T2
3000.0	2.014D-4							T2
3	5							T3
500.0	0.1139	1000.0	0.1028	1700.0	0.09305	2061.0	0.09004	T3
2400.0	0.08917							T4
4	3							T4
32.0	0.01111	212.0	0.01306	572.0	0.01514			S
13	1	2	3	4	5	8	243	S
275	302	303	304	305	306			S

2D CYL COOR(R,T);GHR=6.00,SG=.3HE,MG=.035,AG=.012,OG=.030,C# 2, 3/ 1/81 CARD1 1

THE EMISSIVITIES OF THE MATERIALS :
 E OF SPEC.= .9 E OF POL.TUNG.= .45 E OF NONPOL. TUNG.= .9 E OF G.BLOCK
 = .9 E OF S.S.= .7

B.C.#	H.T. COEFF. HR FOR RADIATION (BTU/MIN.-IN.**2-R**4)
1	.9241E-13
2	.1635E-12
3	.1299E-12
4	.0000E+00

THE COEFF. OF FORCED CONVEC. = .6181 BTU/MIN.- IN.**2-F

BOUNDARY TEMP. (FOR B.C. #4) = 118.00 DEG. F

GAMMA HEATING RATE (GHR) = 6.000 WATT/GR.

VHRSPN = 10.0097 BTU/IN.**3-MIN.

VHRTUN = 107.9256 BTU/IN.**3-MIN.

VHRGBC = 10.0097 BTU/IN.**3-MIN.

VHRSS = 43.8972 BTU/IN.**3-MIN.

AXIAL SECTIONS FOR MIDDLE GAP		
LOWER HGT(IN.)	UPPER HGT(IN.)	MIDGAP(IN.)
0.000	0.000	0.035

THE NUMBER OF NODES: 0
 AN ESTIMATE FOR THE REQUIRED CORE: 300.00 K BYTES
 AN ESTIMATE FOR THE REQUIRED CPU TIME 0 SEC

THE NODES OF INTEREST AT HORIZONTAL PLANES:

(1)	1	2	3	4	5	8	
							243
							275
	308	309	310	311	312		

1 CONSIDERING THE GRAPHITE BLOCK :

AREA OF THE GR. BLOCK IN THE CAPSULE = 0.98342
 AREA OF THE GR. BLOCK IN THE COMPUTER MODEL = 0.98342
 REAL GR. BLOCK AREA - COMPUTER MODEL AREA = 0.0000000
 % ERROR IN GR. BLOCK AREA = 0.0000

CONSIDERING THE STAINLESS STEEL :

AREA OF THE S.S. IN THE CAPSULE = 0.08410
 AREA OF THE S.S. IN THE COMPUTER MODEL = 0.08312
 REAL S.S. AREA - COMPUTER MODEL AREA = 0.00098
 % ERROR IN S.S. AREA = 1.1632

CONSIDERING THE INNER AND OUTER PERIMETERS OF THE S.S. SLEEVE IN BOTH THE CAP,
AND THE COMPUTER MODEL :

INNER PERIMETER OF S.S. IN THE CAPSULE = 2.07110
INNER PERIMETER OF S.S. IN THE COMPUTER MODEL = 2.03610
% ERROR IN THE INNER PERIMETER = 1.69002

OUTER PERIMETER OF S.S. IN THE CAPSUL = 2.13393
OUTER PERIMETER OF S.S. IN THE COMPUTER MODEL = 2.12002
% ERROR IN THE OUTER PERIMETER = 0.6520

CONSIDERING THE GR. BLOCK WITH NO OUTER GAP

THE AREA OF GR. BLOCK IN THE CAPSULE = 1.04485
THE AREA OF THE GR. BLOCK IN THE COMPUTER MODEL = 1.04533
THE DIFFERENCE = -0.00048
% ERROR IN THE AREA = 0.04636

APPENDIX C

FINAL VERSION OF THE 3-D HINT CODE

The three-dimensional HINT code, included in this appendix, processes a given set of basic design data and generates formatted input data for the HEATING5 code in cylindrical coordinates. This data file is created under the name FOR23.DAT.

A second data file, FOR24.DAT is also generated for each run of the 3-D HINT code. This file provides some information about the nature of the heat transfer problem under consideration.

Typical FOR24.DAT and FOR23.DAT are included in Appendix D.

```

C*****
C*
C*          HINT CODE
C*
C* HINT IS A DATA PROCESSING AND INPUT FORMATTING CODE.
C* THIS CODE HAS EVOLVED OUT OF THE NEED FOR AN INPUT
C* GENERATOR FOR THE COMPLEX THREE-DIMENSIONAL HEAT-TRANSFER
C* PROBLEM INVOLVED IN THE THERMAL DESIGN OF THE OC-6 CAPSULE.
C* BASED ON THE BASIC DESIGN DATA FOR THE OC-6 CAPSULE, HINT
C* IS ABLE TO PREPARE AND FORMAT THE INPUT DATA REQUIRED BY
C* THE HEATING5 CODE. THE INVOLVED GEOMETRY IS EITHER TWO- OR
C* THREE-DIMENSIONAL CYLINDRICAL COORDINATES (R,Θ OR R,Θ,Z).
C* THE PROCESSED AND FORMATTED OUTPUT IS WRITTEN ON FOR22.DAT
C* OR FOR23.DAT FOR 2-D OR 3-D PROBLEMS, RESPECTIVELY.
C* FOR EACH CASE (2-D OR 3-D) AN AUXILIARY OUTPUT FILE IS
C* GENERATED WHICH CONTAINS A SUMMARY OF IMPORTANT FEATURES
C* OF THE CASE UNDER INVESTIGATION. FOR 2-D PROBLEMS, THIS
C* FILE IS FOR21.DAT AND FOR 3-D PROBLEMS IT IS FOR24.DAT.
C* HINT WAS DEVELOPED BY:
C*          AMIR S. MOBASHERAN
C*          NUCLEAR ENGR. DEPT.
C*          UNIV. OF TENN., KNOXVILLE
C*
C*****
      DIMENSION N(200), R(200,2), T(200,2), HR(25),
1         Z(200,2), H(15,2), OUTGAP(15),
2         ITEMP(200), IHEAT(200), IBCR(200,2),
3         VHGR(10), TEMP(10),
4         RMIXED(100), RASCND(100), PURE(100), IGEN(100),
5         HMG(10,2),
6         GAP(20)
      REAL MIDGAP(10)
C-----
C      THE FOLLOWING FUNCTION CALCULATES THE EMISSIVITY FUNCTION
C      (FE) FOR RADIATION EXCHANGE BETWEEN TWO CONCENTRIC CYLINDRICAL
C      SURFACES (CAN BE A PART OF CYLINDER) WITH EMISSIVITIES E1 AND E2
C      AND RADII R1 AND R2 RESPECTIVELY.
C
      FE(E1,E2,R1,R2)=1./(1./E1 + (R1/R2)*(1./E2 -1.))
C-----
      WRITE(5,10)
10     FORMAT(2X,'WHAT IS THE NUMBER OF DIMENSIONS FOR THE PROBLEM'
1         , ' UNDER CONSIDERATION (2 OR 3) ?')
      READ(5,*) NODIM
      IF (NODIM .EQ. 3) GO TO 40
      WRITE(5,20)
20     FORMAT(2X,'WHAT IS THE VALUE OF MIDDLE GAS GAP (IN INCH) ?')
      READ(5,*) MIDGAP(1)
      NSIMG = 1
C
      WRITE(5,30)
30     FORMAT(2X,'WHAT IS THE VALUE OF OUTER GAS GAP (IN INCH) ?')
      READ(5,*) OUTGAP(1)
      NSEG = 1
C
40     WRITE(5,50)
50     FORMAT(2X,'WHAT IS THE VALUE OF ANGULAR GAP (IN INCH) ?')
      READ(5,*) ANGGAP
      IF (NODIM .NE. 3) GO TO 90
C-----
C ---- NSEG IS THE # OF SEGMENTS IN THE AXIAL DIRECTION OF CAPSULE ----

```

```

C      WRITE(5,60)
60     FORMAT(2X,'WHAT IS THE NUMBER OF SEGMENTS IN Z DIRECTION ? '
1       , 'THIS NUMBER CAN BE AT MOST 12 OR 13')      ! MAX. GLLR=100
      READ(5,*) NSEG
C
      DO 80 I=1,NSEG
        WRITE(5,70) I
70       FORMAT(/,2X,'WHAT ARE THE LOWER HEIGHT, UPPER HEIGHT, AND'
1         , ' THE OUTGAP WIDTH IN SEGMENT ', '*** ',I1,' ***',/
2         , ' RESPECTIVELY (IN CM,CM,INCH) ?')
        READ(5,*) H(I,1), H(I,2), OUTGAP(I)
        H(I,1) = H(I,1)/2.54
        H(I,2) = H(I,2)/2.54
80      CONTINUE
C
      DATA NGEOTY, NTABFU, NTEMAP, NAFTER /1, 8, 0, 0/
C ----- ASSIGNING LOGICAL UNIT NUMBERS 23 & 24 TO 3-D CASE -----
      DATA LUN, NLU /23, 24/
      GO TO 110
90      NGEOTY = 2
      NTABFU = 4
      NTEMAP = 0
      NAFTER = 50
C ----- ASSIGNING LOGICAL UNIT NUMBERS 22 & 21 TO 2-D CASE -----
      LUN = 22
      NLU = 21
      WRITE(5,100)
100     FORMAT(2X,'WHAT IS THE VALUE OF GAMMA HEATING RATE (GHR)',
1       , ' IN WATT/GR ?')
      READ(5,*) GHR
      GO TO 150
C
110     WRITE(5,120)
120     FORMAT(2X,'HOW MANY STEPS (DIFFERENT WIDTHS) ARE TO BE USED ',
1       , ' IN THE MIDDLE GAP ?',
2       , ' THIS NUMBER CAN BE AT MOST 10 OR 4 (DEPENDING ON NSEG)')
      READ(5,*) NSIMG
      DO 140 I=1, NSIMG
        WRITE(5,130) I
130       FORMAT(2X,'WHAT ARE THE LOWER HIGHT, UPPER HIGHT, AND',
1         , ' THE WIDTH OF REGION *** ',I,' *** IN MIDGAP',
2         , '(RESPECTIVELY (IN CM, CM, AND INCH) ?')
        READ(5,*) HMG(I,1), HMG(I,2), MIDGAP(I)
        HMG(I,1) = HMG(I,1)/2.54
        HMG(I,2) = HMG(I,2)/2.54
140      HMG(I,1) = HMG(I,1)/2.54
150      WRITE(5,160)
160      FORMAT(3X,'TYPE THE CASE # AND THE CURRENT DATE (MO, DAY, YR)')
      READ(5,*) ICASE, IMONTH, IDAY, IYEAR
C
C      WRITE(5,170)
C170     FORMAT(3X,'WHAT IS THE EXPECTED CPU TIME (IN SECONDS) ?')
C      READ(5,*) ICPU
C
      IF (NODIM .EQ. 3) GO TO 180
      NREG = 14 + NSEG * 12
      NBC = 3 + NSEG
      GO TO 230
180     NREG=12 + NSEG *12 + NSIMG *2
      NBC = 2 + NSEG + NSIMG
C-----

