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THE EFFECT OF IODINE DECAY HEAT
ON CHARCOAL ADSORBERS

R. P. Shields
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OAK RIDGE NATIONAL LABORATORY

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U.S. ATOMIC ENERGY COMMISSION

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APRIL 1971

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Oak Ridge, Tennessee
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TABLE OF CONTENTS

	PAGE
I. Introduction	1
II. Charcoal Adsorption Systems	2
Charcoal Adsorber Units	2
Containment Filter Systems	5
III. Mathematical Basis for the Thermal Analysis of a Charcoal Adsorber	9
The General Heat Balance Equation	9
Simplified Mathematical Models of Charcoal Adsorber Unit	11
IV. Development of Computer Codes	13
Heat Source	14
Charcoal Characteristics	17
Volumetric Heat Transfer Coefficient	17
Computer Codes	19
ENIS Code	19
CHART Codes	21
V. Application of Computer Codes	24
Heat Generation by Decay of Radioiodine	24
Charcoal Parameters	29
Volumetric Heat Transfer Coefficient	31
Examples of Code Applications	32
VI. Cooling the Charcoal Adsorber by Natural Air Convection	44
VII. Summary	49
ENIS Code	52
CHART Code	53
Appendices	55
Appendix A. Analytical Solution of the Diffusion Equation for the Infinite Slab Model (Derivation of Equation 23)	56
Appendix B. A Computer Program for Calculating Heat Generation, in a Charcoal Adsorber, Due to Iodine Decay	72
Appendix C. CHART Code.	76
Appendix D. Application of CHART to a Research or Production Type Reactor	80
Appendix E. STACK: An XTRAN Computer Program for Calculating Stack Parameter vs Fraction of Decay Heat Removed from Charcoal Adsorbers	93
References	98

ABSTRACT

A procedure for the thermal analysis of the charcoal adsorber, in a reactor containment system, has been developed to estimate maximum temperatures which may prevail under accident conditions. A differential equation which relates the charcoal temperature to the heat generation rate, air flow rate, and the heat parameters of air and charcoal has been solved both analytically and numerically. The analytical method assumes a two inch thick slab of charcoal only and is applicable to high flow rates. A computer code has been developed for numerical solution of the equation for the charcoal slab in both one and three-dimensions. The principal considerations have been given to very low flows and for times soon after onset of the accident; conditions which pose the greatest threat to the charcoal. Examples are given of the application of this code to reactor off-gas charcoal adsorbers.

I. INTRODUCTION

Modern nuclear reactors are equipped with many sophisticated engineered safeguards to prevent or to limit the release of fission products in the event of a reactor malfunction. All safety measures initiated after an accident are directed toward fixing the fission products into some controllable form such as in solution or in suspension in the case of containment spray systems or onto solid surfaces as in the case of particulate filters and charcoal adsorber units.

In any process that collects the fission products some means must be provided for dissipating the heat generated by radioactive decay. Air flow through the charcoal normally provides this feature for iodine adsorption units; however, certain combinations of iodine loading and reduced air flow can be assumed which will produce a temperature rise into the critical range. Since charcoal is combustible and considering the relative importance of the positive containment of iodine isotopes in safety analyses, it is of importance to investigate the various factors which affect the temperature development and distribution in charcoal adsorbers caused by iodine adsorption under accident conditions.

This report covers part of a continuing program sponsored by the USAEC Division of Operational Safety on the general subject of charcoal adsorbers by iodine decay heat. Earlier phases of the work involved an investigation of the ignition process in charcoal¹ and the influence of iodine fission products on the ignition process.^{2,3} The latter tests were conducted with real iodine fission products produced in an in-pile facility. This report and a brief paper at the Eleventh AEC Air Cleaning Conference⁴ cover the effort to develop and apply a computer program to allow an estimation of the temperature development in full-scale charcoal adsorption systems to be made. During this phase of the program it was necessary that some laboratory measurements be made of certain parameters such as volumetric heat transfer coefficients, heat capacities, charcoal properties, etc; these measurements are essentially complete and will be detailed in a companion report to be issued in the near future. Therefore, this report will be limited to a discussion of the computer programs and their applicability; certain parametric values will be estimated for the purpose of illustrating the use of the program.

II. CHARCOAL ADSORPTION SYSTEMS

Charcoal adsorption systems of various configurations are used in the containment schemes of the several types of nuclear reactors. AEC research and production reactors utilize negative pressure containment with continuous ventilation through gas decontamination systems utilizing charcoal and other components; nuclear power reactors of the boiling water type (BWR) utilize a single-pass gas decontamination system, containing charcoal, located outside the primary containment; some of the nuclear power reactors of the pressurized water type (PWR) utilize large recirculating gas decontamination systems located within the containment. Each type of charcoal system will be subjected to differing iodine loadings and operating conditions following an accident. Systems used in the PWR's will probably be subjected to the most severe combination of iodine loading and operating conditions. Figure 1 is a composite illustration of several of these systems.

Charcoal Adsorber Units

The individual adsorber units which make up the adsorber system for nuclear reactors are available in two configurations. Both types contain a layer of granular charcoal held between perforated sheet metal through which the air flows. The method used for supporting the enclosed layer of charcoal gives rise to the two types of adsorber units generally used.

In one type of unit the charcoal is held between perforated sheet folded in an accordian-like pleat so that about 15 ft² of face area can be contained in a 2 ft x 2 ft frame - the so-called pleated adsorber units. Figure 2 contains a photograph of this type of unit as well as a sketch of construction detail. Such units contain about 55 pounds of charcoal and provide a charcoal depth of approximately one inch. Charcoal adsorber units of the pleated type are generally utilized by the AEC research and production reactors which have the continuous ventilation, negative pressure containments.

The second type of adsorber unit contains two individual layers of charcoal held between perforated metal sheet. These layers are fixed one above the other in a drawer-like metal assembly; these units contain

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Figure 1. Some Features of Fission Product Containment System.

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Figure 2. (a) Pleated-Bed Charcoal Adsorber. End plate removed. (Photograph courtesy of Barnebey-Cheney Co.) (b) Cutaway of 1-in.-pleated-bed adsorber.

approximately 45 pounds of charcoal and present about 8 ft² of face area. These units, often called tray-type adsorbers, present a 2 inch depth of charcoal for the air to pass through. Air enters the outside face, as shown by the arrows in Fig. 3, travels through the charcoal mass, into the void space between the charcoal layers, and finally into the exhaust plenum. In practice, many of these units can be fitted, one above the other, into a metal framework section, as illustrated in Fig. 4, and as many of these sections as needed can be aligned to form the desired adsorber system. Charcoal adsorber units of the tray type are generally utilized in off-gas systems contained in nuclear power reactors of both the BWR and PWR types.

Containment Filter Systems

A complete filter system which serves to remove volatile fission products from containment air following an accident can contain as many as four different types of filters or adsorbers. At the entrance to the system a demister unit may be employed to remove entrained water droplets which could be present in the containment atmosphere following a loss-of-coolant type accident. These water droplets are removed to prevent water-blinding of the particle filtering media following the demister unit. Following the demister one may find a low efficiency particle filter referred to as a roughing or pre-filter. This unit serves to limit the buildup of particle deposits on the high efficiency particle filter (HEPA) units which follow. The charcoal adsorber units are usually located downstream of these HEPA units to remove (or decontaminate) the various forms of radioiodine. In some cases the charcoal adsorbers are followed by a second bank of HEPA filter units to trap any charcoal containing radioiodine which may be blown from the adsorbers. Of course, all these filter-adsorber units will trap some of the released radioiodine and will be subjected to decay heating; however, the charcoal adsorber will be the only unit considered in this report.

AEC research and production reactors are provided with continuously-operating off-gas systems contained in underground concrete cells or in separately-contained aboveground enclosures; these systems exhaust to a gas disposal stack. An example of an underground filter-adsorber system for one AEC reactor is provided in Fig. 5. Nuclear power reactors of the

Figure 3. Tray-Type Charcoal Adsorber.

Figure 4. Assembly of Tray-Type Charcoal Adsorber.

Figure 5. High Flux Isotope Reactor Filter System.

boiling water type generally contained a standby filter system containing HEPA filter and charcoal adsorbers and may contain a heating section for humidity control; these are single-pass systems which exhaust to a stack. Some power reactors of the pressurized water type contain recirculating filter systems within the containment which include demisters, HEPA filter units and, in many cases, charcoal adsorbers; these systems exhaust back into containment. Containment gases are exhausted through a separate system to the stack at some length of time after the accident.

Examples of all these systems along with construction details may be found elsewhere.⁵

III. MATHEMATICAL BASIS FOR THE THERMAL ANALYSIS OF A CHARCOAL ADSORBER

In planning the development of the necessary calculational tools for making a thermal analysis of a charcoal adsorber, it was decided to start with a basic description of heat generation and heat loss founded on accepted heat transfer principles. The plan therefore was to define a mathematical model of the adsorber unit and then produce computer codes to facilitate the calculations. Values of physical parameters critical to the codes are to be measured in the laboratory in a concurrent effort.

The General Heat Balance Equation

The general heat balance performed on a unit volume of the charcoal mass assuming air flows in one direction only is

$$\rho_b C_{p_b} \frac{\partial T_b}{\partial t} + \rho_g C_{p_g} v_g \frac{\partial T_g}{\partial x} = k_b \nabla^2 T_b + q''' \quad (1)$$

where

T_b = temperature of the charcoal mass,

T_g = temperature of the cooling gas,

ρ_b, C_{p_b} = density and specific heat of the charcoal

ρ_g, C_{p_g} = density and specific heat of the cooling gas

t = time

x = distance along the direction of cooling gas flow

v_g = velocity of cooling gas

k_b = effective thermal conductivity of the charcoal

q''' = volumetric heat generation rate in the charcoal mass (heat per unit time per unit volume)

and the operator

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$

The first term on the left is the heat absorbed by the charcoal itself and the second term on the left is the heat absorbed by the cooling gas. The first term on the right is the heat diffused by conduction and the second term on the right is the heat source in the charcoal mass. The heat source depends on the nuclear characteristics of the isotopes adsorbed and is normally a function of time and position along the x direction (gas flow direction). It exists only in the charcoal mass itself and is assumed to be zero in the steel structure of the unit (see Section IV for detailed expression of the heat source).

The heat absorbed by the gas will depend on the capability of the charcoal particles to transfer heat to the gas flowing around them. The heat absorbed by the gas per unit volume of the bed can be expressed as

$$S''' = hA'''_{eff} (T_b - T_g) \quad (2)$$

where

S''' = heat absorbed by the gas per unit volume of charcoal,
Btu/min-in.³

h = film heat transfer coefficient between the surface of the charcoal particles and the gas flowing around them, Btu/min-in.²-°F

A'''_{eff} = an effective surface area of the particles available for heat transfer for each unit volume of bed, 1/in.

Since h and A'''_{eff} are characteristic to the charcoal mass and the cooling gas, we will let

$$H = hA'''_{eff} \quad (3)$$

and we can write

$$S''' = \rho_g C_p v_g \frac{dT_g}{dx} = H(T_b - T_g) \quad (4)$$

where H will be called the "volumetric heat transfer coefficient" between the charcoal mass and the cooling gas; its dimensions are $\text{Btu}/\text{min-in.}^3\text{-}^\circ\text{F.}$

Substituting Eq. (4) into Eq. (1), we get

$$\rho_b C_p \frac{\partial T_b}{\partial t} = k_b \nabla^2 T_b + q''' - H(T_b - T_g). \quad (5)$$

Equation (5), together with Eq. (4), is the basic equation for finding the temperature distribution in the charcoal adsorber.

The volumetric heat transfer coefficient, H , can be calculated approximately by using existing correlations for heat transfer coefficient in packed adsorbers and evaluating the effective heat transfer area per unit volume of the adsorbent. However, the available correlation for heat transfer coefficient in packed adsorbers is not very reliable especially in the low gas flow range. Also, the free surface area of the charcoal particles actually in contact with the cooling gas cannot be evaluated with good accuracy. Therefore, experimental measurement of H is usually needed. For a given charcoal adsorber the volumetric heat transfer coefficient will be a function of the gas flow and the physical properties of both the gas and the charcoal. (A more detailed discussion on the volumetric heat transfer coefficient is given in Section IV).

Simplified Mathematical Models of Charcoal Adsorber Unit

In this work we considered three models of the charcoal adsorber unit, a general description for which has been given in Section II. One model considers the charcoal adsorber as an infinite one-dimensional slab of charcoal, 2 in. thick, with no heat loss to environment except by way of the flowing gas. This model will be referred to as the "infinite slab". A second model considers a finite slab (the dimensions can be varied but the values used were 2 ft by 2 ft in cross section and 2 in. thick). Heat loss is to the flowing gas and by radiation and natural convection to the environment from the four vertical 2 ft by 2 in. side faces of the slab. This model will be referred to as the "3-dimensional slab." A third model represents a single tray-type charcoal adsorber. It includes two charcoal masses (2 ft x 2 ft x 2 in. each) and the steel structure around them. Heat loss is to the flowing gas, to the environment and to the

steel structure itself. This model will be referred to as the "3-dimensional unit" model.

At low gas flows, or when no flow is assumed, the steel structure and heat loss to the environment both have a significant effect on the resulting temperature distribution, and therefore the "3-dimensional unit" model should be used. For relatively high flows it can be assumed that the heat loss to the cooling gas is the dominating cooling effect and the "infinite slab" model can be used.

The temperature distribution for the "infinite slab" model was found by two separate methods, based on Eqs. (4) and (5). One method is analytical in its approach and the other is based on a general heat transfer computer code. Since for the "infinite slab", the gas velocities are assumed to be relatively high, the cooling gas temperature T_g does not rise much while penetrating the charcoal mass and can be considered to be constant. Letting

$$T'_b = T_b - T_g$$

and recalling that in an infinite slab, conduction in the bed occurs only in the X direction, will reduce Eq. (5) to

$$\rho_b C_{pb} \frac{\partial T'_b}{\partial t} = k_b \frac{\partial^2 T'_b}{\partial x^2} + q''' - HT'_b. \quad (6)$$

The boundary conditions are:

$$\frac{\partial T'_b}{\partial x} = 0 \text{ for } x = 0 \text{ and any } t$$

$$\frac{\partial T'_b}{\partial x} = 0 \text{ for } x = l \text{ and any } t$$

$$T_b = T_0 \text{ for } t = 0 \text{ and any } x,$$

where $x = 0$ is the front face of the charcoal mass and $t = 0$ is the time at which radioactive iodine first reaches the charcoal adsorber. The analytical solution of the "infinite slab" is based on Eq. (6) and is explained in Section IV. The detailed solution and its computer program are given in Appendix A.

The second method used to calculate the temperature distribution in the "infinite slab" is based on a general heat transfer computer code and takes into account the change in cooling gas temperature as it propagates

through the charcoal mass. The basic equation to be solved is a one-dimensional form of Eq. (5) where T_g is a function of temperature.

The "3-dimensional slab" and "3-dimensional unit" models must take into account the temperature changes in the cooling gas itself as well as heat transfer to the metal structure. Here, Eq. (5) must be used in its complete form coupled with Eq. (4), i.e.,

$$\rho_b C_{p_b} \frac{\partial T_b}{\partial t} = k_b \left[\frac{\partial^2 T_b}{\partial x^2} + \frac{\partial^2 T_b}{\partial y^2} + \frac{\partial^2 T_b}{\partial z^2} \right] + q''' - H(T_b - T_g) \quad (7)$$

where T_g is given from Eq. (4) by

$$\rho_g C_{p_g} v_g \frac{\partial T_g}{\partial x} = H(T_b - T_g). \quad (8)$$

The initial conditions are

$$T_g = T_o \text{ at } t = 0 \text{ and any } x,$$

$$T_b = T_o \text{ at } t = 0 \text{ and any } x$$

The boundary condition for the cooling gas is

$$T_g = T_o \text{ for } x = 0 \text{ and any } t.$$

The boundary conditions for the adsorber unit are complicated and will be best described in the illustrative case given in Section V. The same general heat transfer computer code as used for the "infinite slab" is used to solve the "3-dimensional slab" model and a description of it is given in Section IV. This same code has the capability to solve the "3-dimensional unit" model but that solution has not been performed.

IV. DEVELOPMENT OF COMPUTER CODES

The transposition of the mathematical models, just discussed, into computer codes is the subject of this section of the report. Relationships for the heat generation and heat transfer characteristics for charcoal masses were developed and then incorporated into the basic heat diffusion equations. Solutions were then developed and coded for the computer.

Heat Source

Heat generation in the charcoal adsorber comes from beta and gamma activity resulting from the radioactive decay of iodine isotopes. Let a_i and g_i be the decay heat per thermal Mw of reactor power produced by the i th isotope from beta and gamma activity, respectively. If the reactor power is $P(t)$ thermal Mw's, then the decay heat of the i th isotope will be $P(t) a_i$ and $P(t) g_i$ Btu/min for beta and gamma activity, respectively. Since only a certain fraction, F , of the radioactive material coming from the reactor is absorbed by the charcoal, the total decay heat in the charcoal bed itself will be

$$F P(t)(a_i + g_i) \text{ Btu/min.}$$

The time dependent decay heat will be then

$$FP(t)(a_i + fg_i)e^{-\lambda_i(t + t_D)} \text{ Btu/min}$$

where λ_i is the decay constant of isotope i , t_D is the time delay between end of fissioning and beginning of actual adsorption, f is the fraction of the gamma heat which does not escape the bed, and t is time elapsed from beginning of actual adsorption. If the volume of the charcoal adsorber is V_b , then the average specific heat generation due to radioactive decay in the bed is

$$q_i'''(x) = \frac{FP(t)}{V_b}(a_i + fg_i)e^{-\lambda_i(t + t_D)} \text{ Btu/min-in.}^3 \quad (9)$$

However, since iodine concentration is not uniform along the depth of the charcoal mass, we will assume here an exponential distribution according to

$$\beta(x) = \beta_0 e^{-bx} \text{ so that } \frac{1}{\ell} \int_0^{\ell} \beta(x) dx = 1$$

where $\beta(x)$ is the ratio between local and average radioactive iodine concentration, β_0 is the ratio between maximum ($x = 0$) and average radioactive iodine concentration and b is the attenuation factor. It is clear that

$$1 = \frac{1}{\ell} \int_0^{\ell} \beta_0 e^{-bx} dx = \frac{\beta_0}{b\ell} (1 - e^{-b\ell}).$$

Therefore

$$\beta_0 = b\ell / (1 - e^{-b\ell})$$

where ℓ is the thickness of the charcoal mass.