```

```

C -----FINDING THE # OF DIFFERENT OUTER GAP WIDTHS ALONG THE Z AXIS --
DO 190 I=1, NSEG
190   GAP(I) = OUTGAP(I)
      CALL DIFGAP(NSEG,GAP,NDIFF)
      NDIFOG = NDIFF
C -- FINDING THE NUMBER OF DIFFERENT MIDDLE GAP WIDTHS ALONG THE Z AXIS
DO 200 I=1, NSIMG
200   GAP(I) = MIDGAP(I)
      CALL DIFGAP(NSIMG,GAP,NDIFF)
      NDIFMG = NDIFF
C ---- FINDING THE NUMBER OF GROSS LATTICE LINES (GLL) IN Z DIRECTION --
NTOTAL = NSEG + NSIMG
DO 210 I=1, NSEG
210   GAP(I) = H(I,1)
DO 220 I=NSEG+1, NTOTAL
220   GAP(I) = HMG(I-NSEG, 2)
      CALL DIFGAP(NTOTAL,GAP,NDIFF)
      NDIFZ = NDIFF
GO TO 240
230   NGLLR = 25
      NGLLZ = 0
GO TO 250
240   NGLLR = 19 + NDIFOG *6 + (NDIFMG-1)
      NGLLZ = NDIFZ
250   NGLLT = 16
C ----- CHOOSING NUMBER OF ITERATIONS -----
NITER = 1500
C-----
C----- FINDING THE NUMBER OF NODES -----
      NODES = ( 230 + 57*NDIFOG + 20*NDIFMG ) * NDIFZ
C---- THE AMOUNT OF CORE IN K BYTES REQUIRED BY HEATN5ET -----
      CORE = (300. + 0.208 * NODES)
C---- AN ESTIMATE FOR THE REQUIRED CPU TIME (IN SECONDES) FOR S.S. CASE
      ICPU = 4 * NODES * NITER/10000
260   C=2.54
      THICK=.040
C-----
C----- ASSIGNING "NUMBER OF MATERIAL" TO REGIONS 1 THROUGH 26 -----
DATA (N(I),I=1,4) /1,2,3,2/, (N(I),I=7,22,3) /6*5/,
1    (N(I),I=6,21,3) /6*2/, (N(I),I=5,20,3) /6*4/,
2    (N(I),I=23,26)/4*4/
C-----
C ----- ASSIGNING "PAIR OF RADII" TO REGIONS 1 THROUGH 26 -----
C -----THE DIAMETER OF THE HOLE AT THE CENTER OF SPCMN=0.130 INCH
      R(1,1)=0.130/2.
      R(1,2)=0.7620/C
      R(2,1)=R(1,2)
      R(2,2)=0.8992/C
      R(3,1)=R(2,2)
      R(3,2)=1.0363/C
      R(4,1)=R(3,2)
      R(4,2)=R(4,1) + MIDGAP(1)
C
      SMLRAD = 1.33462/C
DO 270 I=5,23,3
270   R(I,1) = SMLRAD
C
DO 280 I=24,25
280   R(I,1) = SMLRAD
C
      R(26,1) = R(4,2)

```

```

R(5,2)=1.86150/C - OUTGAP(1)
R(6,1)=R(5,2)
R(6,2)=1.86150/C
R(7,1)=R(6,2)
R(7,2)=R(7,1) + THICK
R(8,2)=2.20499/C - OUTGAP(1)
R(9,1)=R(8,2)
R(9,2)=2.20499/C
R(10,1)=R(9,2)
R(10,2)=2.20499/C + THICK
R(11,2)=2.52536/C - OUTGAP(1)
R(12,1)=R(11,2)
R(12,2)=2.52536/C
R(13,1)=2.52536/C
R(13,2)=R(13,1) + THICK
R(14,2)=2.82930/C - OUTGAP(1)
R(15,1)=R(14,2)
R(15,2)=2.82930/C
R(16,1)=2.82930/C
R(16,2)=R(16,1) + THICK
R(17,2)=3.12655/C - OUTGAP(1)
R(18,1)=R(17,2)
R(18,2)=3.12655/C
R(19,1)=3.12655/C
R(19,2)=R(19,1) + THICK
R(20,2)=3.43135/C - OUTGAP(1)
R(21,1)=R(20,2)
R(21,2)=3.43135/C
R(22,1)=3.43135/C
R(22,2)=R(22,1) + THICK
R(23,2)=2.82930/C
R(24,2)=2.20499/C
R(25,2)=1.67591/C
R(26,2)=1.33462/C

```

```

C-----
C -----ASSIGNING 'PAIR OF TETA'S' TO REGIONS 1 THROUGH 26 -----
DATA (T(I,1),I=1,7) /7*0.0/, (T(I,2),I=1,4) /4*3.14159/
C
T(5,2)=0.82339
T(6,2)=T(5,2) - ANGGAP/R(6,2)
T(7,2)=T(6,2)
DATA (T(I,1),I=8,10) /3*0.82339/
C
T(8,2)=1.15922
T(9,2)=1.15922 - ANGGAP/R(9,2)
T(10,2)=T(9,2)
DATA (T(I,1),I=11,13) /3*1.15922/
C
T(11,2)=1.39576
T(12,2)=T(11,2) - ANGGAP/R(12,2)
T(13,2)=T(12,2)
DATA (T(I,1),I=14,16) /3*1.39576/
C
T(14,2)=1.59192
T(15,2)=T(14,2) - ANGGAP/R(15,2)
T(16,2)=T(15,2)
DATA (T(I,1),I=17,19) /3*1.59192/
C
T(17,2)=1.76764
T(18,2)=T(17,2) - ANGGAP/R(18,2)
T(19,2)=T(18,2)

```

```

DATA (T(I,1),I=20,22) /3*1.76764/,
1 (T(I,2),I=20,22) /3*2.16081/, T(23,1) /2.16081/,
2 T(23,2) /2.25058/, T(24,1) /2.25058/,
3 T(24,2) /2.59213/, T(25,1) /2.59213/,
4 T(25,2) /2.98748/, T(26,1) /0.0/

C
T(24,2)=T(24,2) - (2.* 0.0162926)/(R(24,2)**2 - R(25,2)**2)
T(25,1)=T(24,2)
T(26,2)=3.14159

C-----
C -----ASSIGNING "PAIR OF Z'S", "§ OF INITIAL TEMP. FUNC.", -----
C -----"§ OF HEAT GENERATION FUNC.", AND "§ OF BOUNDARY CONDITION "
C -----TO REGIONS 1 THROUGH 26 OR MORE (IF ANY) . -----
290 DO 300 I=1,26
300 Z(I,1) = H(1,1)
C
DO 310 I=1,4
Z(I,2) = H(NSEG,2)
310 ITEMP(I)=1
DATA (IHEAT(I),I=1,4) /1,0,2,0/
DATA ((IBCR(I,J),J=1,2),I=2,4,2) /2*1,2*2/

C
DO 320 I=7,22,3
Z(I,2) = H(NSEG,2)
ITEMP(I)=4
IHEAT(I)=4
320 IBCR(I,2)=4
C
DO 330 I=23,26
Z(I,2) = H(NSEG,2)
ITEMP(I)=2
330 IHEAT(I)=3
C
DO 340 I=5,20,3
Z(I,2) = H(1,2)
Z(I+1,2) = H(1,2)
ITEMP(I)=2
IHEAT(I)=3
ITEMP(I+1)=3
IHEAT(I+1)=0
IBCR(I+1,1)=3
340 IBCR(I+1,2)=3
IF (NODIM .NE. 3) GO TO 350
Z(4,2) = HMG(1,2)
Z(26,2) = HMG(1,2)

C-----
C -----THE EMMISIVITIES OF THE MATERIALS AND ST. BOLT. CONSTANT ---
350 ZZZZZ=0. ! A DUMMY BECAUSE A NONEXEC. STAT. CANNOT BE LABELED
DATA ESPEC,EPOL,ENONPO,EBLOCK,ESS /0.9, 0.45, 0.9, 0.9, 0.7/
STBOLT = 0.1714E-8/(60.*144.)
IF (NSEG .EQ. 1) GO TO 380

C-----
C ---ASSIGNING THE NECESSARY CHARACTERISTICS TO REGIONS BEYOND REGION 26
NOFGLL=25
DO 370 J=2,NSEG
RHTC2 = 0.0
JOUT=J
M=27+(J-2)*12
DO 360 K=0,10,2
NOFGLL=NOFGLL+1
N(M+K)=4

```

```

R(M+K,1)=R(26,2)
R(M+K,2)=R(6+3*K/2,2) - OUTGAP(J)
T(M+K,1)=T(5+3*K/2,1)
T(M+K,2)=T(5+3*K/2,2)
Z(M+K,1)=H(J,1)
Z(M+K,2)=H(J,2)
ITEMP(M+K)=2
IHEAT(M+K)=3
N(M+K+1)=2
R(M+K+1,1)=R(M+K,2)
R(M+K+1,2)=R(6+3*K/2,2)
T(M+K+1,1)=T(M+K,1)
T(M+K+1,2)=T(6+3*K/2,2)
Z(M+K+1,1)=Z(M+K,1)
Z(M+K+1,2)=Z(M+K,2)
ITEMP(M+K+1)=3
IHEAT(M+K+1)=0
IBCR(M+K+1,1)=J+3
IBCR(M+K+1,2)=J+3
RMIXED(NOFGLL) = R(M+K,2)
RHTC2 = RHTC2 + STBOLT * FE(EBLOCK,ESS,R(M+K,2),R(M+K+1,2))
360   CONTINUE
      HR(JOUT+3) = RHTC2/6.0
370   CONTINUE
380   IF (NSIMG .LE. 1) GO TO 400
C----- DEFINING THE REGIONS THAT ARE GENERATED BY DIFFERENT MIDGAPS ---
C----- THE FOLLOWING DO LOOP DETERMINES THEIR CHARACTERISTICS -----
      DO 390 I=2, 2*(NSIMG - 1), 2
        NOFGLL = NOFGLL + 1
        M = 14 + NSEG *12 + (I - 1)
        N(M) = 2
        R(M,1) = R(3,2)
        R(M,2) = R(3,2) + MIDGAP(I/2 + 1)
        T(M,1) = 0.0
        T(M,2) = 3.14159
        Z(M,1) = HMG(I/2 +1,1)
        Z(M,2) = HMG(I/2 +1,2)
        ITEMP(M) = 1
        IHEAT(M) = 0
        IBCR(M,1) = 3+JOUT + I/2
        IBCR(M,2) = IBCR(M,1)
        N(M+1) = 4
        R(M+1,1) = R(M,2)
        R(M+1,2) = SMLRAD
        T(M+1,1) = 0.0
        T(M+1,2) = 3.14159
        Z(M+1,1) = Z(M,1)
        Z(M+1,2) = Z(M,2)
        ITEMP(M+1) = 2
        IHEAT(M+1) = 3
        IBCR(M+1,1) = 0
        IBCR(M+1,2) = 0
        RMIXED(NOFGLL) = R(M,2)
390   HR (NSEG + 3 + I/2) = STBOLT * FE(ENONPO,EBLOCK,R(3,2),R(M,2))
C-----
400   IF (NODIM .NE. 3) GO TO 480
      WRITE(NLU,410)
410   FORMAT(8(/))
      WRITE(NLU,420) MIDGAP(1), ANGGAP, NSEG, ICASE, IMONTH, IDAY, IYEAR
420   FORMAT(1X, '3D CYL COOR(R,T,Z);SGAS=.3HE,MIDGAP=',F4.3,
1      ' ,AG=',F4.3, ',NSEG=',I1, ',CASE',I2, ',',I2, '//',I2,

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```

C      2  '//,I2,1X,'CARD1 1')
      WRITE(NLU,430)
430    FORMAT(//,2X,'SEGMENT #',3X,'LOWER HEIGHT',3X,'UPPER ',
      1      'HEIGHT',3X,'LH IN CM',3X,'UH IN CM',3X,'OUTGAP WIDTH')
      WRITE(NLU,440)
440    FORMAT(2X,'-----',
      1      '-----')
C
      DO 450 I=1,NSEG
        CM1 = H(I,1) * 2.54
        CM2 = H(I,2) * 2.54
        WRITE(NLU,460) I, H(I,1), H(I,2), CM1, CM2, OUTGAP(I)
450    WRITE(NLU,470)
460    FORMAT(7X,I2,3(7X,F7.3),4X,F7.3,6X,F7.3)
470    FORMAT(2X,'-----',
      1      '-----')
C -----
C ----- GENERATING DATA CARDS #1 THROUGH #5 -----
C
      WRITE(LUN,420) MIDGAP(1), ANGGAP, NSEG, ICASE, IMONTH, IDAY, IYEAR
      GO TO 500
480    WRITE(NLU,410)
      WRITE(LUN,490) GHR, MIDGAP(1), ANGGAP, OUTGAP(1), ICASE, IMONTH, IDAY,
      1      IYEAR
      WRITE(NLU,490) GHR, MIDGAP(1), ANGGAP, OUTGAP(1), ICASE, IMONTH, IDAY,
      1      IYEAR
490    FORMAT(1X,'2D CYL COOR(R,T);GHR=',F4.2,',SG=.3HE,MG=',F4.3,
      1      ',AG=',F4.3,',OG=',F4.3,',C#',I2,',',I2,'//,I2,'//,I2,1X,
      2      'CARD1 1')
500    WRITE(LUN,510) ICPU,NGEOTY,NREG,NBC, NGLLR,NGLLT,NGLLZ,
      1      NTABFU, NTEMAP, NAFTER, NITER
510    FORMAT(I9,8X,I1,I9,8X,'5',9X,8X,'4',8X,'4',I9,1X,'CARD2 2',//,
      1      3I9,9X,8X,I1,8X,'0',8X,I1,7X,'10',1X,'CARD3 3',//,
      2      36X,I9,8X,'5',8X,'7',9X,1X,'CARD4 4',//,
      3      8X,'1',I9,3X,'1.0E-6',45X,1X,'CARD5 5')
C -----
C ----- CREATING R1 & R2 CARDS -----
      DO 520 I=1, NREG
        MARGR1=4+2*I
        MARGR2=MARGR1+1
        WRITE(LUN,530) I,N(I),R(I,1),R(I,2),T(I,1),T(I,2),Z(I,1),
      1      Z(I,2),MARGR1
        WRITE(LUN,540) ITEMP(I),IHEAT(I),IBCR(I,1),IBCR(I,2),MARGR2
520    CONTINUE
530    FORMAT(2I9,4F9.5,2F9.3,1X,'R1',I5)
540    FORMAT(4I9,36X,1X,'R2',I5)
C -----
      M1=MARGR2+1
      M2=MARGR2+2
      M3=MARGR2+3
      M4=MARGR2+4
      M5=MARGR2+5
C
      DATA ITABM1,ITABM2,ITABM3,ITABM4,ITABM5 /-1,-2,-3,-1,-4/
      WRITE(LUN,550) ITABM1, M1, ITABM2, M2, ITABM3, M3, ITABM4, M4,
      1      ITABM5, M5
550    FORMAT(8X,'1',1X,'GRSPECMN',27X,I9,18X,1X,'M',I6,/,
      1      ,8X,'2',2X,'HE-NEON',27X,I9,18X,1X,'M',I6,/,
      2      ,8X,'3',1X,'TUNGSTEN',27X,I9,18X,1X,'M',I6,/,
      3      ,8X,'4',2X,'GRBLOCK',27X,I9,18X,1X,'M',I6,/)

```

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      4      ,8X,'5',1X,'STAINLSS',27X,I9,18X,1X,'M',I6)
C
C ----- FINDING THE VOLUMETRIC HEATING RATE (VHR) FOR EACH MATERIAL ----
C ----- VHR BTU/IN.**3-MIN = DENSITY * 0.932 GR-BTU/IN.**3-MIN-
C WATT * GAMMA HEATING RATE (GHR) WATT/GR
C --- NOTE THE VALUE OF DENSITY IS THAT IN THE UNIT OF : GR/CM.**3
C
      VHGR(1) = 1.79 * 0.932 * GHR
C ----- USING 19.3 * 1.5 = 28.95 AS THE DENSITY OF TUNGSTEN ----
C ----- BECAUSE THE HEAT GENERATION IN TUNGSTEN IS 1.5 AS MUCH AS
C ----- THAT IN GRAPHITE. THIS CHANGE WAS MADE ON JUNE,4,1981 ----
      VHGR(2) = 28.95 * 0.932 * GHR
      VHGR(3) = 1.79 * 0.932 * GHR
      VHGR(4) = 7.85 * 0.932 * GHR
      IF (NODIM .NE. 3) GO TO 580
C
      DO 560 I=1,4
        ITABG = -(4+I)
        NG = M5 + I
        WRITE(LUN,570) I, ITABG, NG
560      CONTINUE
570      FORMAT(I9,45X,I9,9X,1X,'G',I6)
        GO TO 610
580      DO 590 I=1,4
        NG = M5 + I
        WRITE(LUN,600) I, VHGR(I), NG
590      CONTINUE
600      FORMAT(I9,F9.4,54X,1X,'G',I6)
C
610      DUMMY = 0.0
      DATA (TEMP(I),I=1,4) /2100.0, 1400.0, 600.0, 140.0/
      DO 620 I=1,4
        NI = NG + I
        WRITE(LUN,630) I, TEMP(I), NI
620      CONTINUE
630      FORMAT(I9,F9.2,54X,1X,'I',I6)
C-----
C      FINDING THE RADIATION HEAT TRANSFER COEFFICIENTS FOR BOUNDRY
C      CONDITIONS 1 THROUGH 4 (RADIATION AND CONDUCTION)
C      STEFAN-BOLTZMAN CONSTANT: 0.1714 X 10**-8 BTU/HR-FT**2-R**4
C      OR 5.6697 X 10**-8 W/M**2-K**4
C      THE ABOVE CONSTANT IN UNIT OF BTU/MIN-IN**2-R**4 WILL BE :
C
      STBOLT=0.1714E-8/(60.*144.)
C-----
C      WRITE(LUN,90) STBOLT
C90      FORMAT(1H1,5X,'STEFAN-BOLTZMAN CONSTANT =',E9.4,' BTU/MIN-IN.**2
C      1-R**4')
C
C      ESPEC=E OF GRAPH. SPEC., EPOL=E OF POLISHED TUNG., ENONPO=E OF
C      NONPOLISHED TUNG., EBLOCK=E OF GRAPH. BLOCK, ESS=E OF S.S.
C
      HR(1)=STBOLT * FE(ESPEC,EPOL,R(1,2),R(3,1))
      HR(2)=STBOLT * FE(ENONPO,EBLOCK,R(3,2),R(26,1))
      RHTC1 = 0.0
      DO 640 I=5,20,3
640      RHTC1 = RHTC1 + STBOLT * FE(EBLOCK,ESS,R(I,2),R(I+2,1))
      HR(3) = RHTC1/6.0
C
C      THE COEFFICIENT OF FORCED CONVECTION (BTU/MIN-IN**2-F) FOR B.C.4
C

```