The local radioactive iodine concentration then is

$$\beta(x)a_i = \beta_0 a_i e^{-bx} = \frac{b\ell a_i}{1 - e^{-b\ell}} e^{-bx}. \quad (10)$$

However, since b is different for elemental iodine (I_2) and methyl iodide (CH_3I), we must take their local concentrations into account separately. Assuming β_1 and β_2 are the fractions of I_2 and CH_3I , respectively, we get by using Eqs. (9) and (10) that the local specific heat generation in the bed is

$$q_i'''(x,t) = \frac{FP(t)}{V_b} \left[\left(\frac{\beta_1 b_1 \ell}{1 - e^{-b_1 \ell}} e^{-b_1 x} + \frac{\beta_2 b_2 \ell}{1 - e^{-b_2 \ell}} e^{-b_2 x} \right) a_i + fg_i \right] e^{-\lambda_i(t+t_D)} \text{ Btu/min-in.}^3. \quad (11)$$

Note that it was assumed that the gamma heating (indicated by the fg_i term) is not position dependent, hence the term developed in Eq. (10) was not multiplied by fg_i in Eq. (11). Let

$$B_1 = \frac{P(t)}{V_b} \frac{\beta_1 b_1 \ell}{1 - e^{-b_1 \ell}} \quad (12)$$

$$B_2 = \frac{P(t)}{V_b} \frac{\beta_2 b_2 \ell}{1 - e^{-b_2 \ell}} \quad (13)$$

$$G = \frac{P(t)}{V_b} f \quad (14)$$

and we get

$$q_i'''(x,t) = F[(B_1 e^{-b_1 x} + B_2 e^{-b_2 x}) a_i + Gg_i] e^{-\lambda_i(t+t_D)}.$$

Summing up the effect of all the isotopes, we get

$$q'''(x,t) = F[(B_1 e^{-b_1 x} + B_2 e^{-b_2 x}) \sum_{i=1}^m a_i e^{-\lambda_i(t+t_D)} + G \sum_{i=1}^m g_i e^{-\lambda_i(t+t_D)}]. \quad (15)$$

If in addition we take into account that the loading of radioactive material onto the adsorbers is gradual as in the case for recirculating adsorber systems according to:

$$C = C_0(1 - e^{-aRt/V}), \quad (16)$$

where

C = amount of iodine on charcoal at time t

C_0 = initial amount of iodine in containment

a = fraction of iodine removed from air as it passes through charcoal
(assumed here to be 0.9)

R = air flow rate, ft^3/min

V = volume of containment, ft^3

t = time elapsed from beginning of iodine adsorption by charcoal,

Then

$$q'''(x,t) = F[(B_1 e^{-b_1 x} + B_2 e^{-b_2 x}) \sum_{i=1}^m a_i e^{-\lambda_i(t+t_D)} + G \sum_{i=1}^m g_i e^{-\lambda_i(t+c_D)}](1 - e^{-(aR/V)t}), \quad (17)$$

where

$q'''(x,t)$ = heat generation rate per unit volume of charcoal bed

x = distance from front face of charcoal bed in direction of gas flow

t_D = time delay between end of fissioning and beginning of iodine adsorption.

b_1 = attenuation coefficient for elemental iodine

b_2 = attenuation coefficient for methyl iodide

F = fraction of total iodine adsorbed by the charcoal filter

B_1 , B_2 and G are given in Eqs. (12), (13), and (14), respectively.

In those equations

$P(t)$ = reactor power in $\text{Mw}(t)$

V_b = volume of charcoal bed

ℓ = thickness of charcoal layer

$(1 - f)$ = fraction of gamma rays escaping from charcoal mass without capture

β_1 , β_2 = fractions of iodine and methyl iodide, respectively.

a_i , g_i , λ_i = see Table D-3, Appendix D.

A computer program was written for the heat generation rate per unit volume, based on Eq. (17). The program is written in XTRAN which is a version of Fortran IV for the time-sharing computer of Com-Share Company. A listing of this program appears in Appendix B. The program will output the minimum, (at $x = 2.0$ in.), the maximum (at $x = 0.0$), and the average heat generation rates per unit volume as well as the total heat generation rate for the adsorber as functions of time.

Charcoal Characteristics

In order to perform heat transfer calculations in packed adsorbers, one must know adsorbent characteristics like shape, porosity, sphericity and mean diameter of the particles. The porosity in this case is not concerned with internal cavities of the charcoal particles, but only with the void space between the solid particles in packed array. Porosity is defined as volume of void space divided by the total volume of the adsorbent container. Sphericity is defined as the surface area of a sphere having a volume equal to that of the particle divided by the surface area of the particles. Values for these and other parameters will be given in Section V.

Volumetric Heat Transfer Coefficient

In Section III it was shown that the cooling process in adsorbers can be visualized as a volumetric heat sink which can be expressed from Eqs. (2) and (4) as

$$S''' = hA_{eff}''' (T_b - T_g) = H(T_b - T_g). \quad (18)$$

It was emphasized in Section III that some correlations do exist in the literature for calculating the film heat transfer coefficient h , but that they are not very reliable and are usually derived for high Reynolds numbers. In addition, the surface area actually available for heat transfer is not typical for all adsorbers, and it is difficult to estimate it. Experimental work was needed then to evaluate the volumetric heat transfer coefficient, H , for charcoal adsorbers. Such work is being accomplished and will be reported separately. In order to have some approximate values for use here, an analytical approach was used.

If ω is the percentage of adsorbent particle area which is actually available for heat transfer, the volumetric heat transfer coefficient can be expressed as

$$H = hA_{eff}' = h \frac{A_p N \omega}{V_p N \left(\frac{1}{1-d} \right)} = h \omega (1-d) \frac{A_p}{V_p} \quad (19)$$

where

h = film heat transfer coefficient from the particle surface to the gas, Btu/hr-ft²-°F

ω = percentage of area actually available to heat transfer

d = bed porosity

A_p = one particle surface area, ft²

V_p = one particle volume, ft³

N = number of particles per unit volume of bed

$H(\text{Btu/min-in.}^3\text{-}^\circ\text{F}) = 9.65 \times 10^{-6} H(\text{Btu/hr-ft}^3\text{-}^\circ\text{F})$.

In order to evaluate H we must find the heat transfer coefficient (h) between the particle surface and the gas. References 6-9 suggest possible correlations to be used. The one given by Coppage⁹ seems to be most adaptable to our case although like the other three correlations, its applicability is for higher flows than the ones we are interested in. Nevertheless, it will be used as an approximation for the cases discussed in this report. The correlation for the range $6 < G/\mu A < 13,000$ is

$$h = \frac{EGC_p}{d} P_r^{-2/3} (4G/\mu A)^{-m} \quad (20)$$

where

C_p = specific heat, Btu/lb-°F

$G = W/S$, lb/hr-ft²

W = total flow, lb/hr

S = total cross section area of the bed, ft²

A = total particle surface per unit volume of bed

$$= \frac{A_p}{V_p} (1-d), 1/\text{ft}$$

Pr = Prandtl number of gas

μ = dynamic viscosity of gas, lb/hr-ft

E, m = constants which are functions of d .

Computer Codes

ENIS Code

The partial differential equation for the "infinite slab" model and the corresponding boundary conditions assumed are given in Eq. (6). The heat generation q''' is given in Eq. (15). To solve this partial differential equation a change of variables was made so that:

$$T'_b(x,t) = \psi(x,t)e^{-\alpha(H/k)t} (= T_b - T_g) \quad (21)$$

where $\alpha = k_b / \rho_b C_{p_b}$. This reduces Eq. (6) to

$$\frac{\rho C_p}{\alpha} \frac{\partial \psi(x,t)}{\partial t} = k_b \frac{\partial^2 \psi(x,t)}{\partial x^2} + A(x,t) \quad (22)$$

where

$$A(x,t) = (B_1 e^{-b_1 x} + B_2 e^{-b_2 x}) \sum_{i=1}^m a_i e^{-\beta_i t} + G \sum_{i=1}^m g_i e^{-\beta_i t}$$

and

$$\beta_i = \lambda_i - \alpha(H/k_b)$$

and the boundary conditions become

$$\frac{\partial \psi}{\partial x}(0,t) = 0 \text{ at } x = 0$$

$$\frac{\partial \psi}{\partial x}(\ell,t) = 0 \text{ at } x = \ell$$

$$\psi(x,0) = 0 \text{ at } t = 0.$$

By using either Green's theorem or Fourier cosine series expansion, an analytical solution of Eq. (22) is achieved (see Appendix A for details) in the form

$$T'_b(x,t) = \left\{ -\frac{\alpha}{k_b} \left(\frac{B_1}{b_1} (1 - e^{-b_1 \ell}) + \frac{B_2}{b_2} (1 - e^{-b_2 \ell}) \right) \right\}.$$

$$\sum_{i=1}^m \frac{a_i}{\beta_i} (e^{-\lambda_1 t} - e^{-\alpha(H/k)t}) - \frac{\alpha}{k_b} (G) \cdot \sum_{i=1}^m \frac{g_i}{\beta_i} (e^{-\lambda_1 t} - e^{-(\alpha H/k)t}) +$$

$$\frac{2\alpha}{k_b \ell} \sum_{n=1}^{\infty} \left\{ \left[\frac{b_1 B_1}{b_1^2 + (n\pi/\ell)^2} (1 - (-1)^n e^{-b_1 \ell}) \right. \right.$$

$$\left. + \frac{b_2 B_2}{b_2^2 + (n\pi/\ell)^2} (1 - (-1)^n e^{-b_2 \ell}) \right] \cos(n\pi x/\ell) \right\}.$$

$$\sum_{i=1}^m a_i \left[\frac{e^{-\lambda_1 t} - e^{-\alpha(n\pi/\ell)^2 t + [(H/k_b)]t}}{\alpha(n\pi/\ell)^2 - \beta_i} \right] \}. \quad (23)$$

To facilitate the use of this solution it was programmed in Fortran IV. Later the code was expanded to include the time delay parameter and also to allow the change of the volumetric heat transfer coefficient, H , with time. A plotting routine was also incorporated in the program.

The computer code is a numerical expression of Eq. (23) with some additional capabilities added to it. It will accept as input data the constants B_1 , B_2 , and G appearing in the heat generation term, the volumetric heat transfer coefficient, H (which can be changed five times during a single run), the time delay between end of fission and beginning of iodine adsorption in adsorbers, the locations for which printouts of temperature are desired, the time intervals for such printouts and the option to get a plot of the maximum temperature versus time. The computer code, its listing, an output sample and an input format table are given in Appendix A.

This code was used early in the program to study the several variables; its applicability was limited to gas velocities of 40 ft/min and up because of the restriction of keeping the temperature of the gas constant. This deficiency led to the development of a more exact code discussed in the next subsection.

CHART Codes

The CHART code was developed to solve the 3-dimensional models as discussed in Section 3. This model is described mathematically by Eqs. (7) and (8). Such a model is too complicated to be solved analytically. A general heat transfer computer code, named HEATING-2¹⁰, and its modified version, HEATING-3¹¹, were found, after some modifications, to be most suitable for our purpose.

The HEATING heat transfer code is a general transient 3-dimensional code written in Fortran IV language for the IBM 360 computer system. It can accept both rectangular and cylindrical geometry. It solves the steady state problems by the "extrapolated Liebmann method" and the transient problems by first forward time difference in the "explicit method". Thermal properties can be temperature dependent. It can handle as many as 8000 lattice points, 100 regions, 50 materials and 50 boundary conditions. It can handle nonlinear boundary conditions (natural convection or radiation heat transfer) as well as linear ones (forced convection). It will handle problems with heat transfer from surface to surface (like in radiation from one slab to another). The heat generation in each region can be a function of position and/or time. It also has an acceleration procedure to reduce computer time without the code becoming unstable. It has a nodal generator, which means that only region coordinates must be supplied and the program generates the required nodes with their geometrical and thermal properties. The input required is generally simple (see Ref. 10 for input procedures.)

Any general heat transfer computer code for conduction is based on solving numerically the diffusion partial differential equation in the form

$$\rho C_p (\partial T / \partial t) = k \nabla^2 T + Q''' \quad (24)$$

with the corresponding boundary conditions. Heat transfer by convection can be taken into account on the boundaries only. Also the heat generation term Q''' can normally be taken into account as a function of position and time. In the case of HEATING3 this dependence had the form of

$$q'''(X,Y,Z,t) = F_1(X) F_2(Y) F_3(Z) F_4(t) \quad (25)$$

where $F_1(X)$, $F_2(Y)$, and $F_3(Z)$ are each a position dependent function of one coordinate and $F_4(t)$ is a time dependent function defined by a set of points (a table).

If we compare Eq. (24) to Eq. (7) which is the one we want to solve, we see that

$$Q''' = q''' - H(T - T_g) \quad (26)$$

where q''' is given by Eq. (17) and T_g must be solved from Eq. (8).

It can be seen that (a) the heat generation term Q''' is a function of temperature as well as of position and time and (b) the heat generation term has a very complicated form which cannot be expressed in the form of Eq. (25).

In order to include those capabilities a number of subroutines in HEATING3 have been modified and the final version has been called "CHART". Subroutine THRMFR has been modified so that it will call the heat generation subroutine GENFN not more than twice for each node, will do it for every time step and will include in its calling arguments list the current time and temperature. Having that capability, the heat generation subroutine GENFN was rewritten so that the heat generation term can be expressed by any analytical function of position, time, and temperature. Currently Eq. (17) is used for the heat generation term. The subroutine also calculates the cooling gas temperature as function of temperature along the flow direction (based on Eq. 8) and feeds the result into the heat generation term (Eq. 26). Through the use of this technique it is possible to handle adsorber problems which are combined conduction and convection problems, using a basically heat conduction computer code. Inserting Eqs. (17) and (8) into the HEATING3 code changed the criteria which must be met in order to prevent instabilities. The largest time step allowed for stability became somewhat smaller and in addition an upper limit exists for the element size in the cooling gas flow direction.

Subroutines "CALQLT" and "HGNFN" of HEATING3 were modified to include those new criteria for stability; the criteria are described in Appendix C. Additional modifications have been made to accept and print the appropriate input data in the "MAIN" program.

In addition to the regular capabilities of HEATING3 as described in Reference 11 the CHART code can handle the following variables:

1. The power constants B_1 , B_2 and G and attenuation coefficients b_1 and b_2 appearing in Eq. (17).

2. The fraction of total iodine adsorbed by the charcoal filters.
3. The inlet temperature of the cooling gas and its physical properties.
4. The location of the charcoal slab as related to the overall coordinates of the system.
5. The loading rate of the iodine on the adsorbers. A large value will impose an "instantaneous loading".
6. The time delay between end of fissioning (shutdown) and beginning of actual iodine adsorption.
7. The velocity of the cooling gas at the beginning of iodine adsorption and at the time when 95% of the iodine has been absorbed. This gives the flexibility of having normal conditions all the time, accidental conditions (blower slowdown) right from the beginning, or accidental conditions only after 95% of the iodine is already loaded on the adsorbers.
8. The isotopes constants a_i , g_i , and λ_i appearing in Eq. (17).

The CHART code can be used in three ways:

CHART A - Used to compare results with output from ENIS code for the "Infinite Slab" model. By inserting an arbitrary large value (like 10^5) for the heat capacity of the cooling gas the code will not allow the temperature of the gas T_g to change.

CHART B - Used for calculations with the "Infinite Slab" and the "3-dimensional slab" models. True heat capacity for the cooling gas must be used.

CHART C - Used with the "3-dimensional unit" model. The code will define the charcoal slab and the metal structure around it. Actual cooling gas temperature will then be taken into account. A trial run has been run for the "3-dimensional unit" model and it seems to be working well. However, because of the large number of nodes and their small size, the time increment required for stability becomes very small (about 3.0×10^{-3} min), and the computer-time to actual-time ratio became very large (about 26). Even by use of the acceleration capabilities of the modified method

method (see Ref. 10) a complete run of this case requires an inordinate amount of time. Some modifications are needed to reduce the length of such a calculation.

V. APPLICATION OF COMPUTER CODES

To illustrate the application of the codes one must first place values on such critical parameters as heat generation, heat transfer coefficients, and charcoal characteristics and then define typical reactor systems for study. Examples will be given to illustrate the applicability of the codes to recirculating adsorber systems similar to those utilized with power reactors of the pressurized-water type and also to once-through adsorber systems of the type utilized by power reactors of the boiling-water types and by AEC reactors using the negative pressure containment concept.

Heat Generation by Decay of Radioiodine

The equilibrium quantities of the various isotopes of iodine contained in the fuel of a power reactor are substantial. When significant quantities of these isotopes are assumed to be adsorbed on the charcoal surfaces then the heating load is considerable. This heat is generated as a result of the absorption by the charcoal of the kinetic energy of the products of radioactive decay: the beta particles and the gamma photons. The amount of heat produced will, of course, be a function of the quantity of iodine isotopes which have been adsorbed and this quantity will depend upon the quantity available in the fuel for release at the time of the accident.

Isotopes of iodine are formed as a result of fission of ^{235}U as well as through the decay of isotopes of tellurium; depending upon the specific application both modes of production may have to be considered. Both iodine and tellurium are released from molten fuel to about the same extent¹² but the tellurium may subsequently be adsorbed or react in such a way as will preclude all of the iodine produced by its decay from reaching the charcoal. Consequently, when considering the heat generation in charcoal

adsorbers a decision must be made as to what fraction of the iodine (mainly ^{134}I) produced by decay of tellurium (after reactor shutdown) should be included as part of the heating source. An example of the magnitude of this effect is included in the example subsection which follows.