```

      COFC=0.6181
C
C ----- BOUNDARY TEMP.: COOLANT(WATER) TEMP. = BT IN DEG. F -----
C
      BT = 118.0
C
C -----PRINTING THE BOUNDARY CONDITIONS -----
      NB2=NI
      DO 660 I=1, 2 + NSEG + NSING
        NB1 = NB2 + 1
        NB2 = NB1 + 1
        IF (I.EQ. 4) GO TO 650
        WRITE(LUN,670) I, NB1, HR(I), NB2
        GO TO 660
650      WRITE(LUN,680) I, BT, NB1, COFC, NB2
660      CONTINUE
670      FORMAT(I9,8X,'3',54X,1X,'B1',I5,/,9X,D9.4,54X,1X,'B2',I5)
680      FORMAT(I9,8X,'1',F9.2,45X,1X,'B1',I5,/,F9.4,63X,1X,'B2',I5)
C
C ----- ASSIGNING ALL GLL'S IN R DIRECTION TO SUBSCRIPTED VARIABLE
C ----- " RMIXED " IN ORDER TO BE USED BY SUBROUTINE " SORT " .
C
      RMIXED(1) = R(1,1)
      DO 690 I=2,22
690      RMIXED(I) = R(I-1,2)
          RMIXED(23) = R(22,2)
          RMIXED(24) = R(25,2)
          RMIXED(25) = R(26,2)
C
C ----- INVOKING SUBROUTINE "SORT" IN ORDER TO TO PUT THE GLLR'S
C ----- IN ASCENDING ORDER .
      CALL SORT(NGLLR,RMIXED,PURE,ICOUNT)
C ----- PRINTING OUT THE SORTED GROSS LATTICE LINES (IN R DIRECTION) :
      WRITE(LUN,700) (PURE(I),I=1,ICOUNT)
700      FORMAT(8F9.5,1X,'L1')
C -----
      DO 710 I=1, ICOUNT-1
710      IGEN(I) = 1
          WRITE(LUN,720) (IGEN(I), I=1,ICOUNT-1)
720      FORMAT(8I9,1X,'N1')
C -----
      N2 = 0
      DO 730 I=7,22,3
          N1 = N2 + 1
          N2 = N1 + 1
          RASCND(N1) = T(I,1)
730      RASCND(N2) = T(I,2)
          N3 = 12
          DO 740 I=23,26
              N3 = N3 + 1
740      RASCND(N3) = T(I,2)
          WRITE(LUN,750) (RASCND(I), I=1,16)
750      FORMAT(8F9.5,1X,'L2')
C -----
      DO 760 I=1,15
760      IGEN(I) = 1
          IGEN(1) = 2
          IGEN(11) = 2
          IGEN(13) = 2
          IGEN(14) = 2
          WRITE(LUN,770) (IGEN(I), I=1,15)

```

```

770      FORMAT(8I9,1X,'N2')
C ----- ASSIGNING ALL GLL'S IN Z DIRECTION TO SUBSCRIPTED VARIABLE
C ----- "RMIXED" IN ORDER TO BE USED BY SUBROUTINE SORT .
      IF (NODIM .NE. 3) GO TO 830
      RMIXED(1) = H(1,1)
      DO 780 I=2, NSEG+1
780      RMIXED(I) = H(I-1,2)
      DO 790 I=1, NSIMG-1
790      RMIXED(NSEG+1+I) = HMG(I,2)
C
C ----- INVOKING SUBROUTINE "SORT" TO PUT THE GLLZ'S IN ASCENDING
C ----- ORDER . ICOUNT SHOULD BE INITIALIZED TO 0 .
      ICOUNT = 0
      CALL SORT(NGLLZ,RMIXED,PURE,ICOUNT)
C ----- PRINTING OUT THE SORTED GROSS LATTICE LINES (IN Z DIRECTION :
      WRITE(LUN,800) (PURE(I), I=1, ICOUNT)
800      FORMAT(8F9.3,1X,'L3')
C -----
      DO 810 I=1, ICOUNT-1
810      IGEN(I) = 1
      WRITE(LUN,820) (IGEN(I), I=1, ICOUNT-1)
820      FORMAT(8I9,1X,'N3')
C -----
830      WRITE(LUN,840)
840      FORMAT(8X,'1',7X,'11',54X,1X,'T1',5X,/
1          ,4X,'400.0',2X,'0.07132',4X,'600.0',2X,'0.06571'
2          ,4X,'800.0',2X,'0.06036',3X,'1000.0',2X,'0.05513'
3          ,1X,'T1',5X,/
4          ,3X,'1200.0',2X,'0.05021',3X,'1400.0',2X,'0.04551'
5          ,3X,'1600.0',2X,'0.04219',3X,'1800.0',2X,'0.03926'
6          ,1X,'T1',5X,/
7          ,3X,'2000.0',2X,'0.03767',3X,'2200.0',2X,'0.03660'
8          ,3X,'2400.0',2X,'0.03579',18X,1X,'T1',5X)
      WRITE(LUN,850)
850      FORMAT(8X,'2',8X,'5',54X,1X,'T2',5X,/
1          ,6X,'0.0',2X,'5.56D-5',4X,'750.0',3X,'9.9D-5',3X,'1500.0',
2          ,1X,'1.353D-4',3X,'2250.0',1X,'1.701D-4',1X,'T2',5X,/
3          ,3X,'3000.0',1X,'2.014D-4',54X,1X,'T2',5X)
C -----
      WRITE(LUN,860)
860      FORMAT(8X,'3',8X,'5',54X,1X,'T3',5X,/
1          ,4X,'500.0',3X,'0.1139',3X,'1000.0',3X,'0.1028',3X,'1700.0',
2          ,2X,'0.09305',3X,'2061.0',2X,'0.09004',/,
3          ,3X,'2400.0',2X,'0.08917',54X,1X,'T3',5X)
C -----
      WRITE(LUN,870)
870      FORMAT(8X,'4',8X,'4',54X,1X,'T4',5X,/
1          ,5X,'32.0',2X,'0.01111',4X,'212.0',2X,'0.01306',4X,'572.0',
2          ,2X,'0.01514',3X,'2240.0',2X,'0.02478',1X,'T4',5X) !!JAN81
C -----
      IF (NODIM .NE. 3) GO TO 880
C ----- INVOKING SUBROUTINE "VHGRTB" TO CALCULATE AND PRINT THE
C ----- CONTENTS OF THE LAST FOUR TABULAR FUNCTIONS (FOR VOL. H.G.R) ----
      CALL VHGRTB(5,1.79)
C ----- USING 19.3 * 1.5 = 28.95 AS THE DENSITY OF TUNGSTEN -----
C ----- BECAUSE THE HEAT GENERATION IN TUNGSTEN TURNED OUT TO BE
C ----- 1.5 TIMES AS MUCH AS THAT IN GRAPHITE (FROM AN HFIR EXPERIMENT)
C ----- THIS CHANGE WAS MADE ON THURSDAY, JUNE,4,1981. -----
      CALL VHGRTB(6,28.95)
      CALL VHGRTB(7,1.79)
      CALL VHGRTB(8,7.85)

```

```

      GO TO 900
C -----
C ---- THE FOLLOWING NODES ARE THE ONES AT WHICH THE TEMPERATURES
C ---- ARE TO BE MONITORED WHILE RUNNING THE CODE IN 2 DIMENSIONS (R,T)
880   WRITE(LUN,890)
890   FORMAT(7X,'13',8X,'1',8X,'2',8X,'3',8X,'4',8X,'5',8X,'8',
      1      6X,'243',1X,'S',5X,/,
      2      6X,'275',6X,'302',6X,'303',6X,'304',6X,'305',6X,'306',
      1      18X,1X,'S',5X)
C     WRITE(LUN,96)
C     FORMAT(72X,1X,' BLANK')
C
900   IF (NODIM .NE. 3) GO TO 920
      WRITE(NLU,910)
910   FORMAT(1H1)
920   WRITE(NLU,930) ESPEC,EPOL,ENONPO,EBLOCK,ESS
930   FORMAT(/,/,/,6X,'THE EMISSIVITIES OF THE MATERIALS :',/,2X,
      1      'E OF SPEC.',F3.1,3X,'E OF POL.TUNG.',F4.2,3X,'E OF NONPOL.
      2      TUNG.',F3.1,3X,'E OF G.BLOCK',F3.1,3X,'E OF S.S.',F3.1)
C
      WRITE(NLU,940)
940   FORMAT(/,3X,'B.C.#',10X,'H.T. COEFF. HR FOR RADIATION',/,
      1      21X,'(BTU/MIN.-IN.**2-R**4)')
C
      DO 950 K=1,NBC
950   WRITE(NLU,960) K, HR(K)
960   FORMAT(5X,I2,20X,E9.4)
C
      WRITE(NLU,970) COFC
970   FORMAT(/,5X,'THE COEFF. OF FORCED CONVEC. =',F6.4,2X,'BTU/MIN.-
      1      IN.**2-F')
C
      WRITE(NLU,980) BT
980   FORMAT(/,5X,'BOUNDARY TEMP. (FOR B.C. #4) = ',F6.2,' DEG. F')
C
C
      WRITE(NLU,990) GHR
990   FORMAT(/,5X,'GAMMA HEATING RATE (GHR) = ',F5.3,' WATT/GR.')
C
      WRITE(NLU,1000) VHGR(1), VHGR(2), VHGR(3), VHGR(4)
1000  FORMAT(/,5X,'VHRSPN =',F8.4,' BTU/IN.**3-MIN.',
      1      ',/,5X,'VHRTUN =',F8.4,' BTU/IN.**3-MIN.',
      2      ',/,5X,'VHRGBC =',F8.4,' BTU/IN.**3-MIN.',
      3      ',/,5X,'VHRSS =',F8.4,' BTU/IN.**3-MIN.')
```