Equilibrium quantities of the isotopes of iodine at time of reactor shutdown and at various times of decay thereafter were calculated and the results appear in Table 1; in this listing the amounts of iodine produced by decay of tellurium isotopes after reactor shutdown were included. However, in the examples which follow we did not consider the "growing-in" of iodine after shutdown and assumed that the amounts of radioiodine isotopes present at reactor shutdown represent the maximum quantity of heat producing material available for deposit on the charcoal adsorbers. The fission product loading is reduced by limited release of iodine from the fuel, by plateout, and by radiodecay as the isotopes travel from the fuel to the adsorbers; a significant amount of time and plateout could be involved in this travel.

It is most difficult to define the exact quantity of radioiodine that will be released from the fuel in an accident situation and the fraction of that amount which will plateout on surfaces; therefore it is the custom to assume, for a safety analysis, that 25% of the fuel inventory of the iodine will appear in the containment for adsorption onto the charcoal and further, that the isotopes travel from the fuel without decay. Decay heating is allowed to start when the isotope is adsorbed on the charcoal surface.

The assumption concerning decay time places a large burden on the adsorbers since the iodine inventory is reduced very rapidly over the first few minutes following shutdown. Various estimates ranging from tens of minutes to several hours can be made of the length of time from shutdown until arrival of iodine at the adsorber. In the examples that follow, some allowances will be made for decay prior to adsorption on the charcoal. The effect of decay on the iodine quantity values is also illustrated in Table 1 where decay up to 200 minutes is considered.

In Table 2, the curies of iodine at shutdown have been converted into watts of decay power per Mw(t) of reactor power; values are contained

Table 1. Radioactive Iodines Produced in a Reactor, Curies/Mw(t) of Reactor Power

Nuclide Radioactivity, Curies/Mw(t) of Reactor Power

Isotope	Shutdown	20 min	40 min	60 min	80 min	100 min
I-128	3.50E 02*	2.01E 02	1.15E 02	6.62E 01	3.80E 01	2.18E 01
I-129	1.24E-03**	1.24E-03	1.24E-03	1.24E-03	1.24E-03	1.24E-03
I-130m	3.95E 02	8.76E 01	1.94E 01	4.30E 00	9.53E-01	2.11E-01
I-130	1.14E 03	1.12E 03	1.10E 03	1.08E 03	1.06E 03	1.04E 03
I-131	2.88E 04	2.88E 04	2.88E 04	2.88E 04	2.88E 04	2.88E 04
I-132	4.10E 04	4.08E 04	4.07E 04	4.06E 04	4.05E 04	4.04E 04
I-133	5.37E 04	5.37E 04	5.37E 04	5.31E 04	5.27E 04	5.23E 04
I-134	6.08E 04	5.72E 04	5.16E 04	4.51E 04	3.85E 04	3.24E 04
I-135	4.77E 04	4.62E 04	4.46E 04	4.31E 04	4.16E 04	4.02E 04
I-136	2.02E 04	8.99E-01	3.99E-05	1.77E-09	7.89E-14	0.00
I-137	5.21E 04	1.02E-011	0.00	0.00	0.00	0.00
I-138	5.05E 04	0.00	0.00	0.00	0.00	0.00
I-139	4.14E 04	0.00	0.00	0.00	0.00	0.00
Total	3.98E 05	2.28E 05	2.20E 05	2.12E 05	2.03E 05	1.95E 05

* In all tables this shorthand method of density powers of ten will be used; this value is read as 3.5×10^2 or 350.

** This value is read as 1.24×10^{-3} or 0.00124.

Table 1, Continued

Isotope	Shutdown	120 min	140 min	160 min	180 min	200 min
I-128	3.50E 02*	1.24E 01	7.20E 00	4.14E 00	2.38E 00	1.36E 00
I-129	1.24E-03**	1.24E-03	1.24E-02	1.24E-03	1.24E-03	1.24E-03
I-130m	3.95E 02	4.68E-02	1.00E 03	2.30E-03	5.09E-04	1.13E-04
I-130	1.14E 03	1.02E 03	1.04E 03	9.83E 02	9.65E 02	9.47E 02
I-131	2.88E 04	2.87E 04	2.87E 04	2.87E 04	2.87E 04	2.86E 04
I-132	4.10E 04	4.03E 04	4.01E 04	4.00E 04	3.99E 04	3.98E 04
I-133	5.37E 04	5.18E 04	5.14E 04	5.09E 04	5.04E 04	4.98E 04
I-134	6.08E 04	2.70E 04	2.2E 04	1.81E 04	1.47E 04	1.18E 04
I-135	4.77E 04	3.89E 04	3.76E 04	3.63E 04	3.51E 04	3.39E 04
I-136	2.02E 04	0.00	0.00	0.00	0.00	0.00
I-137	5.21E 04	0.00	0.00	0.00	0.00	0.00
I-138	5.05E 04	0.00	0.00	0.00	0.00	0.00
I-139	4.14E 04	0.00	0.00	0.00	0.00	0.00
Total	3.98E 05	1.88E 05	1.81E 05	1.75E 05	1.75E 05	1.65E 05

Table 2. Constants for Iodine Isotopes Produced in a Reactor

Iodine Isotope	Decay Constant (min ⁻¹)	Fraction of Decay Heat Due to		Decay Power (watts/Mw(t) of Reactor Power at Shutdown		
		Beta	Gamma	Discharge Total	From Beta	From Gamma
I-128	2.77E-02	0.827	0.173	1.99E 00	1.65E 00	3.40E-01
I-129	7.74E-14	1	0.0	5.37E-07	5.37E-07	
I-130m	7.56E-02	1	0.0	2.34E-01	2.34E-01	
I-130	9.30E-04	0.220	0.780	9.97E 00	2.19E 00	7.78E 00
I-131	5.98E-05	0.426	0.574	1.18E 02	5.03E 01	6.77E 01
I-132	5.02E-03	0.220	0.780	6.55E 02	1.44E 02	5.11E 02
I-133	5.50E-04	0.490	0.510	3.50E 02	1.72E 02	1.79E 02
I-134	1.31E-02	0.186	0.814	1.18E 03	2.19E 02	9.61E 02
I-135	1.72E-03	0.160	0.840	6.45E 02	1.03E 02	5.42E 02
I-136	5.01E-01	0.480	0.520	5.10E 02	2.45E 02	2.65E 02
I-137	1.84E-00	1	0.0	5.43E 01	5.43E 01	
I-138	7.02E-00	1	0.0	1.02E 03	1.02E 03	
I-139	2.08E-01	1	0.0	4.91E 02	4.91E 02	
				5.04E 03	2.50E 03	2.53E 03

which represent contributions from both beta and gamma emissions; the entire beta and gamma energy is assumed to be converted into heat. The effect of decay time on decay heating is illustrated in Fig. 6 which includes iodine produced by decay of tellurium.

Charcoal Parameters

As noted in Section IV values for certain charcoal parameters or characteristics are needed to perform heat transfer calculations in adsorber units. One must know values for characteristics such as shape, porosity, sphericity and mean diameter of the particles. The porosity in this case is not concerned with internal cavities of the charcoal, only with the void space between the particles when in packed array; porosity is defined as volume of void space divided by the total volume of the container. Sphericity is defined as the surface area of a sphere having a volume equal to that of the particle divided by the surface area of the particle. The bed porosity for 8 x 16 mesh (U.S.) charcoal particles will be somewhere between 0.38 and 0.45 while the sphericity will be between 0.70 and 0.80.

On examination of a sample batch of charcoal, the particles seem to be prismatic in form with a.a.2a as a fairly representative shape. This shape has a sphericity of 0.767. This particular sample has a porosity estimated to be about 0.43. This figure will probably vary no more than 10% from batch to batch.

One cubic centimeter was found to contain 278 particles. With a void fraction of porosity of 0.43 this results in a particle volume of 0.002050 cm^3 or 0.0001251 in.^3 . One particle plus the void or interstitial space occupies 0.0002195 in.^3 . The mean diameter, which is the diameter of a sphere having same volume as an average particle, is equal then to 0.06205 in., which compares favorably with a screen analysis, indicating an average particle diameter of 0.0504 in. If the particle has a prismatic shape of a.a.2a as previously assumed, the volume is $2a^3$ and $a = 0.03970 \text{ in.}$ The total area of this representative particle is $10a^2$ or 0.01576 in.^2 . The effective heat transfer area in the bed will be of course less than this. The above characteristics will be used in any calculation made in this report.

ORNL-DWG 70-9871

Figure 6. Fission Product Iodine Decay Heat as a Function of Time After Shutdown.

The physical properties of a charcoal bed are by no means a constant value. Each property depends on several factors. The apparent density of a charcoal bed is affected by the amount of moisture adsorbed and the method used in packing the bed. The thermal conductivity of charcoal beds is also subject to variations. It is a function of the temperature of the gas which fills the void between the grains and probably also of grain size. The greatest variation in a property is exhibited when measuring the heat capacity (C_p) of a charcoal bed over a range of temperatures. As moisture and other adsorbed gases are desorbed they act as a heat sink and thus cause a large increase in the heat capacity while this is taking place. Heat capacity and thermal conductivity have been studied in the laboratory and will be reported in a separate report.

In the examples which follow, the following values have been assumed:

Heat capacity = $C_p = 0.2 \text{ Btu/lb-}^\circ\text{F}$

Density = $\rho = 35 \text{ lb/ft}^3 = 2.0255 \times 10^{-2} \text{ lb/in.}^3$

Conductivity $k = 0.12 \text{ Btu/hr-ft-}^\circ\text{F} = 1.6667 \times 10^{-4} \text{ Btu/in.-min-}^\circ\text{F}$.

Volumetric Heat Transfer Coefficient

Equation (19) was given previously to relate H (the volumetric heat transfer coefficient) with h (the film heat transfer coefficient from the charcoal particle to the flowing gas) and Eq. (20) was given to aid in estimating values of h ; the needed values of parameters have now been specified and a value for H can be estimated.

Using the characteristics given in the above subsection and assuming that about 80% of the charcoal surface area is available for heat transfer we get from Eq. (19):

$$H = (0.8)(1 - 0.43) \left(\frac{0.01576}{0.0001251} \right) (12)h$$

$$H = 689.4 h \text{ Btu/hr-ft}^3\text{-}^\circ\text{F} \quad (27)$$

From the reported correlation⁹ we get values of 0.272 and 0.341 for E and m assuming $d = 0.43$; then expressing G as $60 \rho V_g$ where V_g is in ft/min and using the properties of the adsorber unit and gas we get,

$$h = 1.0887 V_g^{0.66} \text{ Btu/hr-ft}^2\text{-}^\circ\text{F} \quad (28)$$

Substituting into Eq. (27) we get

$$H = 750.55 \sqrt[0.66]{\frac{v}{g}} \text{ Btu/hr-ft}^3\text{-}^\circ\text{F}$$

or

$$H = 0.00724 \sqrt[0.66]{\frac{v}{g}} \text{ Btu/min-in.}^3\text{-}^\circ\text{F.} \quad (29)$$

Equation (29) was directly incorporated into the computer code for obtaining the volumetric heat transfer coefficient for each specified gas velocity.

Examples of Code Applications

As noted earlier, in order to illustrate the application of the codes one must first define a typical reactor system and then place numerical values on the various input parameters. The following examples are offered.

The following reactor system was defined for the express purpose of illustrating the applicability of the computer code. While the assumed system is similar to current pressurized-water reactors no effort was made to define a particular reactor: reactor power, 3077 Mw(t); volume of containment, $1.14 \times 10^6 \text{ ft}^3$; face area of charcoal adsorber, 2800 ft^2 ; charcoal thickness, 2 inches; superficial air velocity through charcoal, as specified.

Example 1 - As discussed earlier, much of the early work was accomplished with the ENIS code which did not allow the temperature of the flowing air to change; the CHART series of codes was developed to handle a temperature rise in the flowing gas. CHART-A was so defined as to compare with the limitations of ENIS to allow a comparison to be made and to validate the assumptions made in the CHART series. Table 3 compares the output for ENIS, CHART-A, and CHART-B for an identical adsorber system. It is assumed that 25% of the iodine inventory is passed from the reactor core to the charcoal adsorber with 10 minutes decay and then instantly dispersed over the charcoal before additional decay is allowed; the sequence is referred to as "instant loading." The time values in the table refer to time after the iodine has been loaded onto the charcoal and not time from reactor shutdown. It is noted that temperature rise in the flowing air is an important consideration especially at the low flow rates. All of the following examples were done with the CHART-B code.

Table 3. Comparison of Temperature Rise as Calculated for Charcoal Adsorber by Three Computer Codes

Time (min.)		Temperature Rise in Charcoal Adsorber (°F Above Ambient)								
		Inlet Face			Middle			Exit Face		
		Code 1	2	3	Code 1	2	3	Code 1	2	3
Air velocity 20 ft/min	0	8.5	9.2	23.0	1.2	1.2	45.2	1.1	1.1	30.7
	10	8.1	8.8	22.2	1.1	1.1	62.9	1.1	1.1	90.8
	20	7.6	8.2	20.9	1.0	1.0	59.0	1.0	1.0	85.3
	40	6.8	7.3	18.6	0.9	0.9	52.5	0.9	0.9	75.6
	80	5.6	6.2	15.2	0.7	0.8	42.8	0.7	0.7	61.4
Air velocity 40 ft/min	0	5.7	6.3	11.1	0.7	0.7	32.1	0.7	0.7	36.6
	10	5.5	6.0	10.5	0.7	0.7	30.9	0.7	0.7	45.3
	20	5.1	5.6	9.7	0.7	0.7	29.0	0.6	0.6	42.5
	40	4.6	5.0	8.8	0.6	0.6	25.8	0.6	0.6	37.7
	80	3.8	4.1	7.2	0.5	0.5	21.1	0.5	0.5	30.0

Code 1: ENIS code, which is an analytical solution of Eq. (23); temperature of flowing air, t_g , constant.

Code 2: CHART A: compares with ENIS; t_g constant.

Code 3: CHART B: allows t_g to vary.

Example 2 - It is assumed that 25% of the iodine inventory is passed from the core to the charcoal adsorber with 10 minutes decay and then instantly dispersed over the charcoal before additional decay is allowed; this sequence is referred to as "instant loading." Figure 7 shows the maximum charcoal temperature as a function of time as computed by the CHART-B code for two air velocities through the charcoal mass. The time values on this graph refer to time after the iodine has been loaded onto the charcoal and not time from shutdown; the temperature values refer to temperature rise above the assumed starting temperature of the charcoal. At an air velocity of 4 ft/min the maximum temperature rise was approximately 380°F above the starting temperature, and this occurred at about 36 minutes after iodine loading; at a velocity of 20 ft/min the heat transfer is much greater and the maximum temperature rise was only about 90°F at about 8 minutes. It may be noted that the air flow through charcoal is normally about 40 ft/min or greater and further that the ignition point of charcoals normally in use exceed 600°F.

Example 3 - In recirculating adsorber systems the iodine loading will be more gradual than assumed in Example 1. Using Eq. (16), the loading characteristics for various air flows were computed and are illustrated in Fig. 8. This sequence is referred to as "gradual loading." As the air flow rate increases two effects are noted. First the factor in the computer code which controls the loading rate, allows the heat generation rate to increase because iodine is being removed from the containment volume and deposited on the charcoal with less decay. At the same time, the greater air flow increases the heat removal rate and tends to limit the temperature rise. In Fig. 9 the maximum temperature in the charcoal adsorber is plotted against time for air velocities of 2, 4, 10, and 20 ft/min.

Comparison of the effects of "instant" vs "gradual iodine loading" for air velocities of 4 and 20 ft/min may be made with the aid of Fig. 10. Gradual loading lowers the maximum temperature rise by 210°F at 4 ft/min air velocity.

Example 4 - The first two examples demonstrate that air velocity and the schedule of iodine loading are very important parameters. This infers that the most hazardous situation might be one in which the loading

Figure 7. Maximum Charcoal Temperature vs Time for Instant Loading 10 Minutes after Shutdown.

Figure 8. Fraction of Containment Iodine Deposited on Charcoal vs Time.

Figure 9. Maximum Charcoal Temperature vs Time for Gradual Loading.

Figure 10. Temperature (max) of Charcoal vs Time - Instant and Gradual Loading.

of iodine occurred quickly and in which a low flow condition developed as a result of partial blower failure after iodine loading. Figure 11 indicates how the maximum temperature might change in that situation. Specifically the temperatures listed were calculated assuming a normal flow (40 ft/min) for long enough to load 95% of the iodine which would eventually be loaded and then assuming a reduction to a flow of 4 ft/min after that. As can be seen, the maximum temperature rise was not extreme.

Example 5 - The volumetric heat transfer coefficient (H) is calculated for each air flow rate entered in the computer code and the result is applied to determine the transfer of heat from the charcoal to the air. The computer code was used to compare the temperature distribution in the charcoal, using the (H) value calculated by the equations considered to be most representative in lieu of measured values, and using an (H) value reduced by a factor of 10. These two values of (H) were used for 2, 4, and 10 ft/min. Figure 12 is a plot of the maximum temperature vs time under these conditions. As expected there is practically no difference in the two cases for low air flow because the capacity of the air for heat is quickly reached and the air temperature becomes the controlling factor. At increased air velocities the effect of (H) becomes more apparent. As noted earlier in this report, values of (H) were measured in the lab and will be reported in a future report.

Example 6 - The previous examples have utilized the maximum temperature irrespective of the location within the charcoal mass. If the charcoal slab is subdivided as in Fig. 13 then temperature can be calculated at desired locations by use of CHART-B. Figure 13 illustrates maximum temperature at the center and the corner of a charcoal slab.

Example 7 - This calculation illustrates the surface temperature profile of a charcoal slab along the lines 1, 2, 3, 4, and 5, as illustrated in Fig. 14. It is noted that temperature profiles are comparable to within 3 inches of edge of charcoal slab.