```

      WRITE(NLU,1010)
1010  FORMAT(/,5X,'AXIAL SECTIONS FOR MIDDLE GAP',/,
      1      5X,'LOWER HGT(IN.)' 5X,'UPPER HGT(IN.)',5X,'MIDGAP(IN.)')
      DO 1020 I=1, NSIMG
1020  WRITE(NLU,1030) HMG(I,1), HMG(I,2), MIDGAP(I)
1030  FORMAT(10X,F6.3,10X,F6.3,10X,F6.3)
C-----
C----- WRITING THE # OF NODES, REQUIRED CORE, AND REQUIRED CPU TIME
      WRITE(NLU,2) NODES, CORE, ICPU
2     FORMAT(/,5X,'THE NUMBER OF NODES: ',I6,/,5X,
      1      'AN ESTIMATE FOR THE REQUIRED CORE:',F8.2,' K BYTES',/,5X,
      2      'AN ESTIMATE FOR THE REQUIRED CPU TIME',I5,' SEC')
C-----
C----- FINDING AND PRINTING THE NUMBERS OF THE NODES OF INTEREST -----
      WRITE(NLU,3)
3     FORMAT(/,15X,'THE NODES OF INTEREST AT HORIZONTAL PLANES:',/,/)
      NODESP=NODES/NGLLZ

```

```

DO 6 I=0, 2*NGLLZ-1
J=I+1
ISTOP1=1+I*NODESP
ISTOP2=ISTOP1+1
ITTOP1=ISTOP2+1
ITTOP2=ITTOP1+1
IGTOP1=ITTOP2+NSIMG
IGTOP2=ITTOP2+NSIMG+3+I
IGRIGT=243+14*(NSIMG-1)+48*(NSEG-1) +I*(NODESP+1)
IGTC=275+16*(NSIMG-1)+55*(NSEG-1) +I*NODESP
ISBOT1=IGTC+33+(NSIMG-1)*3
ISBOT2=ISBOT1+1
ITBOT1=ISBOT2+1
ITBOT2=ITBOT1+1
IGBOT1=ITBOT2+1
WRITE(NLU,4) J, ISTOP1, ISTOP2, ITTOP1, ITTOP2, IGTOP1, IGTOP2,
1 IGRIGT, IGTC,
2 ISBOT1, ISBOT2, ITBOT1, ITBOT2, IGBTOT1
4 FORMAT(1X, '(I2,)', 5X, 6I5, /, 65X, I5, /, 45X, I5, /, 10X, 5I5, /,
1 '-----',
2 '-----')
6 CONTINUE
C-----THE FOLLOWING PART OF THIS PROGRAM CALCULATES THE AMOUNT OF
C-----ERROR INVOLVED IN THE DEVELOPMENT OF THE COMPUTATIONAL MODEL.
C----- FINDING THE AREA OF THE GR. BLOCK IN THE CAPSULE -----
C
1040 PI=3.14159
SSINR=3.3490/C
GBREAL=(( SSINR - OUTGAP(1))**2 )*PI/4. - (( R(4,2)**2)*PI/2. )
RHOLE = 0.3175/C
GBREAL = GBREAL - (RHOLE **2)*PI/4.
C
C -----FINDING THE AREA OF THE S.S. IN THE CAPSULE -----
SSREAL = ((3.4506/C)**2 - (3.3490/C)**2) *PI/4.
C----- FINDING THE INNER & OUTER PERIMETERS OF S.S. IN THE CAPSULE --
C
RSSIN = (3.3490/C) * PI/2.
RSSOUT = (3.4506/C) * PI/2.
C ----- FINDING THE AREA OF THE GR. BLOCK IN THE COMPUTER MODEL ----
C----- ALSO, FINDING THE AREA OF THE S.S. IN THE COMPUTER MODEL -----
C----- AND CALCULATING THE INNER AND OUTER PERIMETER OF THE S.S.-----
C----- IN THE COMPUTER MODEL . -----
C ----- VARIABLE INITIALIZATION -----
DATA GBMODL, SSMODL, SSINM, SSOUTM, AREAM /5*0.0/
C
DO 1050 I=5,20,3
GBMODL = GBMODL + (R(I,2)**2 - R(26,2)**2)*(T(I,2)-T(I,1))/2.
K=I+2
SSMODL = SSMODL + (R(K,2)**2 - R(K,1)**2)*(T(K,2)-T(K,1))/2.
SSINM = SSINM + R(K,1) * (T(K,2) - T(K,1))
SSOUTM = SSOUTM + R(K,2) * (T(K,2) - T(K,1))
AREAM=AREAM+(R(K,1)**2-R(26,2)**2)*(T(I,2)-T(I,1))/2.
1050 CONTINUE
C----- ADDING THE AREA OF REGIONS 23-25 TO THE PREVIOUS GBMODL--
C
DO 1060 J=23,25
GBMODL = GBMODL + (R(J,2)**2 - R(26,2)**2)*(T(J,2)-T(J,1))/2.
AREAM=AREAM+(R(J,2)**2-R(26,2)**2)*(T(J,2)-T(J,1))/2.
1060 CONTINUE
C
GBMODL=GBMODL+(R(26,2)**2-R(26,1)**2)*(T(26,2)-T(26,1))/2.

```

```

AREAM=AREAM+(R(26,2)**2-R(26,1)**2)*(T(26,2)-T(26,1))/2.
DIFFGB= GBREAL - GBMODL
PCTGB = ABS(DIFFGB)/GBREAL*100.
DIFFSS= SSREAL - SSMODL
PCTSS = ABS(DIFFSS)/SSREAL*100.
DIFIN = RSSIN - SSINM
PCTIN = ABS(DIFIN)/RSSIN * 100.
DIFOUT = RSSOUT - SSOUTM
PCTOUT = ABS(DIFOUT)/RSSOUT * 100.

C
WRITE(NLU,1070) GBREAL, GBMODL, DIFFGB, PCTGB, SSREAL, SSMODL,
1 DIFFSS, PCTSS
1070 FORMAT(1H1,2X,'CONSIDERING THE GRAPHITE BLOCK :',
1//,5X,'AREA OF THE GR. BLOCK IN THE CAPSULE =',F10.5,/
2,5X,'AREA OF THE GR. BLOCK IN THE COMPUTER MODEL =',F10.5,/
3,5X,'REAL GR. BLOCK AREA - COMPUTER MODEL AREA =',F10.7,
4//,5X,'% ERROR IN GR. BLOCK AREA =',F9.4,
5//,2X,'CONSIDERING THE STAINLESS STEEL :',
6//,5X,'AREA OF THE S.S. IN THE CAPSULE =',F10.5,
7//,5X,'AREA OF THE S.S. IN THE COMPUTER MODEL =',F10.5,
8//,5X,'REAL S.S. AREA - COMPUTER MODEL AREA =',F10.5,
9//,5X,'% ERROR IN S.S. AREA =',F9.4)

C
C----- PRINTING THE RESULTS CONCERNING THE INNER & OUTER PERIMETERS
C----- OF THE S.S. SLEEVE IN THE CAPSUL AND THE COMPUTER MODEL -----
C
WRITE(NLU,1080) RSSIN, SSINM, PCTIN, RSSOUT, SSOUTM, PCTOUT
1080 FORMAT(//,2X,'CONSIDERING THE INNER AND OUTER PERIMETERS OF THE
1 S.S. SLEEVE IN BOTH THE CAPSULE AND THE COMPUTER MODEL :',
2//,5X,'INNER PERIMETER OF S.S. IN THE CAPSULE =',F10.5
3//,5X,'INNER PERIMETER OF S.S. IN THE COMPUTER MODEL =',F10.5
4//,5X,'% ERROR IN THE INNER PERIMETER =',F10.5
5//,5X,'OUTER PERIMETER OF S.S. IN THE CAPSUL =',F10.5
6//,5X,'OUTER PERIMETER OF S.S. IN THE COMPUTER MODEL =',F10.5
7//,5X,'% ERROR IN THE OUTER PERIMETER =',F10.4)

C
C ----- CONSIDERING THE AREA OF THE GR. BLOCK BOUNDED BY S.S.
C ----- AND THE MIDDLE GAS GAP -----
C
AREAC = ((3.3490/C)**2)*PI/4. - ((R(4,2)**2)*PI/2.)
AREAC = AREAC - (RHOLE **2)*PI/4.
DIFFCM = AREAC - AREAM
PCTCM = ABS(DIFFCM)/AREAC*100.

C
WRITE(NLU,1090) AREAC, AREAM, DIFFCM, PCTCM
1090 FORMAT(//,2X,'CONSIDERING THE GR. BLOCK WITH NO OUTER GAP'
1 ,//,5X,'THE AREA OF GR. BLOCK IN THE CAPSULE =',F10.5
2 ,//,5X,'THE AREA OF THE GR. BLOCK IN THE COMPUTER MODEL ='
3 ,F10.5//,5X,'THE DIFFERENCE =',F10.5
4 ,//,5X,'% ERROR IN THE AREA =',F10.5)

C
STOP
1100 END
C
C ***** SUBROUTINE FOR FINDING THE # OF DIFFERENT #'S IN A SET OF #'S
SUBROUTINE DIFGAP (NSGMNT,GAP,NDIFF)
DIMENSION GAP(20)
IF (NSGMNT .GT. 1) GO TO 10
NDIFF = 1
RETURN
10 NSAME = 0

```

```

DO 60 I=1,NSGMNT
  IF (I .EQ. 1) GO TO 30
  IF (I .EQ. NSGMNT) GO TO 60
  DO 20 J=1, I-1
    IF ( GAP(I) .EQ. GAP(J) ) GO TO 60
20  CONTINUE
30  DO 50 K=I,NSGMNT-1
    IF ( GAP(I) .EQ. GAP(K+1) ) GO TO 40
    GO TO 50
    NSAME = NSAME + 1
50  CONTINUE
60  CONTINUE
NDIFF=NSGMNT - NSAME
RETURN
END

C ***** SUBROUTINE FOR SORTING THE GLL'S IN ASCENDING ORDER *****
SUBROUTINE SORT(NGLL,RMIXED,PURE,ICOUNT)
  DIMENSION RMIXED(100), RASCND(100), PURE(100)
  DO 40 I=1, NGLL
C ---- ASSIGNING A VERY LARGE NUMBER TO THE DUMMY X :
    X =10.E+30
    DO 20 J=1, NGLL
      IF (RMIXED(J) - X) 10,20,20
C ---- REMEMBER THE SMALLEST VALUE :
10    X = RMIXED(J)
C ---- DETERMINING THE INDEX LOCATION FOR LATER REFERENCE :
      INDEX = J
20    CONTINUE
C ---- ASSIGNMENT OF THE ENCOUNTERED SMALLEST ELEMENT INTO RASCND
    RASCND(I) = X
    IF (I .EQ. 1) GO TO 30
    IF (RASCND(I) - RASCND(I-1)) 30,40,30
30    ICOUNT = ICOUNT + 1
    PURE(ICOUNT) = RASCND(I)
C ---- REMOVING ENCOUNTERED SMALLEST ELEMENT FROM THE RMIXED LIST :
40    RMIXED(INDEX) =10.E+30
    RETURN
  END

C
C ***** SUBROUTINE FOR CALCULATING AND PRINTING THE TAB. FUNC. 4-8 ***
SUBROUTINE VHGRTB(I,DNSTY)
  DIMENSION GHRTAB(50), VHGR(50)
  DATA (GHRTAB(M),M=1,41,2)
  1 /0.000, 3.043, 5.189, 7.067, 9.091, 10.110, 11.114
  2 ,11.831, 12.543, 13.760, 14.315, 16.016, 17.197, 17.984
  3 ,18.953, 19.685, 20.311, 21.386, 22.370, 23.945, 24.500/
  DATA (GHRTAB(M),M=2,42,2)
  1 /1.875, 3.0, 4.0, 5.0, 6.0, 6.5, 7.0
  2 ,7.25, 7.50, 7.75, 7.875, 8.024, 7.875, 7.75
  3 ,7.50, 7.25, 7.0, 6.50, 6.0, 5.0, 4.76/
  K=I
  DO 10 M=2,42,2
10  VHGR(M) = DNSTY * 0.932 * GHRTAB(M)
    WRITE(23,20) K, K
20  FORMAT(8X,I1,7X,'21',54X,1X,'T',I1,5X)
    DO 30 M=8,40,8
      WRITE(23,40) GHRTAB(M-7),VHGR(M-6),GHRTAB(M-5),VHGR(M-4)
      1GHRTAB(M-3),VHGR(M-2),GHRTAB(M-1),VHGR(M), K
30  CONTINUE
40  FORMAT(8F9.3,1X,'T',I1,5X)
50  WRITE(23,50) GHRTAB(41), VHGR(42), K
    FORMAT(2F9.3,54X,1X,'T',I1)
    RETURN
  END

```

APPENDIX D

TYPICAL OUTPUTS OF THE 3-D HINT CODE

The formatted input data required by the HEATING5 code, in three-dimensional cylindrical coordinates, are seen on pages 122-127. These are the contents of data file FOR23.DAT WHICH is generated by running the three-dimensional HINT code.

The contents of a typical FOR24.DAT, are shown on pages 128-131. The numbers of the nodes of interest, for this typical case, are also seen in this file.

```

3D CYL COOR(R,T,Z);SGAS=.3HE,MIDGAP=.055,AG=.005,NSEG=7,CASE25, 6/ 2/81 CARD1 1
3595      1      104      5      4      4      13 CARD2 2
64      16      11      8      0      0      10 CARD3 3
      0      5      7      CARD4 4
      CARD5 5
1      600      1.0E-6
1      1      0.06500      0.30000      0.00000      3.14159      0.000      16.016 R1 6
1      1      0      0      0.00000      3.14159      0.000      16.016 R2 7
2      2      0.30000      0.35402      0.00000      3.14159      0.000      16.016 R1 8
1      0      1      1      0.00000      3.14159      0.000      16.016 R2 9
3      3      0.35402      0.40799      0.00000      3.14159      0.000      16.016 R1 10
1      2      0      0      0.00000      3.14159      0.000      8.661 R2 11
4      2      0.40799      0.46299      0.00000      3.14159      0.000      8.661 R1 12
1      0      2      2      0.00000      3.14159      0.000      3.937 R2 13
5      4      0.52544      0.67787      0.00000      0.82339      0.000      3.937 R1 14
2      3      0      0      0.00000      0.81657      0.000      3.937 R2 15
6      2      0.67787      0.73287      0.00000      0.81657      0.000      16.016 R1 16
3      0      3      3      0.00000      0.81657      0.000      16.016 R2 17
7      5      0.73287      0.77287      0.00000      0.81657      0.000      16.016 R1 18
4      4      0      4      0.82339      1.15922      0.000      3.937 R2 19
8      4      0.52544      0.81311      0.82339      1.15922      0.000      3.937 R1 20
2      3      0      0      0.82339      1.15346      0.000      3.937 R2 21
9      2      0.81311      0.86811      0.82339      1.15346      0.000      16.016 R1 22
3      0      3      3      0.82339      1.15346      0.000      16.016 R2 23
10     5      0.86811      0.90811      0.82339      1.15346      0.000      16.016 R1 24
4      4      0      4      1.15922      1.39576      0.000      3.937 R2 25
11     4      0.52544      0.93924      1.15922      1.39576      0.000      3.937 R1 26
2      3      0      0      1.15922      1.39073      0.000      3.937 R2 27
12     2      0.93924      0.99424      1.15922      1.39073      0.000      16.016 R1 28
3      0      3      3      1.15922      1.39073      0.000      16.016 R2 29
13     5      0.99424      1.03424      1.15922      1.39073      0.000      3.937 R1 30
4      4      0      4      1.39576      1.59192      0.000      3.937 R2 31
14     4      0.52544      1.05890      1.39576      1.59192      0.000      3.937 R1 32
2      3      0      0      1.39576      1.58743      0.000      16.016 R2 33
15     2      1.05890      1.11390      1.39576      1.58743      0.000      16.016 R1 34
3      0      3      3      1.39576      1.58743      0.000      16.016 R2 35
16     5      1.11390      1.15390      1.39576      1.58743      0.000      3.937 R1 36
4      4      0      4      1.59192      1.76764      0.000      3.937 R2 37
17     4      0.52544      1.17593      1.59192      1.76764      0.000      3.937 R1 38
2      3      0      0      1.59192      1.76358      0.000      16.016 R2 39
18     2      1.17593      1.23093      1.59192      1.76358      0.000      16.016 R1 40
3      0      3      3      1.59192      1.76358      0.000      16.016 R2 41
19     5      1.23093      1.27093      1.59192      1.76358      0.000      3.937 R1 42
4      4      0      4      1.76764      2.16081      0.000      3.937 R2 43
20     4      0.52544      1.29593      1.76764      2.16081      0.000      3.937 R1 44
2      3      0      0      1.76764      2.16081      0.000      16.016 R2 45
21     2      1.29593      1.35093      1.76764      2.16081      0.000      16.016 R1 46
3      0      3      3      1.76764      2.16081      0.000      16.016 R2 47
22     5      1.35093      1.39093      1.76764      2.16081      0.000      16.016 R1 48
4      4      0      4      2.16081      2.25058      0.000      16.016 R2 49
23     4      0.52544      1.11390      2.16081      2.25058      0.000      16.016 R1 50
2      3      0      0      2.25058      2.48975      0.000      16.016 R2 51
24     4      0.52544      0.86811      2.25058      2.48975      0.000      16.016 R1 52
2      3      0      0      2.48975      2.98748      0.000      16.016 R2 53
25     4      0.52544      0.65981      2.48975      2.98748      0.000      8.661 R1 54
2      3      0      0      0.00000      3.14159      0.000      8.661 R2 55
26     4      0.46299      0.52544      0.00000      3.14159      0.000      6.102 R1 56
2      3      0      0      0.82339      3.937      6.102 R2 57
27     4      0.52544      0.68487      0.00000      0.82339      3.937      6.102 R1 58
2      3      0      0      0.81657      3.937      6.102 R2 59
28     2      0.68487      0.73287      0.00000      0.81657      3.937      6.102 R1 60
3      0      5      5      0.82339      1.15922      3.937      6.102 R2 61
29     4      0.52544      0.82011      0.82339      1.15922      3.937      6.102 R1 62