Example 8 - In this calculation we apply CHART-B to a once-through charcoal adsorber system. For purposes of this illustration a hypothetical reactor and adsorber system was defined as: power level, 350 Mw(t); iodine release, 25% of inventory with 90% as I_2 and 10% as CH_3I ; transit time between core and charcoal, 10 minutes; size of adsorber system,

Figure 11. Maximum Charcoal Temperature vs Time for High Air Flow Followed by Low Air Flow.

Figure 12. Temperature (Max.) of Charcoal vs Time-Effect of Change (H).

Figure 13. 3-Dimensional Slab Calculation, Maximum Temperature vs Time.

Figure 14. Surface Temperature of Charcoal Slab.

600 ft² face area by 2 inches depth; normal linear velocity of air, 40 ft/min; abnormal linear velocities of 20 and 4 ft/min; efficiency of charcoal, 99%. The temperature response of the charcoal under instant loading conditions is given in Fig. 15. The manner in which these calculations were made is detailed in Appendix D.

Example 9 - Calculations of the quantities of iodine available were made assuming (1) only the iodine released directly from the fuel reaches the charcoal or (2) all the iodine, including that produced by decay of tellurium after reactor shutdown, reaches the charcoal; this was accomplished through use of a computer code called ORIGEN¹³. Other assumptions include: (1) 25% of iodine inventory in a 3000 Mw(t) reactor reaches containment 10 minutes after shutdown, (2) iodine is deposited on 2800 ft² of charcoal adsorber (with a 2 inch depth of charcoal) at a rate such that 95% of the total iodine eventually deposited is deposited in about 100 minutes. The results are contained in Fig. 16. By including that iodine produced by decay of tellurium (after shutdown) the heating load at its maximum is increased by about 19%.

VI. COOLING THE CHARCOAL ADSORBER BY NATURAL AIR CONVECTION

A model reactor complex has been described earlier in this report and used for the development of computer codes to calculate the temperature distribution caused by the decay heat of the radioactive iodines adsorbed on the charcoal adsorbers. These calculations show that air flow rates as low as 4 ft/min can effectively remove the decay heat from charcoal adsorbers. The very important question that remains is the consequences of no forced air flow through the charcoal adsorbers. Can the natural means of heat transfer dissipate the decay heat through the air exit duct and the walls of the adsorber? To answer this question some preliminary calculations were made to determine the rate that heat can be dissipated from a model adsorber when the charcoal is at a temperature of 475°F. A further consideration is given to enhancing the natural flow of air through the charcoal by adding a stack near the exit of the charcoal adsorber.

In order to check the possibility of cooling the charcoal adsorbers by natural convection some rough calculations have been made for steady state conditions.

Figure 15. Maximum Temperature vs Time.

Figure 16. Decay Power of Fission Product Iodine vs Time from 3000 Mw(t) Reactor.

The driving force by natural convection is

$$\Delta P = Z(\rho_c - \rho_h) \quad (30)$$

where

ΔP = driving pressure in lb_f/ft^2

Z = elevation of unit

ρ_c = density of air at cold side (bottom of unit)

ρ_h = density of air at hot side (top of unit).

The driving pressure required on the pressure resistance through the bed can be calculated by

$$\Delta P = 2.8508 \times 10^{-5} \left(\frac{L \mu V_g F_f}{g_c D_p^2 F_{Re}} \right). \quad (31)$$

The correct gas velocity will be achieved by balancing the driving force with the pressure drop required. Equating Eqs. (30) and (31), we get then

$$V_g = \frac{g_c D_p^2 F_{Re} Z(\rho_c - \rho_h)}{2.8508 \times 10^{-5} L \mu F_f} \quad (32)$$

where

Z = distance separating the cold air and hot air - 6.75 ft

ρ_c = density of air at 100°F = $0.07087 \text{ lb}/\text{ft}^3$

ρ_h = density of air at exit conditions of 475°F = $0.0420 \text{ lb}/\text{ft}^3$

g_c = $32.17 \text{ ft}/\text{sec}^2$

D_p = $0.00517^2 = 0.00002673 \text{ ft}^2$

F_{Re} = 48.0

L = total bed thickness = $18 \times (2/12) = 3.0 \text{ ft}$

μ = $0.04594 \text{ lb}/\text{ft-hr}$

F_f = 1500.0

Substituting the above values in Eq. (32) gives for the natural gas velocity

$$V_g = 0.2626 \text{ ft}/\text{min} = 15.76 \text{ ft}/\text{hr}.$$

The heat transferred to the cooling air can be calculated by

$$q_g = W C_p (T_h - T_c) = V_g \rho_a C_p (T_h - T_c). \quad (33)$$

To this, one can add the heat lost from the duct surface to the ambient atmosphere by natural convection and radiation as

$$q_w = CA_w(T_w - T_c)^{1.33} + \epsilon A_w \sigma (T_w^4 - T_c^4) \quad (34)$$

where

W = rate of flow of air in lb/min

C_p = specific heat of air = 0.245 Btu/lb-°F

A_w = external surface of the duct around the adsorber = 40 ft²

T_h = hot exit temperature of cooling air = 475°F

T_c = cold or ambient temperature = 560°R (100°F)

T_w = average temperature of the wall = 747°R (287°F)

ϵ = emissivity of wall surface = 0.5

C = empirical constant for natural convection = 0.221

σ = Steffan-Boltzmann constant = 0.173×10^{-8} Btu/hr-ft-°R⁴.

It was assumed here that the ambient temperature is 100°F (which is an optimistic value) and that the exit temperature of the cooling air at the top is allowed to reach the temperature limit of 475°F. The adsorber container itself is assumed to contain three columns of adsorber units with 18 charcoal slabs in each column. The size of the duct around the adsorber is taken to be 31-1/2 in. high, 83-1/2 in. wide and 28 in. deep. This gives about 40 ft² of external surface area around the duct and 12 ft² flow area of the gas in vertical direction. Based on the above assumptions, we can have an estimate of the amount of cooling that can be expected by natural means and without using a stack.

The heat transferred to the air using Eq. (33) is then

$q = WC_p \Delta T = V_g \rho A C_p \Delta T = 15.76 (0.0564) (12) (0.245) (375) = 980$ Btu/hr
and the heat transferred to ambient air using Eq. (34) will be

$$\begin{aligned} q_w &= 0.221 \times 40 \times 182^{1.333} + 0.5 \times 40 \times 0.173 \times 10^{-8} (742^4 - 560^4) \\ &= 9101 + 7085 = 16,186 \text{ Btu/hr.} \end{aligned}$$

So the total heat loss by natural means will be

$$q_t = q_g + q_w = 980 + 16,186 = 17,166 \text{ Btu/hr} = 5.03 \text{ Kw.}$$

The total maximum heat generation in the model adsorber for 27 charcoal trays was computed to be 56.5 Kw using the assumed reactor system. This means that even with optimistic assumptions the heat nominally assumed to be generated in the charcoal bed cannot be removed by normal air convection around the adsorber container.

Since only a small fraction of the total heat can be removed from the adsorber by natural convection, it might be desirable to increase the thermal buoyancy by adding an emergency stack to the system. The pressure loss through the system is the sum of the pressure drop through the ductwork, the bed and stack. If the emergency stack can be located close enough to the bed and an opening provided to the outside air, then the pressure drop in the ductwork can be ignored and the total ΔP will then be equal to the sum of the frictional resistances in the stack and in the bed plus 1-1/2 velocity heads based on the bed velocity plus 1-1/2 velocity heads based on the stack velocity.

A program was written in X-Tran for the Com-Share Computer called STACK which calculates the fraction of the maximum heat generated from the peak heat generation rate on a steady state basis for any given ambient temperature, stack height, and diameter. A listing of this program appears in Appendix E. Calculations are based on Eqs. (35) and (36). The results of this program are shown in Fig. 17 for ambient temperature of 100°F stack heights from 0 to 100 ft and stack diameters from 1.0 to 4.0 ft where the total maximum heat generation for the total adsorber is 732 Kw. Figure 18 gives the same data for ambient temperature of 240°F.

Results indicate that a stack 3 feet in diameter and 35 feet in height would control the heat generation under an assumed ambient temperature of 100°F; for an ambient temperature of 240°F the dimensions would be 4 feet in diameter and 70 feet in height.

VII. SUMMARY

In this report two major objectives have been pursued. One, to suggest a method which might be applied to do a thermal analysis of a charcoal adsorber and two, to provide calculational means to apply the analysis. Specifically, the points itemized below have been presented.

1. A description of an assumed reactor complex with the necessary details to place the charcoal adsorber of the system in context so it will be seen as part of the whole system while considering the likelihood of its becoming heated by the decay heat of the iodine.

Figure 17. Fraction of Heat Removed vs Height of Stack.

Figure 18. Fraction of Heat Removed vs Height of Stack.

2. The all important consideration of the quantity of iodines which will be adsorbed on the charcoal. In this connection it is emphasized strongly that any statement as to the amount of iodine available for adsorption must be presented as a function of time.

The source of the iodine activity is defined, in the main, as the iodine present in the reactor at the time of the postulated accident but the radioactive decay of tellurium provides a source which continues to produce iodine after the reactor is shutdown. The extent to which the daughters of the tellurium isotopes should be included was not pursued but a calculation was made to illustrate the contribution of this mode of iodine production to the entire iodine inventory.

3. Advantage has been taken of the time intervals which are inherent in the span of time from reactor shutdown to the time when the charcoal adsorbers have adsorbed that quantity of iodine which can be a threat to the charcoal. Since in the early minutes after reactor shutdown the iodine isotopes decay very rapidly, the heat generating power is also decreasing at a rapid rate and so reduces the maximum heat load that can accumulate on the charcoal.
4. Computational procedures have been developed for use in estimating the temperature distribution in charcoal adsorbers. Three different mathematical models have been taken to analyze the problem. Computer codes were developed for the study and are briefly described.

ENIS Code

An analytical solution of the differential equation was accomplished by assuming that the temperature of air moving rapidly through the bed would not increase significantly. This code is not useful for low flows which are of most interest. It is useful, however, to make any studies of interest at high air flow rates and in this work provides a check on the numerical method.

CHART Code

A numerical method, employing a general heat program for the computer, was used to solve the heat distribution problem resulting from iodine decay heat in a three-dimensional slab of charcoal. This code was used in three ways:

CHART A: Used to compare results with output from ENIS code; does not allow temperature of gas, T_g , to change.

CHART B: Used for calculations with "Infinite Slab" and "3-dimensional Slab" models; true heat capacity of gas must be used as T_g changes.

CHART C: Used with the "3-Dimensional Unit" model; this was not fully operational at present time.

5. A calculational procedure has been developed for estimating the maximum heat which the charcoal adsorber can lose by natural means when no air is flowing through the system.
6. It was found that a vertical air duct (chimney) made a part of the adsorber exit and extending well up into the containment can create a natural air flow which will remove the maximum heat generated in the adsorber. The mathematical calculation for this consideration is presented along with a computer program (STACK) for solving the problem.
7. Details for the mathematical developments have been included as appendices.

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APPENDICES

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Appendix A. Analytical Solution of the Diffusion Equation for the Infinite Slab Model (Derivation of Equation 23)

I. Solution by Green's Theorem

The diffusion equation and its boundary conditions for the infinite slab model (Eq. 22) are given as

$$\rho_b C_p \frac{1}{\alpha} \frac{\partial \psi}{\partial t} = k_b \frac{\partial^2 \psi}{\partial x^2} + q'''(x, t)$$

Initial condition: $\psi(x, 0) = 0$

Boundary condition 1: $\frac{\partial \psi}{\partial x}(0, t) = 0$

Boundary condition 2: $\frac{\partial \psi}{\partial x}(\ell, t) = 0$

where

$$q'''(x, t) = +Be^{-bx} \sum_{i=1}^m a_i e^{-\beta_i t} + G \sum_{i=1}^m g_i e^{-\beta_i t}. \quad (A-1)$$

(For simplicity the double exponential $B_1 e^{-b_1 x} + B_2 e^{-b_2 x}$ was replaced by Be^{-bx} since the procedure of solution is the same.)

Here the one-dimensional Green theorem for conduction* can be used where instead of initial temperature $f(x, t)$ we have heat generation $A(x, t)$ per unit time, per unit volume. We get then:

$$\psi(x, t) = \int_0^t \int_0^\ell u(x, x', t-\tau) \frac{q'''(x', \tau)}{\rho_b C_p} dx' d\tau \quad (A-2)$$

where $u(x, t-\tau)$ is the corresponding Green function for instantaneous plane source of unit strength at $t = 0$ and at x' , for a slab $0 \leq x \leq \ell$ with no heat flow over the boundaries $x = \pm \ell$.

The required Green function is:

$$u(x, t-\tau) = \frac{1}{\ell} \left[1 + 2 \sum_{n=1}^{\infty} e^{-\frac{\alpha n^2 \pi^2}{\ell^2} (t-\tau)} \cos \frac{n\pi x}{\ell} \cos \frac{n\pi x'}{\ell} \right].$$

Substituting this equation into Eq. (A-2) we get

*Carslaw, H. W. and Jaeger, J. C., "Conduction of Heat in Solids," Oxford University Press, 1959, Paragraph 14.3III(7).

$$\begin{aligned}
 \psi(x,t) &= \int_0^t \int_0^{\ell} \frac{q'''(x',\tau)}{\ell \rho_b C_{p_b}} \left[1 + 2 \sum_{n=1}^{\infty} e^{-\alpha n^2 \pi^2 (t-\tau) / \ell^2} \cos \frac{n\pi x}{\ell} \cos \frac{n\pi x'}{\ell} \right] dx' d\tau \\
 &= \frac{1}{\rho_b C_{p_b} \ell} \int_0^t \int_0^{\ell} q'''(x',\tau) dx' d\tau + \frac{2}{\rho_b C_{p_b} \ell} \sum_{n=1}^{\infty} \\
 &\quad \int_0^{\ell} e^{-\frac{\alpha n^2 \pi^2}{\ell^2} (t-\tau)} \cos \frac{n\pi x}{\ell} \int_0^{\ell} q'''(x',\tau) \cos \frac{n\pi x'}{\ell} dx' d\tau. \quad (A-3)
 \end{aligned}$$

Using Eq. (A-1), we get:

$$\int_0^{\ell} q'''(x',\tau) dx' = G \ell \sum_{i=1}^m g_i e^{-\beta_i \tau} + \frac{B}{b} (1 - e^{-b\ell}) \sum_{i=1}^m a_i e^{-\beta_i \tau} \quad (A-4)$$

and

$$\begin{aligned}
 \int_0^{\ell} q'''(x',\tau) \cos \frac{n\pi x'}{\ell} dx' &= G \sum_{i=1}^m g_i e^{-\beta_i \tau} \left[\sin \frac{n\pi x'}{\ell} \right]_0^{\ell} \frac{\ell}{n\pi} \\
 &+ B \left(\sum_{i=1}^m a_i e^{-\beta_i \tau} \right) \int_0^{\ell} e^{-bx} \cos \frac{n\pi}{\ell} x' dx' \\
 &= B \left(\sum_{i=1}^m a_i e^{-\beta_i \tau} \right) \left[\frac{e^{-bx'}}{b^2 + \left(\frac{n\pi}{\ell}\right)^2} \left(-b \cos \frac{n\pi x'}{\ell} + \frac{n\pi}{\ell} \sin \frac{n\pi}{\ell} x' \right) \right]_0^{\ell} \\
 &= B \left(\sum_{i=1}^m a_i e^{-\beta_i \tau} \right) \left[\frac{-b(-1)^n e^{-b\ell} + b}{b^2 + \left(\frac{n\pi}{\ell}\right)^2} \right] \\
 &= bB \left(\sum_{i=1}^m a_i e^{-\beta_i \tau} \right) \left[\frac{1 - (-1)^n e^{-b\ell}}{b^2 + \left(\frac{n\pi}{\ell}\right)^2} \right]. \quad (A-5)
 \end{aligned}$$

Substituting Eq. (A-4) and (A-5) into Eq. (A-3), we get:

$$\begin{aligned}
 \psi(x,t) &= \int_0^t \left[\frac{G}{\rho_b C p_b} \sum_{i=1}^m g_i e^{-\beta_i \tau} + \frac{B}{\ell \rho_b C p_b} (1 - e^{-b\ell}) \sum_{i=1}^m a_i e^{-\beta_i \tau} \right. \\
 &\quad \left. + \frac{2bB}{\rho_b C p_b \ell} \left(\sum_{i=1}^m a_i e^{-\beta_i \tau} \right) \sum_{n=1}^{\infty} \frac{1 - (-1)^n e^{-b\ell}}{b^2 + \left(\frac{n\pi}{\ell}\right)^2} e^{-\alpha n^2 \pi^2 / \ell^2 (t-\tau)} \cos \frac{n\pi x}{\ell} \right] d\tau \\
 \psi(x,t) &= \frac{G}{\rho_b C p_b \ell} \sum_{i=1}^m g_i \int_0^t e^{-\beta_i \tau} d\tau + \frac{B(1 - e^{-b\ell})}{\rho_b C p_b b \ell} \sum_{i=1}^m a_i \int_0^t e^{-\beta_i \tau} d\tau \\
 &\quad + \frac{2Bb}{\rho_b C p_b \ell} \sum_{n=1}^{\infty} \frac{(1 - (-1)^n e^{-b\ell})}{b^2 + \left(\frac{n\pi}{\ell}\right)^2} \cos \frac{n\pi x}{\ell} \sum_{i=1}^m a_i \int_0^t e^{-\beta_i \tau - \frac{\alpha n^2 \pi^2}{\ell^2} (t-\tau)} d\tau \\
 \int_0^t e^{-\beta_i \tau} d\tau &= \left[-\frac{1}{\beta_i} e^{-\beta_i \tau} \right]_0^t = \frac{1}{\beta_i} (1 - e^{-\beta_i t}) \\
 \int_0^t e^{-\frac{\alpha n^2 \pi^2}{\ell^2} t - (\beta_i - \frac{n^2 \pi^2 \alpha}{\ell^2}) \tau} d\tau &= \frac{e^{-\beta_i t} - e^{-\alpha n^2 \pi^2 t / \ell^2}}{\alpha - \beta_i} \quad (A-6)
 \end{aligned}$$

Substituting back into Eq. (A-6), we get:

$$\begin{aligned}
 \psi(x,t) &= \frac{G}{\rho_b C p_b} \sum_{i=1}^m \frac{g_i}{\beta_i} (1 - e^{-\beta_i t}) + \frac{B(1 - e^{-b\ell})}{\rho_b C p_b b \ell} \sum_{i=1}^m \frac{a_i}{\beta_i} (1 - e^{-\beta_i t}) \\
 &\quad + \frac{2Bb}{\rho_b C p_b \ell} \sum_{n=1}^{\infty} \frac{[1 - (-1)^n e^{-b\ell}]}{b^2 + \left(\frac{n\pi}{\ell}\right)^2} \cos \frac{n\pi x}{\ell} \sum_{i=1}^m \frac{a_i (e^{-\beta_i t} - e^{-\alpha n^2 \pi^2 t / \ell^2})}{\frac{\alpha n^2 \pi^2}{\ell^2} - \beta_i}
 \end{aligned}$$

Remembering from Eq. (21) that

$$T_b'(x,t) = T_b(x,t) - T_g = \psi(x,t) e^{-\alpha(H/k)t}$$

and from Eq. (22a) that

$$\beta_i = \lambda_i - \alpha(H/k),$$

we can get the solution for T_b' as given in Eq. (23) in the report.

II. Solution by Fourier Consine Series Expansion

Again the diffusion equation is given by:

$$\frac{\partial^2 \psi(x,t)}{\partial x^2} - \frac{1}{\alpha} \frac{\partial \psi(x,t)}{\partial t} = \frac{P}{k} e^{-bx} \sum_{i=1}^m a_i e^{-\beta_i t} - \frac{G}{k} \sum_{i=1}^m g_i e^{-\beta_i t}. \quad (A-8)$$

The boundary conditions are:

$$(a) \psi(x,0) = 0$$

$$(b) \frac{\partial \psi}{\partial x} \Big|_{x=0} = 0.$$

We expand the solution (if any) in a Fourier cosine series.

$$\psi(x,t) \sim \sum_{n=0}^{\infty} c_n(t) \cos \frac{n\pi x}{l}$$

where

$$c_n(t) = \frac{2}{l} \int_0^l \psi(x,t) \cos \frac{n\pi x}{l} dx.$$

The set of all $c_n(t)$ uniquely determines $\psi(x,t)$ and is called the finite cosine transform of $\psi(x,t)$. We assume $\partial^2 \psi(x,t) / \partial x^2$ is continuous and get:

$$\begin{aligned} \frac{2}{l} \int_0^l \frac{\partial^2 \psi(x,t)}{\partial x^2} \cos \frac{n\pi x}{l} dx &= \frac{2}{l} \left[\frac{\partial \psi(x,t)}{\partial x} \cos \frac{n\pi x}{l} \right]_0^l \\ &+ \frac{2}{l} \left[\frac{n\pi}{l} \int_0^l \frac{\partial \psi(x,t)}{\partial x} \sin \frac{n\pi x}{l} dx \right]. \end{aligned}$$

The first term is zero since $\frac{\partial \psi}{\partial x} \Big|_{x=0} = 0$.

$$\frac{n\pi}{l} \int_0^l \frac{\partial \psi(x,t)}{\partial x} \sin \frac{n\pi x}{l} dx = \frac{n\pi}{l} \left[\psi(x,t) \sin \frac{n\pi x}{l} \right]_0^l - \frac{n^2 \pi^2}{l^2} \int_0^l \psi(x,t) \cos \frac{n\pi x}{l} dx.$$

Therefore:

$$\frac{2}{l} \int_0^l \frac{\partial^2 \psi(x,t)}{\partial x^2} \cos \frac{n\pi x}{l} dx = - \frac{n^2 \pi^2}{l^2} \left[\frac{2}{l} \int_0^l \psi(x,t) \cos \frac{n\pi x}{l} dx \right]$$

Therefore the cosine transform of

$$\frac{\partial^2 \psi(x,t)}{\partial x^2} = - (n\pi/l)^2 c_n(t).$$

$$\frac{2}{l} \int_0^l \frac{\partial \psi(x,t)}{\partial t} \cos \frac{n\pi x}{l} dx = \frac{\partial}{\partial t} \left[\frac{2}{l} \int_0^l \psi(x,t) \cos \frac{n\pi x}{l} dx \right] = \frac{dc_n(t)}{dt}.$$

Therefore the equation to be solved to find the cosine transform is:

$$- (n\pi/l)^2 c_n(t) - \frac{1}{\alpha} \frac{dc_n(t)}{dt} = A_n(t). \quad (A-9)$$

where

$$A_n(t) = \frac{2}{l} \int_0^l \left[-\frac{B}{K} e^{-bx} \sum_{i=1}^m a_i e^{-\beta_i t} - \frac{G}{k} \sum_{i=1}^m g_i e^{-\beta_i t} \right] \cos \frac{n\pi x}{l} dx.$$

Rewrite (A-9) to get:

$$\frac{dc_n(t)}{dt} + \alpha(n\pi/l)^2 c_n(t) = -\alpha A_n(t)$$

then:

$$e^{(n\pi/l)^2 t} \frac{dc_n(t)}{dt} + \alpha \left(\frac{n\pi}{l}\right)^2 c_n(t) e^{\alpha(n\pi/l)^2 t} = -\alpha A_n(t) e^{\alpha(n\pi/l)^2 t}. \quad (A-10)$$

Note that:

$$\begin{aligned} \frac{d}{dt} [e^{\alpha(n\pi/l)^2 t} c_n(t)] &= e^{\alpha(n\pi/l)^2 t} \frac{d}{dt} c_n(t) \\ &+ \alpha \left(\frac{n\pi}{l}\right)^2 c_n(t) e^{\alpha(n\pi/l)^2 t}. \end{aligned}$$

Then Eq. (A-10) can be written, using $t = \tau$,

$$\frac{d}{d\tau} [e^{\alpha(n\pi/l)^2 \tau} c_n(\tau)] = -\alpha A_n(\tau) e^{\alpha(n\pi/l)^2 \tau}.$$

Integrating from 0 to τ gives:

$$e^{\alpha (n\pi/\ell)^2 t} c_n(t) - c_n(0) = \int_0^t -\alpha A_n(\tau) e^{\alpha (n\pi/\ell)^2 \tau} d\tau \quad (A-11)$$

$$c_n(t) = - e^{-\alpha (n\pi/\ell)^2 t} \int_0^t A_n(\tau) e^{\alpha (n\pi/\ell)^2 \tau} d\tau$$

(The condition $\psi(x,0) = 0$ requires that $c_n(0) = 0$. For $n = 0$ Eq. (A-9) becomes:

$$\frac{dc_0(t)}{dt} = -\alpha A_0(t)$$

or

$$c_0(t) - c_0(0) = -\alpha \int_0^t A_0(\tau) d\tau$$

which is in agreement with Eq. (A-11). To evaluate the integral in (A-11) we first find $A_n(t)$.

$$A_n(t) = \frac{-2B}{\ell k} \sum_{i=1}^m a_i e^{-\beta_i t} \int_0^{\ell} e^{-bx} \cos \frac{n\pi x}{\ell} dx - \frac{2G}{k\ell} \sum_{i=1}^m g_i e^{-\beta_i t} \int_0^{\ell} \cos \frac{n\pi x}{\ell} dx$$

For $n \neq 0$:

$$\begin{aligned} \int_0^{\ell} e^{-bx} \cos \frac{n\pi x}{\ell} dx &= \left[\frac{e^{-bx}}{b^2 + \left(\frac{n\pi}{\ell}\right)^2} \left(-b \cos \frac{n\pi x}{\ell} + \frac{n\pi}{\ell} \sin \frac{n\pi x}{\ell} \right) \right]_0^{\ell} \\ &= \frac{b}{b^2 + \left(\frac{n\pi}{\ell}\right)^2} (1 - (-1)^n e^{-b\ell}) \end{aligned}$$

and

$$\int_0^{\ell} \cos (n\pi x/\ell) dx = 0.$$

For $n = 0$:

$$\int_0^{\ell} e^{-bx} \cos (n\pi x/\ell) dx = \int_0^{\ell} e^{-bx} dx = (1/b)(1 - e^{-b\ell})$$

and

$$\int_0^{\ell} \cos (n\pi x/\ell) dx = \ell.$$

For $n \neq 0$:

$$\int_0^t A_n(\tau) e^{i(n\pi/\alpha)^2 \tau} d\tau = \frac{-2Bb}{lk} \frac{1 - (-1)^n e^{-b\ell}}{b^2 + (\frac{n\pi}{\ell})^2} \sum_{i=1}^m a_i \int_0^t e^{[\alpha(n\pi/\ell)^2 - \beta_i] \tau} d\tau$$

$$= \frac{-2Bb}{lk} \frac{1 - (-1)^n e^{-b\ell}}{b^2 + (\frac{n\pi}{\ell})^2} \sum_{i=1}^m a_i \left[\frac{e^{\alpha(n\pi/\ell)^2 t} - e^{-\beta_i t}}{\alpha(n\pi/\ell)^2 - \beta_i} \right]$$

For $n = 0$:

$$\int_0^t A_0(\tau) d\tau = \frac{-B}{lk b} (1 - e^{-b\ell}) \sum_{i=1}^m a_i \int_0^t e^{-\beta_i \tau} d\tau$$

$$= \frac{G}{k} \sum_{i=1}^m g_i \int_0^t e^{-\beta_i \tau} d\tau$$

From (A-11) we have:

$$c_n(t) = -\alpha e^{-\alpha(\frac{n\pi}{\ell})^2 t} \int_0^t A_n(\tau) e^{\alpha(n\pi/\ell)^2 \tau} d\tau$$

Therefore

$$= \alpha e^{-\alpha(n\pi/\ell)^2 t} \frac{2Bb}{lk} \frac{1 - (-1)^n e^{-b\ell}}{b^2 + (\frac{n\pi}{\ell})^2} \sum_{i=1}^m a_i \left[\frac{e^{[\alpha(n\pi/\ell)^2 - \beta_i] t} - 1}{\alpha(n\pi/\ell)^2 - \beta_i} \right]$$

Therefore:

$$c_n(t) = \frac{2\alpha Bb}{lk} \frac{1 - (-1)^n e^{-b\ell}}{b^2 + (\frac{n\pi}{\ell})^2} \sum_{i=1}^m a_i \left[\frac{e^{-\beta_i t} - e^{-\alpha(n\pi/\ell)^2 t}}{\alpha(n\pi/\ell)^2 - \beta_i} \right]$$

and

$$c_0(t) = -\alpha \int_0^t A_0(\tau) d\tau = -\frac{B\alpha}{lk b} (1 - e^{-b\ell}) \sum_{i=1}^m \frac{a_i}{\beta_i} (e^{-\beta_i t} - 1)$$

$$= \frac{C\alpha}{k} \sum_{i=1}^m \frac{g_i}{\beta_i} (e^{-\beta_i t} - 1).$$

For $t = 0$ both of these quantities are 0 so the boundary condition $(x, 0) = 0$ is satisfied. Finally we get then:

$$\begin{aligned} \psi(x,t) = & \frac{-B}{b\rho_b C p_b \ell} (1 - e^{-b\ell}) \sum_{i=1}^m \frac{a_i}{\beta_i} (e^{-\beta_i t} - 1) \\ & - \frac{G}{\rho_b C p_b} \sum_{i=1}^m \frac{g_i}{\beta_i} (e^{-\beta_i t} - 1) + \frac{2Bb}{\rho_b C p_b \ell} \sum_{n=1}^{\infty} \\ & \left[\frac{1 - (-1)^n e^{-b\ell}}{b^2 + \left(\frac{n\pi}{\ell}\right)^2} \cos \frac{n\pi x}{\ell} \sum_{i=1}^m a_i \left[\frac{e^{-\beta_i t} - e^{-\alpha(n\pi/\ell)^2 t}}{\alpha \left(\frac{n\pi}{\ell}\right)^2 - \beta_i} \right] \right] \end{aligned} \quad (A-12)$$

Equation (A-12) is the same as Eq. (A-7) and here too we can substitute

$$T_b(x,t) - T_g = Q(x,t) = \psi(x,t) e^{-\alpha(H/k)t}$$

and

$$\beta_i = \lambda_i - \alpha(H/k)$$

to get the solution appearing in Eq. (31) in the report.

Note: Both Eqs. (A-7) and (A-11) are solutions for the single exponential Be^{-bx} . The solution for double exponential $B_1 e^{-b_1 x} + B_2 e^{-b_2 x}$ is reached the same way.

ENIS Code

LEVEL 18 (SEPT 69)

05/360 FORTRAN H

DATE 71.055/18.CB.30

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COMPILER OPTIONS = NAME= MAIN,CPT=00,LINECT=40,SOURCE,EBCDIC,NOLIST,NODECK,LCAD,MAP,NOEDIT,ACIC,XREF
COHAKCOAL IGNITION STUDIES
ISN 0002      REAL*8 AA(7)/0.214200,1.521500,4.666901,1.783250,1.764470,
              , 4.154270,1.519800, GG(7)/0.379520,1.196601,1.034440,
              , 8.182220,2.022470, 1.331460,7.795300, LAMBDA(7)/2.76670-2,
              , 9.25620-4,5.97450-5,5.02450-3,5.80050-4, 1.30750-2,1.72530-3, L/CHAR 20
              , 2.0000, SMALB1/9.210400, SB1SC, RCNFI, PICVL, SMALB2/1.020400, CHAR 25
              , SB2SC, RTWOL, K/1.66670-4, ALPHA/4.1140-2, BTACHG, ALFHDK(4), CHAR 30
              , FACT, APICVL, APILSQ, CEXH, CURSUM(5), TIME(100), BETA(6,7), CHAR 35
              , SLMB, CEX1(7), EXHADD, H(6), EX3, X(5), ANGLE, TMDLAY, TCHNGE(7)/CHAR 40
              , 7*1.0070, TIMES, DELTAT, A(7), G(7), EXCHNG(7), TMLAC, TTIME, CHAR 45
              , ALPHA, AMPILS, SHIBP1, SB2RP2, EXPHIL, EXPB2L,EXH
ISN 0003      INTEGER*4 PLTAC/0/ CHAR 55
ISN 0004      DIMENSION CLCMP(7), TCFXY(100,5), TSTART(5) CHAR 60
ISN 0005      10 READ(5,1000) F(1), DELTAT, TMDLAY, (X(I),I=1,5), IPLOT, CHAR 65
              , ISWTC, HIGH1, HIGH2, BIGG CHAR 70
ISN 0006      RCNFI = -SMALP1*L CHAR 75
ISN 0007      RTWOL = -SMALH2*L CHAR 80
ISN 0008      SHIBP1 = SMALB1*HIGH1 CHAR 85
ISN 0009      SB2RP2 = SMALB2*HIGH2 CHAR 90
ISN 0010      SB1SC = SMALH1*L*2 CHAR 95
ISN 0011      SB2SC = SMALH2*L*2 CHAR 100
ISN 0012      EXPHIL = DEXP(RCNFI) CHAR 105
ISN 0013      EXPB2L = DEXP(RTWOL) CHAR 110
ISN 0014      PICVL = 3.141592657/L CHAR 115
ISN 0015      IF (ISWTC) 20,40,20 CHAR 120
ISN 0016      20 ISWTC = ISWTC + 1 CHAR 125
ISN 0017      DO 30 I=2,ISWTC CHAR 130
ISN 0018      READ(5,10100) F(I),TCHNGE(I) CHAR 135
ISN 0019      30 CONTINUE CHAR 140
ISN 0020      40 ALPHA = ALPHA/K CHAR 145
ISN 0021      DO 40 I=1,ISWTC CHAR 150
ISN 0022      ALFHDK(I) = ALPHA*K*F(I) CHAR 155
ISN 0023      DO 50 J=1,7 CHAR 160
ISN 0024      50 BETA(I,J) = LAMBDA(J) - ALFHDK(I) CHAR 165
ISN 0025      60 CONTINUE CHAR 170
ISN 0026      WRITE(6,10200) F(1), TMDLAY, (X(I),I=1,5) CHAR 175
ISN 0027      TMDLAY = TMDLAY*(40.000) CHAR 180
ISN 0028      CONST1 = -ALPHA*(HIGH1*(1.0 - EXPHIL)/SMALH1 + BIGG2*(1.0 - CHAR 185
              , EXPB2L)/SMALP2)/(K*L) CHAR 190
ISN 0029      CONST2 = -ALPHA*BIGG/K CHAR 195
ISN 0030      CONST3 = 2.0*ALPHA/(K*L) CHAR 200
ISN 0031      DO 70 JX=1,5 CHAR 205
ISN 0032      70 TSTART(JX) = 0.0 CHAR 210
ISN 0033      IF (TMDLAY-1.0E-6) 80,80,100 CHAR 215
ISN 0034      80 DO 90 I=1,7 CHAR 220
ISN 0035      A(I) = AA(I) CHAR 225
ISN 0036      G(I) = GG(I) CHAR 230
ISN 0037      90 CONTINUE CHAR 235
ISN 0038      GO TO 120 CHAR 240
ISN 0039      100 DO 110 I=1,7 CHAR 245
ISN 0040      EXCHNG(I) = -(LAMBDA(I)*TMDLAY CHAR 250
ISN 0041      FACT = DEXP(EXCHNG(I)) CHAR 255
ISN 0042      A(I) = FACT*AA(I) CHAR 260
ISN 0043      G(I) = FACT*GG(I) CHAR 265
ISN 0044      110 CONTINUE CHAR 270
ISN 0045      120 TIMES = TIMES + DELTAT CHAR 275
ISN 0046      TCHNGE = 1 CHAR 280
ISN 0047      TMLAC = 0.000 CHAR 285