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2	3	0	0						R2	63
30	2	0.82011	0.86811	0.82339	1.15346	3.937	6.102	R1	64	
3	0	5	5					R2	65	
31	4	0.52544	0.94624	1.15922	1.39576	3.937	6.102	R1	66	
2	3	0	0					R2	67	
32	2	0.94624	0.99424	1.15922	1.39073	3.937	6.102	R1	68	
3	0	5	5					R2	69	
33	4	0.52544	1.06590	1.39576	1.59192	3.937	6.102	R1	70	
2	3	0	0					R2	71	
34	2	1.06590	1.11390	1.39576	1.58743	3.937	6.102	R1	72	
3	0	5	5					R2	73	
35	4	0.52544	1.18293	1.59192	1.76764	3.937	6.102	R1	74	
2	3	0	0					R2	75	
36	2	1.18293	1.23093	1.59192	1.76358	3.937	6.102	R1	76	
3	0	5	5					R2	77	
37	4	0.52544	1.30293	1.76764	2.16081	3.937	6.102	R1	78	
2	3	0	0					R2	79	
38	2	1.30293	1.35093	1.76764	2.16081	3.937	6.102	R1	80	
3	0	5	5					R2	81	
39	4	0.52544	0.69687	0.00000	0.82339	6.102	7.874	R1	82	
2	3	0	0					R2	83	
40	2	0.69687	0.73287	0.00000	0.81657	6.102	7.874	R1	84	
3	0	6	6					R2	85	
41	4	0.52544	0.83211	0.82339	1.15922	6.102	7.874	R1	86	
2	3	0	0					R2	87	
42	2	0.83211	0.86811	0.82339	1.15346	6.102	7.874	R1	88	
3	0	6	6					R2	89	
43	4	0.52544	0.95824	1.15922	1.39576	6.102	7.874	R1	90	
2	3	0	0					R2	91	
44	2	0.95824	0.99424	1.15922	1.39073	6.102	7.874	R1	92	
3	0	6	6					R2	93	
45	4	0.52544	1.07790	1.39576	1.59192	6.102	7.874	R1	94	
2	3	0	0					R2	95	
46	2	1.07790	1.11390	1.39576	1.58743	6.102	7.874	R1	96	
3	0	6	6					R2	97	
47	4	0.52544	1.19493	1.59192	1.76764	6.102	7.874	R1	98	
2	3	0	0					R2	99	
48	2	1.19493	1.23093	1.59192	1.76358	6.102	7.874	R1	100	
3	0	6	6					R2	101	
49	4	0.52544	1.31493	1.76764	2.16081	6.102	7.874	R1	102	
2	3	0	0					R2	103	
50	2	1.31493	1.35093	1.76764	2.16081	6.102	7.874	R1	104	
3	0	6	6					R2	105	
51	4	0.52544	0.71287	0.00000	0.82339	7.874	9.449	R1	106	
2	3	0	0					R2	107	
52	2	0.71287	0.73287	0.00000	0.81657	7.874	9.449	R1	108	
3	0	7	7					R2	109	
53	4	0.52544	0.84811	0.82339	1.15922	7.874	9.449	R1	110	
2	3	0	0					R2	111	
54	2	0.84811	0.86811	0.82339	1.15346	7.874	9.449	R1	112	
3	0	7	7					R2	113	
55	4	0.52544	0.97424	1.15922	1.39576	7.874	9.449	R1	114	
2	3	0	0					R2	115	
56	2	0.97424	0.99424	1.15922	1.39073	7.874	9.449	R1	116	
3	0	7	7					R2	117	
57	4	0.52544	1.09390	1.39576	1.59192	7.874	9.449	R1	118	
2	3	0	0					R2	119	
58	2	1.09390	1.11390	1.39576	1.58743	7.874	9.449	R1	120	
3	0	7	7					R2	121	
59	4	0.52544	1.21093	1.59192	1.76764	7.874	9.449	R1	122	
2	3	0	0					R2	123	
60	2	1.21093	1.23093	1.59192	1.76358	7.874	9.449	R1	124	

3	0	7	7					R2	125
61	4	0.52544	1.33093	1.76764	2.16081	7.874	9.449	R1	126
2	3	0	0					R2	127
62	2	1.33093	1.35093	1.76764	2.16081	7.874	9.449	R1	128
3	0	7	7					R2	129
63	4	0.52544	0.71687	0.00000	0.82339	9.449	11.024	R1	130
2	3	0	0					R2	131
64	2	0.71687	0.73287	0.00000	0.81657	9.449	11.024	R1	132
3	0	8	8					R2	133
65	4	0.52544	0.85211	0.82339	1.15922	9.449	11.024	R1	134
2	3	0	0					R2	135
66	2	0.85211	0.86811	0.82339	1.15346	9.449	11.024	R1	136
3	0	9	9					R2	137
67	4	0.52544	0.97824	1.15922	1.39576	9.449	11.024	R1	138
2	3	0	0					R2	139
68	2	0.97824	0.99424	1.15922	1.39073	9.449	11.024	R1	140
3	0	8	8					R2	141
69	4	0.52544	1.09790	1.39576	1.59192	9.449	11.024	R1	142
2	3	0	0					R2	143
70	2	1.09790	1.11390	1.39576	1.58743	9.449	11.024	R1	144
3	0	8	8					R2	145
71	4	0.52544	1.21493	1.59192	1.76764	9.449	11.024	R1	146
2	3	0	0					R2	147
72	2	1.21493	1.23093	1.59192	1.76358	9.449	11.024	R1	148
3	0	8	8					R2	149
73	4	0.52544	1.33493	1.76764	2.16081	9.449	11.024	R1	150
2	3	0	0					R2	151
74	2	1.33493	1.35093	1.76764	2.16081	9.449	11.024	R1	152
3	0	8	8					R2	153
75	4	0.52544	0.71897	0.00000	0.82339	11.024	12.992	R1	154
2	3	0	0					R2	155
76	2	0.71897	0.73287	0.00000	0.81657	11.024	12.992	R1	156
3	0	9	9					R2	157
77	4	0.52544	0.85411	0.82339	1.15922	11.024	12.992	R1	158
2	3	0	0					R2	159
78	2	0.85411	0.86811	0.82339	1.15346	11.024	12.992	R1	160
3	0	9	9					R2	161
79	4	0.52544	0.98024	1.15922	1.39576	11.024	12.992	R1	162
2	3	0	0					R2	163
80	2	0.98024	0.99424	1.15922	1.39073	11.024	12.992	R1	164
3	0	9	9					R2	165
81	4	0.52544	1.09990	1.39576	1.59192	11.024	12.992	R1	166
2	3	0	0					R2	167
82	2	1.09990	1.11390	1.39576	1.58743	11.024	12.992	R1	168
3	0	9	9					R2	169
83	4	0.52544	1.21693	1.59192	1.76764	11.024	12.992	R1	170
2	3	0	0					R2	171
84	2	1.21693	1.23093	1.59192	1.76358	11.024	12.992	R1	172
3	0	9	9					R2	173
85	4	0.52544	1.33693	1.76764	2.16081	11.024	12.992	R1	174
2	3	0	0					R2	175
86	2	1.33693	1.35093	1.76764	2.16081	11.024	12.992	R1	176
3	0	9	9					R2	177
87	4	0.52544	0.72287	0.00000	0.82339	12.992	16.016	R1	178
2	3	0	0					R2	179
88	2	0.72287	0.73287	0.00000	0.81657	12.992	16.016	R1	180
3	0	10	10					R2	181
89	4	0.52544	0.85811	0.82339	1.15922	12.992	16.016	R1	182
2	3	0	0					R2	183
90	2	0.85811	0.86811	0.82339	1.15346	12.992	16.016	R1	184
3	0	10	10					R2	185
91	4	0.52544	0.98424	1.15922	1.39576	12.992	16.016	R1	186

2	3	0	0						R2	187
92	2	0.98424	0.99424	1.15922	1.39073	12.992	16.016	R1	188	
3	0	10	10					R2	189	
93	4	0.52544	1.10390	1.39576	1.59192	12.992	16.016	R1	190	
2	3	0	0					R2	191	
94	2	1.10390	1.11390	1.39576	1.58743	12.992	16.016	R1	192	
3	0	10	10					R2	193	
95	4	0.52544	1.22093	1.59192	1.76764	12.992	16.016	R1	194	
2	3	0	0					R2	195	
96	2	1.22093	1.23093	1.59192	1.76358	12.992	16.016	R1	196	
3	0	10	10					R2	197	
97	4	0.52544	1.34093	1.76764	2.16081	12.992	16.016	R1	198	
2	3	0	0					R2	199	
98	2	1.34093	1.35093	1.76764	2.16081	12.992	16.016	R1	200	
3	0	10	10					R2	201	
99	2	0.40799	0.43299	0.00000	3.14159	8.661	10.236	R1	202	
1	0	11	11					R2	203	
100	4	0.43299	0.52544	0.00000	3.14159	8.661	10.236	R1	204	
2	3	0	0					R2	205	
101	2	0.40799	0.42599	0.00000	3.14159	10.236	13.976	R1	206	
1	0	12	12					R2	207	
102	4	0.42599	0.52544	0.00000	3.14159	10.236	13.976	R1	208	
2	3	0	0					R2	209	
103	2	0.40799	0.42399	0.00000	3.14159	13.976	16.016	R1	210	
1	0	13	13					R2	211	
104	4	0.42399	0.52544	0.00000	3.14159	13.976	16.016	R1	212	
2	3	0	0					R2	213	
1	GRSPECMN				-1			M	214	
2	HE-NEON				-2			M	215	
3	TUNGSTEN				-3			M	216	
4	GRBLOCK				-1			M	217	
5	STAINLSS				-4			M	218	
1						-5		G	219	
2						-6		G	220	
3						-7		G	221	
4						-8		G	222	
1	2100.00							I	223	
2	1400.00							I	224	
3	600.00							I	225	
4	140.00							I	226	
1	3							B1	227	
	.9241D-13							B2	228	
2	3							B1	229	
	.1641D-12							B2	230	
3	3							B1	231	
	.1308D-12							B2	232	
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	.1306D-12							B2	236	
6	3							B1	237	
	.1301D-12							B2	238	
7	3							B1	239	
	.1296D-12							B2	240	
8	3							B1	241	
	.1294D-12							B2	242	
9	3							B1	243	
	.1293D-12							B2	244	
10	3							B1	245	
	.1292D-12							B2	246	
11	3							B1	247	
	.1632D-12							B2	248	