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C		INITIAL VALUES COMPLETED OR ASSIGNED.	CHAR 290
C		START MAIN CALCULATION	CHAR 295
C			CHAR 300
ISN 0044		TIME(1) = 0.100	CHAR 305
ISN 0049		DO 130 I=1,5	CHAR 310
ISN 0050		TCFXT(1,1) = 0.0	CHAR 315
ISN 0051	130	CONTINUE	CHAR 320
ISN 0052		WRITE(6,10+00) TIME(1), (TCFXT(1,JX),JX=1,5)	CHAR 325
ISN 0053		DO 230 JT=2,100	CHAR 330
ISN 0054		TIME(JT) = TIMES + DELTAT*DELCAT(JT)	CHAR 335
ISN 0055		IF (TIME(JT)-TCHNGE(ICHNGE+1)) 170,140,140	CHAR 340
ISN 0056	140	WRITE(6,20+00) H(ICHNGE+1)	CHAR 345
ISN 0057		TMLAG = - TIME(JT)	CHAR 350
ISN 0058		ICHNGE= ICHNGE + 1	CHAR 355
ISN 0059		DO 150 I=1,7	CHAR 360
ISN 0060		EXCHNG(I) = - LAMHCA(I)*TIME(JT)	CHAR 365
ISN 0061		FACT = DEXP(EXCHNG(I))	CHAR 370
ISN 0062		A(I) = FACT*A(I)	CHAR 375
ISN 0063		G(I) = FACT*G(I)	CHAR 380
ISN 0064	150	CONTINUE	CHAR 385
ISN 0065		DO 160 J=1,4	CHAR 390
ISN 0066	160	TSTACT(JX) = TCFXT(JT-1,JX)	CHAR 395
ISN 0067	170	SUM1 = 0.0	CHAR 400
ISN 0068		SUM2 = 0.0	CHAR 405
ISN 0069		TTIME = TIME(JT) + TMLAG	CHAR 410
ISN 0070		DO 180 I=1,7	CHAR 415
ISN 0071		DEX1(I) = DEXP(- LAMHCA(I)*TTIME)	CHAR 420
ISN 0072		EXH = (-ALPHCK(ICHNGE)*TTIME)	CHAR 425
ISN 0073		IF (EXH.LT.170.) EXH=-170.	
ISN 0074		DEXH = EXP(EXH)	CHAR 435
ISN 0075		RTACHG = PLTA(ICHNGE+1)	CHAR 440
ISN 0076		SUM1 = SUM1 + A(I)*(DEX1(I) - DEXH)/RTACHG	CHAR 445
ISN 0077		SUM2 = SUM2 + G(I)*(DEX1(I) - DEXH)/RTACHG	CHAR 450
ISN 0078		CONTINUE	CHAR 455
ISN 0079	180	DO 220 JX=1,5	CHAR 460
ISN 0080		OLHSUM(JX) = 0.0	CHAR 465
ISN 0081		ANGLE = -ICVL*X(JX)	CHAR 470
ISN 0082		CSTHET = COSC(ANGLE)	CHAR 475
ISN 0083		CSN = 1.000	CHAR 480
ISN 0084		CSNX = CSTHET	CHAR 485
ISN 0085		DO 200 N=1,100	CHAR 490
ISN 0086		NPICVL = PICVL*DELCAT(N)	CHAR 495
ISN 0087		NPILSC = NPICVL**2	CHAR 500
ISN 0088		ANPILS = ALPHAK*NPILSQ	CHAR 505
ISN 0089		EX3 = -(ANPILS + ALPHCK(ICHNGE))*TTIME	
ISN 0090		IF (EX3.LT.170.) EX3=-170.	
ISN 0091		SUM3 = 0.0	CHAR 510
ISN 0092		DO 190 I=1,7	CHAR 515
ISN 0093		SUM3 = SUM3 + A(I)*(DEX1(I) - DEXP(EX3)) / (ANPILS +	CHAR 520
ISN 0094		HTACHG)	CHAR 525
ISN 0095	190	CONTINUE	CHAR 530
ISN 0096		CMPE = OLHSUM(JX)	CHAR 535
ISN 0097		OLHSUM(JX) = OLHSUM(JX) + (SH1NH1*(1.000 - EXPH1) * (-	CHAR 540
ISN 0098		1.000)**N) / (NPILSC + NPILSQ) + SH2NH2* (1.000 - EXPH2) * (-	CHAR 545
		1.000)**N) / (NPILSQ + NPILSQ) * CSNX * SUM3	CHAR 550
ISN 0099		CSNN = CSN	CHAR 555
ISN 0100		CSNX = 2.000*CSNX*CSSTHET - CSN	CHAR 560

ISN 0101	CSN = CSN	CHAR 565
ISN 0102	FACT = DAHS(CFRE - DUBSUM(JX))	CHAR 570
ISN 0103	IF (FACT.LT.CFRE*1.0E-6) GO TO 210	CHAR 575
ISN 0104	CONTINUE	CHAR 580
ISN 0105	200 TCFXT(JT,JX) = CONST1*SUN1 + CONST2*SUN2 + CONST3*DUBSUM(JX)	CHAR 585
ISN 0106	210 + TSTART(JX)	CHAR 590
ISN 0107	220 CONTINUE	CHAR 595
ISN 0108	WRITE(6,10400) TIME(JT),(TCFXT(JT,JX),JX=1,5)	CHAR 600
ISN 0109	230 CONTINUE	CHAR 605
ISN 0110	IF (TIME(JT) 240,350,240	CHAR 610
ISN 0111	240 TMAX = C,0	CHAR 615
ISN 0112	DO 250 JT=1,91,10	CHAR 620
ISN 0113	TMAX = AMAX(TMAX,TCFXT(JT,1),TCFXT(JT+1,1),TCFXT(JT+2,1),	CHAR 625
	TCFXT(JT+3,1),TCFXT(JT+4,1),TCFXT(JT+5,1),TCFXT(JT+6,1),	CHAR 630
	TCFXT(JT+7,1),TCFXT(JT+8,1),TCFXT(JT+9,1))	CHAR 635
ISN 0114	250 CONTINUE	CHAR 640
ISN 0115	DO 260 JT=1,10	CHAR 645
ISN 0116	IF (TMAX-10.0**1) 270,270,260	CHAR 650
ISN 0117	260 CONTINUE	CHAR 655
ISN 0118	WRITE(6,10500)	CHAR 660
ISN 0119	GO TO 350	CHAR 665
ISN 0120	270 TMAX = 1 - 2	CHAR 670
ISN 0121	TCIV = TMAX/10.0**TMAX	CHAR 675
ISN 0122	ITCIV = IFIX(TCIV + 10.0/10)	CHAR 680
ISN 0123	DELY = FLOAT(ITCIV)*(10.0**TMAX)	CHAR 685
ISN 0124	DELY = 10.0*DELY	CHAR 690
ISN 0125	IF (TIME(JT) 280,280,290	CHAR 695
ISN 0126	280 CALL LINEAR (10.0,10.0,1,0.0,10.0,1,10.0,15,CLCMP)	CHAR 700
ISN 0127	CALL SYMBOL (10.0,9.0,20,5HALIGN,90.0,5)	CHAR 705
ISN 0128	CALL SYMBOL (15.0,0.0,20,5HALIGN,0.0,5)	CHAR 710
ISN 0129	CALL SYMBOL (11.0,4.0,40,28HSTUDIES ON CHARCOAL IGNITION,0.0,4)	CHAR 715
ISN 0130	CALL ADVANC (CLCMP)	CHAR 720
ISN 0131	PLTAC = 99	CHAR 725
ISN 0132	290 CALL LINEAR (10.0,DELY,10,0.0,DELY,10,13.0,15,CLCMP)	CHAR 730
ISN 0133	CALL SYMBOL (11.0,9.5,0.14,11HTEMPERATURE,0.0,11)	CHAR 735
ISN 0134	CALL SYMBOL (13.0,10.0,0,20,	CHAR 740
	44HTEMPERATURE VERSUS TIME IN A CHARCOAL FILTER,0.0,44)	CHAR 745
ISN 0135	CALL SYMBOL (11.0,0.0,0.14,15HTIME IN MINUTES,0.0,15)	CHAR 750
ISN 0136	CALL CURVE (11.0,0.0,0,CLCMP)	CHAR 755
ISN 0137	DO 310 JT=1,100	CHAR 760
ISN 0138	IF (TCFXT(JT,1)-TMAX) 300,300,310	CHAR 765
ISN 0139	300 CALL CURVE (2,TIME(JT),TCFXT(JT,1),CLCMP)	CHAR 770
ISN 0140	310 CONTINUE	CHAR 775
ISN 0141	CALL ADVANC (CLCMP)	CHAR 780
ISN 0142	CALL LINEAR (10.0,10.0,1,0.0,10.0,1,-10.0,15,CLCMP)	CHAR 785
ISN 0143	CALL SYMBOL (11.0,9.0,40,28HSTUDIES ON CHARCOAL IGNITION,0.0,28)	CHAR 790
ISN 0144	CALL SYMBOL (13.0,6.0,0,20,23HDATA FOR PRECEDING PLOT,0.0,23)	CHAR 795
ISN 0145	CALL SYMBOL (13.0,7.0,0,14,28HTHE ORIGINAL VALUE OF H WAS,0.0,28)	CHAR 800
ISN 0146	CALL NUMBER (16.0,7.0,0,14,H(1),0.0,7HIF(1,4))	CHAR 805
ISN 0147	CALL NUMBER (16.0,6.0,0,14,TMDELAY,0.0,6HIF(5,1))	CHAR 810
ISN 0148	CALL SYMBOL (13.0,6.0,0,14,65H7EPD TIME ON THE PLOT INDICATES	CHAR 815
	MINUTES AFTER THE INCIDENT,0.0,45)	CHAR 820
ISN 0149	IF (ISWCH) 320,340,320	CHAR 825
ISN 0150	320 CALL SYMBOL (13.0,5.0,0,14,64HTHE VALUE OF H WAS CHANGED AS INDIC	CHAR 830
	ATED BELOW AT THE GIVEN TIMES,0.0,44)	CHAR 835
ISN 0151	CALL SYMBOL (15.0,4.0,0,14,25HTIME	CHAR 840
ISN 0152	DO 330 I=2,ISWCH	CHAR 845
ISN 0153	YY = 4.0 - FLOAT(I-1)*0.5	CHAR 850

ISN 0154	CALL NUMBER (4.5,YY,0.14,TCNCE(1),0.71(F11.3))	CHAR 855
ISN 0155	CALL NUMBER (7.25,YY,0.14,H(1),J.7,F(E11.4))	CHAR 860
ISN 0156	340 CALL ADVANC (CLCMP)	CHAR 865
ISN 0157	350 DO 360 I=1,7	CHAR 870
ISN 0158	360 TCNCE(I) = 1.0070	CHAR 875
ISN 0159	GO TO 10	CHAR 880
ISN 0160	370 WRITE(6,10600)	CHAR 885
ISN 0161	380 STOP 5678	CHAR 890
ISN 0162	10000 FORMAT (30I5.6,FF7.3/2I10,1020.6)	CHAR 895
ISN 0163	10100 FORMAT (2E30.6)	CHAR 900
ISN 0164	10200 FORMAT (1H,T40,'TEMPERATURE OF FILTER AS A FUNCTION',T40,'OF POSI'CHAR 905	
	,T10, AND TIME',T10,T50,'H = VOLUMETRIC HEAT TRANSFER COEFFICIENT =CHAR 910	
	,',E12.4/1H,T10,'TIME LAG BETWEEN INCIDENT AND INSTANT AT WHICH',CHAR 915	
	,50 OF INVENTORY IS DEPOSITED ON FILTER IS ',F5.2,' HOURS',T10/1H,CHAR 920	
	,T20,'H = ',F12.2/1H,T10,'TIME')'	CHAR 925
ISN 0165	10300 FORMAT(1H,T20,	CHAR 930
	, 'VOLUMETRIC HEAT TRANSFER COEFFICIENT CHANGING TO ',F14.6)	CHAR 935
ISN 0166	10400 FORMAT (1H,F12.3,10X,FF20.6)	
ISN 0167	10500 FORMAT (1H,T20,'DATA OUTSIDE RANGE OF PLOT ROUTINE')	CHAR 945
ISN 0168	10600 FORMAT (1H,T20,'WRONG NUMBER OF DATA CARDS FOR VALUE OF ISWCH: SPCHAR 950	
	,ECIFIED')	CHAR 955
ISN 0169	END	CHAR 960

Table A-1. Input Data Required for ENIS Code

Column	Format	Variable Name	Variable Meaning	Units
<u>Card No. 1</u>				
1-15	0.XXXXXXD+XX (D15.6)	H(1)	First value of the volumetric heat transfer coefficient	Btu/min-in. ³ -°F
16-30		DELTAT	Time increment to be used for a given run	Minute
31-45		TMDLAY	The time delay before radioactive material is deposited on filter.	Hours
46-52	XXX.XXX F6.3	X(1)	Distance from leading edge of filter of the points at which the temperature is to be computed.	Inch
53-59		X(2)		
60-66		X(3)		
67-73		X(4)		
74-80		X(5)		
<u>Card No. 2</u>				
1-10	XXXXXXXXXX I10	1PLOT	Leave blank if no plots are desired. Any non-zero integer in col. 10 will cause plots to be generated.	Dimensionless
11-20		ICHNGE	Leave blank if volumetric heat transfer coefficient remains constant throughout a given case. Contains the number of <u>changes</u> , up to 5, in col. 20 otherwise.	"
21-40	0.XXXXXXD+XX (D20.6)	BIGB1	Denotes β "power" of I for the reactor under consideration.	tons of U in. ³ of bed
41-60		BIGB2	Same as BIGB1 but for CH ₃ I.	"
61-80		BIGG	Denotes γ "power" for the reactor under consideration.	"

Column	Format	Variable Name	Variable Meaning	Units
<u>Cards 3-7</u>				
0-20	0.XXXXXXE+XY E20.6	H(I)	"New" values of the volumetric heat transfer coefficient	Btu/min-in. ³ -°F
21-40		TCHNGE(I)	Time at which change to H(I) takes effect.	Minute

Table A-2. Output from ENIS Code

TEMPERATURE OF FILTER AS A FUNCTION
OF POSITION AND TIME

H = VOLUMETRIC HEAT TRANSFER COEFFICIENT = 0.11950 00
TIME LAG BETWEEN INCIDENT AND INSTANT AT WHICH 25% OF INVENTORY IS DEPOSITED ON FILTER IS 0.17 HOURS

TIME X	X =				
	0.0	0.25	0.50	1.00	2.00
0.0	0.0	0.0	0.0	0.0	0.0
0.2000 01	0.4149608 01	0.1756852 01	0.1154092 01	0.5122401 00	0.4962222 00
0.4000 01	0.4095752 01	0.1733932 01	0.1138962 01	0.5013392 00	0.4895892 00
0.6000 01	0.4043092 01	0.1711502 01	0.1124152 01	0.4987041 00	0.4830962 00
0.8000 01	0.3991562 01	0.1689572 01	0.1109662 01	0.4921502 00	0.4767402 00
0.1000 02	0.3941212 01	0.1668112 01	0.1095492 01	0.4857342 00	0.4705172 00
0.1200 02	0.3891932 01	0.1647122 01	0.1081622 01	0.4794532 00	0.4644262 00
0.1400 02	0.3843732 01	0.1626582 01	0.1068052 01	0.4733032 00	0.4584612 00
0.1600 02	0.3796572 01	0.1606442 01	0.1054772 01	0.4672812 00	0.4526212 00
0.1800 02	0.3750432 01	0.1586812 01	0.1041772 01	0.4613852 00	0.4469022 00
0.2000 02	0.3705292 01	0.1567572 01	0.1029052 01	0.4556112 00	0.4413012 00
0.2200 02	0.3661122 01	0.1548742 01	0.1016602 01	0.4499562 00	0.4358162 00
0.2400 02	0.3617902 01	0.1530302 01	0.1004412 01	0.4444182 00	0.4304432 00
0.2600 02	0.3575602 01	0.1512262 01	0.9924832 00	0.4389932 00	0.4251812 00
0.2800 02	0.3534212 01	0.1494602 01	0.9808032 00	0.4336402 00	0.4200262 00
0.3000 02	0.3493702 01	0.1477322 01	0.9693672 00	0.4283742 00	0.4149762 00
0.3200 02	0.3454042 01	0.1460302 01	0.9581692 00	0.4231742 00	0.4100292 00
0.3400 02	0.3415232 01	0.1443822 01	0.9472052 00	0.4180372 00	0.4051812 00
0.3600 02	0.3377232 01	0.1427602 01	0.9364682 00	0.4134822 00	0.4004312 00
0.3800 02	0.3340022 01	0.1411722 01	0.9259522 00	0.4088852 00	0.3957762 00
0.4000 02	0.3303602 01	0.1396162 01	0.9156532 00	0.4039832 00	0.3912142 00
0.4200 02	0.3267942 01	0.1380932 01	0.9055652 00	0.3993752 00	0.3867432 00
0.4400 02	0.3233022 01	0.1366012 01	0.8956832 00	0.3948592 00	0.3823712 00
0.4600 02	0.3198822 01	0.1351392 01	0.8860032 00	0.3904322 00	0.3780652 00
0.4800 02	0.3165322 01	0.1337082 01	0.8765192 00	0.3860932 00	0.3738542 00
0.5000 02	0.3132522 01	0.1323052 01	0.8672272 00	0.3818382 00	0.3697252 00
0.5200 02	0.3100392 01	0.1309312 01	0.8581212 00	0.3776672 00	0.3656772 00
0.5400 02	0.3068912 01	0.1295852 01	0.8491992 00	0.3735772 00	0.3617082 00
0.5600 02	0.3038082 01	0.1282662 01	0.8404552 00	0.3695662 00	0.3578162 00
0.5800 02	0.3007872 01	0.1269742 01	0.8318852 00	0.3656332 00	0.3539982 00
0.6000 02	0.2978272 01	0.1257072 01	0.8234852 00	0.3617762 00	0.3502542 00
0.6200 02	0.2949242 01	0.1244662 01	0.8152512 00	0.3579932 00	0.3465872 00
0.6400 02	0.2920842 01	0.1232492 01	0.8071792 00	0.3542812 00	0.3429792 00
0.6600 02	0.2892992 01	0.1220572 01	0.7992662 00	0.3506412 00	0.3394452 00
0.6800 02	0.2865682 01	0.1208882 01	0.7915062 00	0.3470682 00	0.3359782 00
0.7000 02	0.2838922 01	0.1197412 01	0.7838982 00	0.3435642 00	0.3325762 00
0.7200 02	0.2812692 01	0.1186142 01	0.7764372 00	0.3401252 00	0.3292372 00
0.7400 02	0.2786972 01	0.1175162 01	0.7691202 00	0.3367512 00	0.3259412 00
0.7600 02	0.2761742 01	0.1164352 01	0.7619432 00	0.3334392 00	0.3227452 00
0.7800 02	0.2737042 01	0.1153752 01	0.7549032 00	0.3301882 00	0.3195892 00
0.8000 02	0.2712722 01	0.1143362 01	0.7479972 00	0.3269972 00	0.3164912 00
0.8200 02	0.2689022 01	0.1133142 01	0.7412222 00	0.3238642 00	0.3134502 00
0.8400 02	0.2665702 01	0.1123162 01	0.7345752 00	0.3207902 00	0.3104642 00
0.8600 02	0.2642832 01	0.1113352 01	0.7280532 00	0.3177712 00	0.3075322 00
0.8800 02	0.2620392 01	0.1103722 01	0.7216532 00	0.3148062 00	0.3046552 00
0.9000 02	0.2598332 01	0.1094272 01	0.7153712 00	0.3118952 00	0.3018262 00
0.9200 02	0.2576792 01	0.1085002 01	0.7092062 00	0.3090362 00	0.2990492 00
0.9400 02	0.2555602 01	0.1075912 01	0.7031552 00	0.3062282 00	0.2963222 00
0.9600 02	0.2534812 01	0.1066982 01	0.6972142 00	0.3034692 00	0.2936412 00
0.9800 02	0.2514412 01	0.1058222 01	0.6913832 00	0.3007592 00	0.2910142 00
0.1000 03	0.2494382 01	0.1049612 01	0.6856572 00	0.2980972 00	0.2884262 00
0.1020 03	0.2474732 01	0.1041172 01	0.6800342 00	0.2954822 00	0.2858852 00

0.1040 03	0.245543E 01	0.103267E 01	0.674513E 00	0.592912E 00	0.283389E 00
0.1060 03	0.243449E 01	0.102473E 01	0.669090E 00	0.290386E 00	0.280935E 00
0.1080 03	0.241790E 01	0.101673E 01	0.663744E 00	0.287904E 00	0.278524E 00
0.1100 03	0.239964E 01	0.100888E 01	0.658533E 00	0.285464E 00	0.276154E 00
0.1120 03	0.238170E 01	0.100117E 01	0.653394E 00	0.283064E 00	0.273824E 00
0.1140 03	0.236409E 01	0.993591E 00	0.648345E 00	0.280708E 00	0.271534E 00
0.1160 03	0.234680E 01	0.986148E 00	0.643384E 00	0.278390E 00	0.269282E 00
0.1180 03	0.232981E 01	0.978835E 00	0.638509E 00	0.276111E 00	0.267048E 00
0.1200 03	0.231312E 01	0.971650E 00	0.633718E 00	0.273870E 00	0.264890E 00
0.1220 03	0.229672E 01	0.964590E 00	0.629010E 00	0.271666E 00	0.262749E 00
0.1240 03	0.228061E 01	0.957651E 00	0.624382E 00	0.269499E 00	0.260647E 00
0.1260 03	0.226478E 01	0.950832E 00	0.619833E 00	0.267367E 00	0.258571E 00
0.1280 03	0.224922E 01	0.944129E 00	0.615360E 00	0.265270E 00	0.256533E 00
0.1300 03	0.223393E 01	0.937540E 00	0.610963E 00	0.263206E 00	0.254528E 00
0.1320 03	0.221890E 01	0.931062E 00	0.606639E 00	0.261176E 00	0.252555E 00
0.1340 03	0.220413E 01	0.924693E 00	0.602387E 00	0.259179E 00	0.250614E 00
0.1360 03	0.218960E 01	0.918430E 00	0.598205E 00	0.257213E 00	0.248704E 00
0.1380 03	0.217532E 01	0.912271E 00	0.594092E 00	0.255279E 00	0.246824E 00
0.1400 03	0.216128E 01	0.906214E 00	0.590047E 00	0.253375E 00	0.244973E 00
0.1420 03	0.214747E 01	0.900256E 00	0.586067E 00	0.251501E 00	0.243152E 00
0.1440 03	0.213389E 01	0.894395E 00	0.582151E 00	0.249656E 00	0.241359E 00
0.1460 03	0.212054E 01	0.888630E 00	0.578298E 00	0.247840E 00	0.239593E 00
0.1480 03	0.210740E 01	0.882957E 00	0.574506E 00	0.246051E 00	0.237855E 00
0.1500 03	0.209447E 01	0.877376E 00	0.570775E 00	0.244290E 00	0.236143E 00
0.1520 03	0.208175E 01	0.871893E 00	0.567103E 00	0.242556E 00	0.234457E 00
0.1540 03	0.206924E 01	0.866477E 00	0.563488E 00	0.240848E 00	0.232797E 00
0.1560 03	0.205692E 01	0.861157E 00	0.559929E 00	0.239166E 00	0.231151E 00
0.1580 03	0.204480E 01	0.855919E 00	0.556426E 00	0.237509E 00	0.229540E 00
0.1600 03	0.203287E 01	0.850763E 00	0.552976E 00	0.235876E 00	0.227965E 00
0.1620 03	0.202113E 01	0.845687E 00	0.549579E 00	0.234268E 00	0.226399E 00
0.1640 03	0.200957E 01	0.840689E 00	0.546234E 00	0.232683E 00	0.224858E 00
0.1660 03	0.199819E 01	0.835767E 00	0.542940E 00	0.231121E 00	0.223340E 00
0.1680 03	0.198698E 01	0.830920E 00	0.539694E 00	0.229582E 00	0.221843E 00
0.1700 03	0.197594E 01	0.826145E 00	0.536498E 00	0.228065E 00	0.220368E 00

Appendix B. A Computer Program for Calculating Heat Generation, in a Charcoal Adsorber, Due to Iodine Decay

This program, listed on the following page, is in XTRAN, a version of Fortran IV for the time-sharing computer of the COM-Share Company. The heat generation rate due to the decay of iodine on the charcoal adsorber of the reactor system described on page 28 of the text is calculated for various times after reactor shutdown. Table B-1 is a listing of the output as it comes from the computer.

Listing of Code for Heat Developed in the Charcoal Bed (Q''')

/CHRHG/

```

D'N A(13) , G(13) , D(13) , Q(21)
OPEN(3,INPUT, /MST-CHQDT/)
READ(3,300)(( A(13) , G(13) , D(13)) , 13=1,11 )
7 F'T(10/, $PROGRAM CHRHG REVISED 10/9/70$)
WRITE (1,7)
WRITE(1,100)
A'T P
WRITE(1,220)
220 F'T($FRACTION OF TOTAL HEAT = $,Z)
A'T FAC
WRITE (1,225)
225 F'T ($TIME DELAY -MINUTES = $,Z)
ACCEPT TD
WRITE(1,110)
A'T TI
WRITE (1,301)
301 F'T($FINAGGLE FACTOR (NORMALLY 1.0) = $,Z)
A'T CAP
WRITE(1,307)
307 F'T($TYPE OF LOADING (0=INSTANT,1=GRADUAL) = $,Z)
A'T JS
WRITE(1,200)
WRITE (1,201)
WRITE (1,202)
T=TD
5 SA = 0.0
SG = 0.0
DO 15 J = 1,13
E = EXP(-D(J)*T)
A1=A(J)*E
G1=G(J)*E
SA=SA+A1
SG=SG+G1
IF(JS.EQ.0) DR =1.
IF(JS.EQ.1) DR = 1. - EXP(-0.08819*(T-TD))
15 CONTINUE
X = 0.0
DO 20 I=1,21
Q(I) =(((0.063250*EXP(-9.2104*X))+8.969E-4*EXP(-1.0234*X))
      *SA)+(1.9079E-3*P*SG))*FAC *DR
X = X+0.1
20 CONTINUE
Q0 = (Q(1)+Q(21))/2.0
QS = 0.0
DO 30 K=2,20
QS=QS+Q(K)
30 CONTINUE
QA = 0.05*(Q0+QS)
WTM = 14.17638 * QA/CAP
WRITE(1,210)T,Q(21) , Q(1) , QA , WTM
T = T + TI
IF(T.LT.181.0) GO TO 5
100 F'T($FRACTION LOCALLY DEPOSITED GAMMAS = $,Z)
110 F'T($TIME INCREMENT (MINUTES) = $,Z)
200 F'T(6/, $ TIME MIN. Q''' MAX. Q''' AVG. Q'''
      TOTAL HEATS)
201 F'T($ MIN. BTU/HR*FT3 BTU/HR*FT3 BTU/HR*FT3
      MEGAWATTS$)
202 F'T($***** ***** ***** *****
      *****$,/)
210 F'T(F5.1,4(2X,1PE11.4))
300 F'T(3E15.5)
CLOSE(3)
END

```


Table B-1. Output of the XTRAN Program for Comparing Heat Generation Rate from Iodine Decay Heat on Charcoal

PROGRAM CHRHG REVISED 10/9/70
 FRACTION LOCALLY DEPOSITED GAMMAS = .5
 FRACTION OF TOTAL HEAT = .25
 TIME DELAY -MINUTES = 10
 TIME INCREMENT (MINUTES) = 2
 FINAGGLE FACTOR (NORMALLY 1.0) = 1
 TYPE OF LOADING (0=INSTANT,1=GRADUAL) = 1

TIME MIN. *****	MIN. Q''' BTU/HR*FT3 *****	MAX. Q''' BTU/HR*FT3 *****	AVG. Q''' BTU/HR*FT3 *****	TOTAL HEAT MEGAWATTS *****
10.0	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
12.0	4.8761E-03	9.9507E-02	1.0698E-02	1.5165E-01
14.0	8.8441E-03	1.8056E-01	1.9407E-02	2.7513E-01
16.0	1.2063E-02	2.4638E-01	2.6478E-02	3.7536E-01
18.0	1.4664E-02	2.9964E-01	3.2196E-02	4.5642E-01
20.0	1.6757E-02	3.4255E-01	3.6799E-02	5.2167E-01
22.0	1.8429E-02	3.7692E-01	4.0483E-02	5.7390E-01
24.0	1.9756E-02	4.0426E-01	4.3411E-02	6.1540E-01
26.0	2.0799E-02	4.2581E-01	4.5715E-02	6.4807E-01
28.0	2.1608E-02	4.4260E-01	4.7506E-02	6.7346E-01
30.0	2.2224E-02	4.5546E-01	4.8876E-02	6.9288E-01
32.0	2.2682E-02	4.6510E-01	4.9899E-02	7.0738E-01
34.0	2.3011E-02	4.7210E-01	5.0638E-02	7.1786E-01
36.0	2.3233E-02	4.7693E-01	5.1144E-02	7.2503E-01
38.0	2.3368E-02	4.7999E-01	5.1459E-02	7.2950E-01
40.0	2.3423E-02	4.8161E-01	5.1619E-02	7.3177E-01
42.0	2.3440E-02	4.8205E-01	5.1652E-02	7.3224E-01
44.0	2.3400E-02	4.8153E-01	5.1583E-02	7.3126E-01
46.0	2.3322E-02	4.8023E-01	5.1430E-02	7.2910E-01
48.0	2.3214E-02	4.7832E-01	5.1211E-02	7.2599E-01
50.0	2.3082E-02	4.7590E-01	5.0938E-02	7.2212E-01
52.0	2.2930E-02	4.7309E-01	5.0623E-02	7.1765E-01
54.0	2.2763E-02	4.6997E-01	5.0274E-02	7.1271E-01
56.0	2.2584E-02	4.6661E-01	4.9900E-02	7.0740E-01
58.0	2.2397E-02	4.6307E-01	4.9506E-02	7.0181E-01
60.0	2.2202E-02	4.5938E-01	4.9097E-02	6.9601E-01
62.0	2.2003E-02	4.5560E-01	4.8677E-02	6.9007E-01
64.0	2.1801E-02	4.5175E-01	4.8251E-02	6.8402E-01
66.0	2.1597E-02	4.4786E-01	4.7820E-02	6.7791E-01
68.0	2.1392E-02	4.4395E-01	4.7387E-02	6.7178E-01
70.0	2.1187E-02	4.4004E-01	4.6954E-02	6.6563E-01
72.0	2.0982E-02	4.3614E-01	4.6522E-02	6.5951E-01

74.0	2.0779E-02	4.3226E-01	4.6092E-02	6.5342E-01
76.0	2.0577E-02	4.2841E-01	4.5665E-02	6.4737E-01
78.0	2.0377E-02	4.2459E-01	4.5243E-02	6.4139E-01
80.0	2.0179E-02	4.2083E-01	4.4826E-02	6.3547E-01
82.0	1.9983E-02	4.1710E-01	4.4413E-02	6.2962E-01
84.0	1.9790E-02	4.1343E-01	4.4007E-02	6.2385E-01
86.0	1.9600E-02	4.0982E-01	4.3606E-02	6.1817E-01
88.0	1.9413E-02	4.0626E-01	4.3211E-02	6.1257E-01
90.0	1.9228E-02	4.0275E-01	4.2822E-02	6.0706E-01
92.0	1.9046E-02	3.9931E-01	4.2439E-02	6.0163E-01
94.0	1.8868E-02	3.9592E-01	4.2063E-02	5.9630E-01
96.0	1.8692E-02	3.9259E-01	4.1693E-02	5.9105E-01
98.0	1.8519E-02	3.8931E-01	4.1329E-02	5.8589E-01
100.0	1.8348E-02	3.8610E-01	4.0971E-02	5.8083E-01
102.0	1.8181E-02	3.8294E-01	4.0620E-02	5.7584E-01
104.0	1.8016E-02	3.7983E-01	4.0275E-02	5.7095E-01
106.0	1.7855E-02	3.7679E-01	3.9935E-02	5.6614E-01
108.0	1.7696E-02	3.7379E-01	3.9602E-02	5.6141E-01
110.0	1.7539E-02	3.7085E-01	3.9274E-02	5.5677E-01
112.0	1.7385E-02	3.6797E-01	3.8952E-02	5.5220E-01
114.0	1.7234E-02	3.6513E-01	3.8636E-02	5.4772E-01
116.0	1.7086E-02	3.6235E-01	3.8326E-02	5.4332E-01
118.0	1.6940E-02	3.5961E-01	3.8020E-02	5.3899E-01
120.0	1.6796E-02	3.5693E-01	3.7720E-02	5.3474E-01
122.0	1.6655E-02	3.5429E-01	3.7426E-02	5.3056E-01
124.0	1.6516E-02	3.5170E-01	3.7136E-02	5.2646E-01
126.0	1.6380E-02	3.4916E-01	3.6852E-02	5.2242E-01
128.0	1.6245E-02	3.4666E-01	3.6572E-02	5.1846E-01
130.0	1.6113E-02	3.4421E-01	3.6297E-02	5.1456E-01
132.0	1.5984E-02	3.4179E-01	3.6027E-02	5.1073E-01
134.0	1.5856E-02	3.3942E-01	3.5761E-02	5.0696E-01
136.0	1.5730E-02	3.3709E-01	3.5500E-02	5.0326E-01
138.0	1.5607E-02	3.3481E-01	3.5243E-02	4.9962E-01
140.0	1.5485E-02	3.3256E-01	3.4991E-02	4.9604E-01
142.0	1.5365E-02	3.3035E-01	3.4742E-02	4.9252E-01
144.0	1.5248E-02	3.2817E-01	3.4498E-02	4.8906E-01
146.0	1.5132E-02	3.2604E-01	3.4258E-02	4.8566E-01
148.0	1.5018E-02	3.2394E-01	3.4022E-02	4.8231E-01
150.0	1.4906E-02	3.2187E-01	3.3790E-02	4.7901E-01
152.0	1.4795E-02	3.1984E-01	3.3561E-02	4.7577E-01
154.0	1.4686E-02	3.1785E-01	3.3336E-02	4.7258E-01
156.0	1.4579E-02	3.1588E-01	3.3115E-02	4.6945E-01
158.0	1.4474E-02	3.1395E-01	3.2897E-02	4.6636E-01
160.0	1.4370E-02	3.1205E-01	3.2683E-02	4.6332E-01
162.0	1.4268E-02	3.1018E-01	3.2472E-02	4.6033E-01
164.0	1.4167E-02	3.0834E-01	3.2264E-02	4.5739E-01
166.0	1.4068E-02	3.0653E-01	3.2060E-02	4.5449E-01
168.0	1.3970E-02	3.0475E-01	3.1858E-02	4.5164E-01
170.0	1.3874E-02	3.0300E-01	3.1660E-02	4.4883E-01
172.0	1.3779E-02	3.0127E-01	3.1465E-02	4.4606E-01
174.0	1.3686E-02	2.9957E-01	3.1273E-02	4.4334E-01
176.0	1.3593E-02	2.9790E-01	3.1084E-02	4.4065E-01
178.0	1.3503E-02	2.9626E-01	3.0897E-02	4.3801E-01
180.0	1.3413E-02	2.9463E-01	3.0713E-02	4.3540E-01

STOP

(\$MAINS) 300+2

+

Appendix C. CHART Code

A. Stability Criteria for "CHART"

HEATING3, like any other heat transfer code which uses the explicit method for its transient calculations has a limit on the size of time step used if stability is to be guaranteed. The basic heat conduction equation used in HEATING3 is (see Eq. 2-22, Ref. 10):

$$T_J(t + \Delta t) = T_g(t) + \frac{\Delta t}{C_g} \left[\sum_{i=1}^m J_i K_i (T_i(0) - T_g(0)) + \theta_J(t) \right] \quad C-1$$

and the stability criteria for this equation is (Eq. 2-23 in Ref. 10):

$$\Delta t_{\max} \leq \left(\frac{C_J}{\sum_{i=1}^m J_i K_i} \right)_{\min \text{ for all } J} \quad C-2$$

The stability criteria given in Eq. C-2 does not include the heat generation term Q_J . This is correct assuming that θ_J is not itself a function of temperature. However, in our case (see Eqs. 17 and 26):

$$Q_J = q''' - H(T - T_g). \quad C-3$$

The mathematical stability for Eq. (C-1) if Q_J is itself a function of temperature should include the coefficient of the temperature. In general any vectorial equation in the form

$$\alpha_1 \vec{V}_1 + \alpha_2 \vec{V}_2 + \dots + \alpha_n \vec{V}_n = 0$$

where $\alpha_1, \alpha_2, \dots, \alpha_n$ are scalar coefficients of the vectors $\vec{V}_1, \vec{V}_2, \dots, \vec{V}_n$ in order to be stable must satisfy the condition that

$$\alpha_1 + \alpha_2 + \dots + \alpha_n \geq 0.$$

In the case of the heat conduction equation the system of vectors becomes

$$-\sum_{i=1}^m K_{i,J} (T_i - T_J) + \frac{C_J}{\Delta t} (T_J' - T_J) = 0$$

and therefore the stability criteria becomes like in Eq. (C-2)

In our case the system of vectors becomes

$$-\sum_{i=1}^m K_{i,J} (T_i - T_J) + V_J H (T_J - T_g) + \frac{C_J}{\Delta t} (T_J' - T_J) = 0$$

and therefore the stability criteria is

$$(\Delta t)_{\max} \leq \left(\frac{C_J}{\sum_{i=1}^n J_i K_i + V_J H} \right) \min \text{ for all} \quad \text{C-4}$$

where V_J is the volume of the node element and H is our volumetric heat transfer coefficient. This criteria is incorporated now in CHART. The modified method included in HEATING3 (see Ref. 11) was changed here to include the correct criteria for stability as given in Eq. (C-4).