12	3							B1	249
.1629D-12	3							B2	250
13	3							B1	251
.1629D-12	3							B2	252
0.06500	0.30000	0.35402	0.40799	0.42399	0.42599	0.43299	0.46299	L1	
0.52544	0.65981	0.67787	0.68487	0.69687	0.71287	0.71687	0.71887	L1	
0.72287	0.73287	0.77287	0.81311	0.82011	0.83211	0.84811	0.85211	L1	
0.85411	0.85811	0.86811	0.90811	0.93924	0.94624	0.95824	0.97424	L1	
0.97824	0.98024	0.98424	0.99424	1.03424	1.05890	1.06590	1.07790	L1	
1.09390	1.09790	1.09990	1.10390	1.11390	1.15390	1.17593	1.18293	L1	
1.19493	1.21093	1.21493	1.21693	1.22093	1.23093	1.27093	1.29593	L1	
1.30293	1.31493	1.33093	1.33493	1.33693	1.34093	1.35093	1.39093	L1	
1	1	1	1	1	1	1	1	N1	
1	1	1	1	1	1	1	1	N1	
1	1	1	1	1	1	1	1	N1	
1	1	1	1	1	1	1	1	N1	
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1	1	1	1	1	1	1	1	N1	
1	1	1	1	1	1	1	1	N1	
0.00000	0.81657	0.82339	1.15346	1.15922	1.39073	1.39576	1.58743	L2	
1.59192	1.76358	1.76764	2.16081	2.25058	2.48975	2.98748	3.14159	L2	
2	1	1	1	1	1	1	1	N2	
1	1	2	1	2	2	1			
0.000	3.937	6.102	7.874	8.661	9.449	10.236	11.024	L3	
12.992	13.976	16.016							
2	1	1	1	1	1	1	2	N3	
1	2								
1	11							T1	
400.0	0.07132	600.0	0.06571	800.0	0.06036	1000.0	0.05513	T1	
1200.0	0.05021	1400.0	0.04551	1600.0	0.04219	1800.0	0.03926	T1	
2000.0	0.03767	2200.0	0.03660	2400.0	0.03579			T1	
2	5							T2	
0.0	5.56D-5	750.0	9.9D-5	1500.0	1.353D-4	2250.0	1.701D-4	T2	
3000.0	2.014D-4							T2	
3	5							T3	
500.0	0.1139	1000.0	0.1028	1700.0	0.09305	2061.0	0.09004		
2400.0	0.08917							T3	
4	4							T4	
32.0	0.01111	212.0	0.01306	572.0	0.01514	2240.0	0.02478	T4	
5	21							T5	
0.000	3.128	3.043	5.005	5.189	6.673	7.067	8.341	T5	
9.091	10.010	10.110	10.844	11.114	11.678	11.831	12.095	T5	
12.543	12.512	13.760	12.929	14.315	13.138	16.016	13.386	T5	
17.197	13.138	17.984	12.929	18.953	12.512	19.685	12.095	T5	
20.311	11.678	21.386	10.844	22.370	10.010	23.945	8.341	T5	
24.500	7.941							T5	
6	21							T6	
0.000	33.727	3.043	53.963	5.189	71.950	7.067	89.938	T6	
9.091	107.926	10.110	116.919	11.114	125.913	11.831	130.410	T6	
12.543	134.907	13.760	139.404	14.315	141.652	16.016	144.333	T6	
17.197	141.652	17.984	139.404	18.953	134.907	19.685	130.410	T6	
20.311	125.913	21.386	116.919	22.370	107.926	23.945	89.938	T6	
24.500	85.621							T6	
7	21							T7	
0.000	3.128	3.043	5.005	5.189	6.673	7.067	8.341	T7	
9.091	10.010	10.110	10.844	11.114	11.678	11.831	12.095	T7	
12.543	12.512	13.760	12.929	14.315	13.138	16.016	13.386	T7	
17.197	13.138	17.984	12.929	18.953	12.512	19.685	12.095	T7	
20.311	11.678	21.386	10.844	22.370	10.010	23.945	8.341	T7	
24.500	7.941							T7	
8	21							T8	

0.000	13.718	3.043	21.949	5.189	29.265	7.067	36.581	T8
9.091	43.897	10.110	47.555	11.114	51.213	11.831	53.042	T8
12.543	54.872	13.760	56.701	14.315	57.615	16.016	58.705	T8
17.197	57.615	17.984	56.701	18.953	54.872	19.685	53.042	T8
20.311	51.213	21.386	47.555	22.370	43.897	23.945	36.581	T8
24.500	34.825							T8

3D CYL COOR(R,T,Z);SGAS=.3HE,MIDGAP=.055,AG=.005,NSEG=7,CASE24, 6/ 1/81 CARD1 1

SEGMENT #	LOWER HEIGHT	UPPER HEIGHT	LH IN CM	UH IN CM	OUTGAP WIDTH
1	0.000	3.937	0.000	10.000	0.055
2	3.937	6.102	10.000	15.500	0.048
3	6.102	7.874	15.500	20.000	0.036
4	7.874	9.449	20.000	24.000	0.020
5	9.449	11.024	24.000	28.000	0.016
6	11.024	12.992	28.000	33.000	0.014
7	12.992	16.016	33.000	40.680	0.010

THE EMISSIVITIES OF THE MATERIALS :
 E OF SPEC.= .9 E OF POL.TUNG.= .45 E OF NONPOL. TUNG.= .9 E OF G.BLOCK=
 .9 E OF S.S.= .7

B.C.# H.T. COEFF. HR FOR RADIATION
 (BTU/MIN.-IN.**2-R**4)

1	.9241E-13
2	.1641E-12
3	.1308E-12
4	.0000E+00
5	.1306E-12
6	.1301E-12
7	.1296E-12
8	.1294E-12
9	.1293E-12
10	.1292E-12
11	.1632E-12
12	.1629E-12
13	.1629E-12

THE COEFF. OF FORCED CONVEC. = .6181 BTU/MIN.- IN.**2-F

BOUNDARY TEMP. (FOR B.C. #4) = 118.00 DEG. F

GAMMA HEATING RATE (GHR) = .000 WATT/GR.

VHRSPN = 0.0000 BTU/IN.**3-MIN.
 VVRTUN = 0.0000 BTU/IN.**3-MIN.
 VHRGEC = 0.0000 BTU/IN.**3-MIN.
 VHRSS = 0.0000 BTU/IN.**3-MIN.

AXIAL SECTIONS FOR MIDDLE GAP		
LOWER HGT(IN.)	UPPER HGT(IN.)	MIDGAP(IN.)
0.000	8.661	0.055
8.661	10.236	0.025
10.236	13.976	0.018
13.976	16.016	0.016

THE NUMBER OF NODES: 7799
 AN ESTIMATE FOR THE REQUIRED CORE: 1922.19 K BYTES
 AN ESTIMATE FOR THE REQUIRED CPU TIME 4679 SEC

THE NODES OF INTEREST AT HORIZONTAL PLANES:

(1)	1	2	3	4	8	11		573
	695	696	697	698	699		653	
(2)	710	711	712	713	717	721		1283
	1404	1405	1406	1407	1408		1362	
(3)	1419	1420	1421	1422	1426	1431		1993
	2113	2114	2115	2116	2117		2071	
(4)	2128	2129	2130	2131	2135	2141		2703
	2822	2823	2824	2825	2826		2780	
(5)	2837	2838	2839	2840	2844	2851		3413
	3531	3532	3533	3534	3535		3489	
(6)	3546	3547	3548	3549	3553	3561		4123
	4240	4241	4242	4243	4244		4198	
(7)	4255	4256	4257	4258	4262	4271		4833
	4949	4950	4951	4952	4953		4907	
(8)	4964	4965	4966	4967	4971	4981		5543
	5658	5659	5660	5661	5662		5616	
(9)	5673	5674	5675	5676	5680	5691		6253
	6367	6368	6369	6370	6371		6325	
(10)	6382	6383	6384	6385	6389	6401		6963
	7076	7077	7078	7079	7080		7034	
(11)	7091	7092	7093	7094	7098	7111		7673
	7785	7786	7787	7788	7789		7743	

(12)	7800 7801 7802 7803 7807 7821		
	8494 8495 8496 8497 8498	8452	8383
(13)	8509 8510 8511 8512 8516 8531		
	9203 9204 9205 9206 9207	9161	9093
(14)	9218 9219 9220 9221 9225 9241		
	9912 9913 9914 9915 9916	9870	9803
(15)	9927 9928 9929 9930 9934 9951		
	1062110622106231062410625	10579	10513
(16)	106361063710638106391064310661		
	1133011331113321133311334	11288	11223
(17)	113451134611347113481135211371		
	1203912040120411204212043	11997	11933
(18)	120541205512056120571206112081		
	1274812749127501275112752	12706	12643
(19)	127631276412765127661277012791		
	1345713458134591346013461	13415	13353
(20)	134721347313474134751347913501		
	1416614167141681416914170	14124	14063
(21)	141811418214183141841418814211		
	1487514876148771487814879	14833	14773
(22)	148901489114892148931489714921		
	1558415585155861558715588	15542	15483

1 CONSIDERING THE GRAPHITE BLOCK :

AREA OF THE GR. BLOCK IN THE CAPSULE = 0.90485
 AREA OF THE GR. BLOCK IN THE COMPUTER MODEL = 0.90485
 REAL GR. BLOCK AREA - COMPUTER MODEL AREA = -0.0000019
 % ERROR IN GR. BLOCK AREA = 0.0002

CONSIDERING THE STAINLESS STEEL :

AREA OF THE S.S. IN THE CAPSULE = 0.08410
AREA OF THE S.S. IN THE COMPUTER MODEL = 0.08455
REAL S.S. AREA - COMPUTER MODEL AREA = -0.00045
% ERROR IN S.S. AREA = 0.5363

CONSIDERING THE INNER AND OUTER PERIMETERS OF THE S.S. SLEEVE IN BOTH THE CAPSULE AND THE COMPUTER MODEL :

INNER PERIMETER OF S.S. IN THE CAPSULE = 2.07110
INNER PERIMETER OF S.S. IN THE COMPUTER MODEL = 2.07110
% ERROR IN THE INNER PERIMETER = 0.00009

OUTER PERIMETER OF S.S. IN THE CAPSULE = 2.13393
OUTER PERIMETER OF S.S. IN THE COMPUTER MODEL = 2.15648
% ERROR IN THE OUTER PERIMETER = 1.0568

CONSIDERING THE GR. BLOCK WITH NO OUTER GAP

THE AREA OF GR. BLOCK IN THE CAPSULE = 1.01639
THE AREA OF THE GR. BLOCK IN THE COMPUTER MODEL = 1.01687
THE DIFFERENCE = -0.00048
% ERROR IN THE AREA = 0.04766

VITA

Amir Sassan Mobasheran was born in Tehran, Iran on August 20, 1952. He received the Bachelor of Science degree in physics from The University of Tehran, Iran in September 1976. In June 1977 Amir entered The University of Tennessee as a graduate student in the Department of Nuclear Engineering. He was appointed as a teaching assistant in Spring 1978 and was awarded a graduate research contract under Professor Hall C. Roland in November 1979. He received the Master of Science degree with a major in Nuclear Engineering and a minor in Mathematics in December 1981.