Inserting Eq. (8) for calculating the cooling gas temperature for every increment along its flow created an additional stability problem. The differential equation added is (see Eq. 8):

$$\frac{dT_g}{dx} = \frac{HA(T - T_g)}{8CpV_g A} \quad \text{C-5}$$

For such an equation to be stable we must have

$$\rho Cp V_g A - A \Delta X H \geq 0$$

or

$$\Delta X \leq \left(\frac{\rho Cp V_g}{H} \right) \quad \text{C-6}$$

This stability criteria was also incorporated into CHART as part of the HGREN subroutine. The modified method used in HEATING3 (see Ref. 11) was also used here although reduced to the simpler case of Eq. (C-5). This eliminates the requirement of using too many subdivisions along the direction of gas flow.

Table C-1. Input Table for CHART

Card	Col.	Format	Variable Name	Variable Meaning	Units
A	1-12	D12.4	BIGB1 (B1)*	Reactor constant γ beta heat due to elemental iodine (p. 15)	Mw(t)/in. ³
	13-24	0.XXXXD+XX	BIGB2 (B2)	Reactor constant - beta heat due to methyl iodide (p. 15)	Mw(t)/in. ³
	25-36		BIGG (G)	Reactor constant - gamma heat due to iodine decay (p. 15)	Mw(t)/in. ³
	37-48		SMLB1 (b ₁)	Attenuation coefficient for iodine	Dimensionless
	49-60		SMLB2 (b ₂)	Attenuation coefficient for methyl iodide	Dimensionless
B	1-12	D12.4	GIT (T _g)	Gas initial temperature	°F
	13-24	0.XXXXD+XX	GDEN	Gas density	lb/in. ³
	25-36		GSPH	Specific heat of gas	Btu/lb-°F
	37-48		DELX	Thickness of division of charcoal adsorber.	Inches
	49-60		DIMA	When more than one layer of charcoal is considered DIMA represents lattice point where 1st layer begins and DIMB represents beginning of 2nd layer in flow direction. No number-program assumes zero.	
	61-72		DIMB		
C	1-12	D12.4	BUCOEF	Buildup coefficient - governs rate of iodine accumulation on charcoal (see pp. 16 and 88)	1/in.
	13-24	0.XXXXD+XX	TMDLAY (t _D)	Time delay between end of fissioning and beginning of iodine adsorption	Min.
	25-36		BGGVEL (v _g)	Beginning gas velocity	in./min
	37-48		ACGVEL	Accident gas velocity	in./min
D1	1-15	D15.6	AA(I) (a ₁)	Beta heat/thermal Mw of reactor power for individual isotopes	Btu/min-Mw(t)
	16-30	0.000000D+XX	GG(I) (g ₁)	Gamma heat/thermal Mw of reactor power for individual isotopes	Btu/min-Mw(t)
	31-45		LAMBDA(I) (λ ₁)	Decay constant of iodine isotopes	1/min.
REPEAT D2, D3			One card for each isotope.		

Cards for HEATING3 follow* (notation used in text, see page 16 and Appendix D).

Table C-1 (continued). Summary and Format of Input

The following table is a concentrated summary of the format and information needed to prepare the input data deck. Except for the IT cards, columns 73 through 80 of each card are reserved for identification, and the user may or may not choose to punch this information. The table in this column gives proposed identification names for the cards and, in parentheses, the reference sections in the report where more information can be found. The first line in each format box includes the variable name actually used in the program and, in parentheses, the format of that variable. The rest of the box includes a short explanation of the input in that box. In some cards, where free space is available, e.g., G or I cards, additional notes have been included to describe the way the input information will be used in the program itself.

JONES(I), Job Description, Format 1844, (3.5.1)

Columns 1-9	Columns 10-18	Columns 19-27	Columns 28-36	Columns 37-45	Columns 46-54	Columns 55-63
NGEOM (I9) Geometry type. 1-R0Z 6-KYZ 2-R0 7-KY 3-RZ 8-KZ 4-R 9-X 5-Z	NOREG (I9) Total number of regions. (Cards R1 & R2) Maximum 100	MATLT (I9) Total number of materials. (Cards M) Maximum 50	NINTFN (I9) Total number of initial tempera- ture functions. (Cards I) Maximum 25	NPDFN (I9) Total number of position depen- dent functions. (Cards P) Maximum 50	NGENFN (I9) Total number of heat generation functions. (Cards G) Maximum 20	NTDFN (I9) Total number of time dependent functions. (Cards T) Maximum 20
IGT (I9) Total number of gross lattice lines in X or R direction. (Entries in L1) Maximum 50	JGT (I9) Total number of gross lattice lines in Y or 0 direction. (Entries in L2) Maximum 50	KGT (I9) Total number of gross lattice lines in Z direction. (Entries in L3) Maximum 50	NBUTPT (I9) Total number of boundaries. (Cards B1 & B2) Maximum 50	INITEN (I9) Total number of lattice points with temperatures specified on IT cards. Maximum 1750	JIN (I9) Unit number for reading initial temperature from IT cards (if any). (5 on IBM)	JOUT (I9) Unit number for writing final temperature on IT cards. (7 on IBM)
NTYPE (I9) Problem type. 1 steady state; -1 transient. (See section 3.5.4(a) for other types)	NUTX (I9) Maximum number of steady state iterations. (Recommend 300- 500)	NEX1 (I9) Inactive, leave blank.	NEX (I9) Inactive, leave blank.	NDTA (I9) Number of time steps between printed outputs. Next entry must be blank.	NPRINT (I9) Number of times output will be printed. (Entries in 0 card), preceding entry must be blank. Maximum 100	INEGRE (I9) Temperature units in °C, and radi- ation is involved enter 1; otherwise leave blank.
EPI (E9.8) Steady state con- vergence crite- rion. (Recommend 10-5)	NEFA (E9.8) Steady state over- relaxation factor $1.0 \leq \beta < 2.0$ (Recommend 1.9)	DELTA (E9.8) Time increment for transient problem.	KTFCT (I9) Factor by which stable time incre- ment is increased if modified method is used.	TTI (E9.8) Initial time. (See section 3.5.5(e) for more info.)	TFE (E9.8) Final time.	
NOREG (I9) Region number. Maximum 100	MATL (I9) Region material number. (Card M)	NRIN (E9.8) Smaller X or R region dimension.	NRRT (E9.8) Larger X or R region dimension.	THLT (E9.8) Smaller Y or 0 region dimension.	THRT (E9.8) Larger Y or 0 region dimension.	ZZBK (E9.8) Smaller Z region dimension.
INTEN (I9) Region initial temperature function number. (Card I)	NGEN (I9) Region heat generation function number. (Card G)	NBDIN (I9) Boundary condi- tion on smaller X or R. (Card B)	NBDRT (I9) Boundary condi- tion on larger X or R. (Card B)	NBDLT (I9) Boundary condi- tion on smaller Y or 0. (Card B)	NBDRT (I9) Boundary condition on larger Y or 0. (Card B)	NBDK (I9) Boundary condi- tion on smaller Z. (Card B)
MAT (I9) Material number. Maximum 50	MATNAM (A8) Material name.	CONDTY (E9.8) CONDUCTIVITY if constant; if temperature de- pendent, leave blank.	DENSTY (E9.8) DENSITY if con- stant; if tempera- ture dependent or steady state only, leave blank.	SPHEAT (E9.8) SPECIFIC HEAT if constant; if temperature de- pendent or steady state only, leave blank.	NCON (I9) Number of pairs in C cards. Leave blank and omit C cards if constant. Maximum 25	NDEN (I9) Number of pairs in D cards. Leave blank and omit D cards if constant or steady state. Maximum 25
T ₁ (E9.8) Temperature	V ₁ (E9.8) Conductivity	T ₂ (E9.8) Temperature	V ₂ (E9.8) Conductivity	(Can be repeated for up to 25 pairs. Omit for constant		
T ₁ (E9.8) Temperature	V ₁ (E9.8) Density	T ₂ (E9.8) Temperature	V ₂ (E9.8) Density	(Can be repeated for up to 25 pairs. Omit for constant steady state problem.)		
T ₁ (E9.8) Temperature	V ₁ (E9.8) Specific heat	T ₂ (E9.8) Temperature	V ₂ (E9.8) Specific heat	(Can be repeated for up to 25 pairs. Omit for constant or steady state problem.)		
NGN (I9) Heat generation function number. Maximum 20	NGNTM (I9) Time dependent function number. (Card T)	NWNR (I9) Position depend- ent function number in X or R direction. (Card P)	NWNRTH (I9) Position depend- ent function number in Y or 0 direction. (Card P)	NWNTZ (I9) Position depend- ent function number in Z direction. (Card P)	NOTE: The heat generation will be $g(x,y,z,t) = F_1(x) \cdot F_2(y) \cdot F_3(z) \cdot F_4(t)$ $F_n(v)$ are position dependent functions and $F_4(t)$ is the t th time dependent function.	
INTM (I9) initial tempera- ture function number. Maximum 25	ITPR (I9) Position dependent function number in X or R direction. (Card P)	ITMTH (I9) Position depend- ent function number in Y or 0 direction. (Card P)	ITMTH (I9) Position dependent function number in Z direction. (Card P)	NOTE: The initial temperature will be $T_0(x,y,z) = F_1(x) \cdot F_2(y) \cdot F_3(z)$ where $F_n(v)$ are position dependent functions.		
NPT (I9) Position depend- ent function number. Maximum 50	NPAR (I9) Number of coeffi- cients in P2 cards. Maximum 9	NOTE: P1 and P2 establish the position dependent function in the form $F_n(v) = A_{n,1} + A_{n,2}v + A_{n,3}v^2 + A_{n,4}\cos(A_{n,5}v) + A_{n,6}\exp(A_{n,7}v) + A_{n,8}\sin(A_{n,9}v)$ where v is x , y , or z .				

concentrated summary of the format and information needed to pre-
 Except for the IT cards, columns 73 through 80 of each card are
 ion, and the user may or may not choose to punch this information.
 gives proposed identification names for the cards and, in paren-
 tions in the report where more information can be found. The first
 includes the variable name actually used in the program and, in
 of that variable. The rest of the box includes a short explanation
 In some cards, where free space is available, e.g., G or I cards,
 is included to describe the way the input information will be used

ES(1), Job Description, Format 18A4, (3.5.1)						Card 1
Columns 28-36	Columns 37-45	Columns 46-54	Columns 55-63	Columns 64-72	Columns 73-80	
INTFN (I9) Total number of initial tempera- ture functions. (Cards I) Maximum 25	WDFN (I9) Total number of position depen- dent functions. (Cards P) Maximum 50	WGENFN (I9) Total number of heat generation functions. (Cards G) Maximum 20	NTDFN (I9) Total number of time dependent functions. (Cards T) Maximum 20	IOUT (I9) If isothermal plots are desired, enter 2; otherwise leave blank.	Card 2 (3.5.2)	
NDIFF (I9) Total number of boundaries. (Cards B1 & B2) Maximum 50	INITPT (I9) Total number of lattice points with temperatures specified on IT cards. Maximum 1756	JIN (I9) Unit number for reading initial temperature from IT cards (if any). (5 on IM)	JOUT (I9) Unit number for punching final temperature on IT cards. (7 on IM)		Card 3 (3.5.3)	
EX (I9) Inactive, leave blank.	NDTA (I9) Number of time steps between printed outputs. Next entry must be blank.	NPRINT (I9) Number of times output will be printed. (Entries in 0 card), preceding entry must be blank. Maximum 100	INTEMP (I9) Temperature units. If °C, and radi- ation is involved, enter 1; otherwise, leave blank.		Card 4 (3.5.4)	
INFACT (I9) Factor by which table time incre- ment is increased (modified method used).	TIME (E9.8) Initial time. (See section 3.5.5(e) for more info.)	TIME (E9.8) Final time.			Card 5 (3.5.5)	
NDT (E9.8) Larger X or Y region dimension.	THLT (E9.8) Smaller Y or 0 region dimension.	THRT (E9.8) Larger Y or 0 region dimension.	ZZBK (E9.8) Smaller Z region dimension.	ZZFR (E9.8) Larger Z region dimension.	R1	
NDT (I9) Boundary condition on larger X or Y. (Card B)	NDHLT (I9) Boundary condi- tion on smaller Y or 0. (Card B)	NDHRT (I9) Boundary condition on larger Y or 0. (Card B)	NDDBK (I9) Boundary condi- tion on smaller Z. (Card B)	NDDFR (I9) Boundary condition on larger Z. (Card B)	R2	
NSHTY (E9.8) NSHTY if con- stant; if tempera- ture dependent or steady state only, leave blank.	SPHEAT (E9.8) SPECIFIC HEAT if constant; if temperature de- pendent or steady state only, leave blank.	NCON (I9) Number of pairs in C cards. Leave blank and omit C cards if constant. Maximum 25	NDEN (I9) Number of pairs in D cards. Leave blank and omit D cards if constant or steady state. Maximum 25	NSHT (I9) Number of pairs in S cards. Leave blank and omit S cards if constant or steady state. Maximum 25	M	
(E9.8) conductivity	(Can be repeated for up to 25 pairs. Omit for constant conductivity.)				C	
(E9.8) density	(Can be repeated for up to 25 pairs. Omit for constant density or steady state problem.)				D	
(E9.8) specific heat	(Can be repeated for up to 25 pairs. Omit for constant specific heat or steady state problem.)				S	
WTH (I9) Position depend- ent function number in Y or 0 direction. (Card P)	WTHZ (I9) Position depend- ent function number in Z direction. (Card P)	NOTE: The heat generation will be $g(x,y,z,t) = F_1(x) \cdot F_2(y) \cdot F_3(z) \cdot T_4(t)$ where $F_m(v)$ are position dependent functions, and $T_4(v)$ is 4th time dependent function.			G (3.5.8)	
WZ (I9) Position dependent function number in direction. (Card P)	NOTE: The initial temperature will be $T_0(x,y,z) = F_1(x) \cdot F_2(y) \cdot F_3(z)$ where $F_m(v)$ are position dependent functions.			I (3.5.9)		
Publish the position dependent function in the form $F_m(v) = A_{m,1} + A_{m,2}v + A_{m,3}v^2 + A_{m,4} \cos(A_{m,5}v) + A_{m,6} \exp(A_{m,7}v) + A_{m,8} \sin(A_{m,9}v)$ or					P1 (3.5.10)	

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T ₁ (E9.8) Temperature	V ₁ (E9.8) Specific heat	T ₂ (E9.8) Temperature	V ₂ (E9.8) Specific heat	(Can be repeated for up to 25 pairs. Unit for constant or steady state problem.)		
NGM (I9) Heat generation function number. Maximum 20	NGMTM (I9) Time dependent function number. (Card T)	NGNR (I9) Position dependent function number in I or R direction. (Card P)	NGNTH (I9) Position dependent function number in Y or 0 direction. (Card P)	NGNZ (I9) Position dependent function number in Z direction. (Card P)	NOTE: The heat generation will be $q(x,y,z,t) = F_i(x) \cdot F_j(y) \cdot F_k(z) \cdot F_q(t)$ where $F_q(t)$ are position dependent is t-th time dependent function.	
INTM (I9) Initial temperature function number. Maximum 25	ITMR (I9) Position dependent function number in X or R direction. (Card P)	ITMTH (I9) Position dependent function number in Y or 0 direction. (Card P)	ITMZ (I9) Position dependent function number in Z direction. (Card P)	NOTE: The initial temperature will be $T_0(x,y,z) = F_i(x) \cdot F_j(y) \cdot F_k(z)$ where $F_m(v)$ are position dependent functions.		
NFN (I9) Position dependent function number. Maximum 50	NPAR (I9) Number of coefficients in P2 cards. Maximum 9	NOTE: P1 and P2 establish the position dependent function in the form $F_m(v) = A_{m,1} + A_{m,2}V + A_{m,3}V^2 + A_{m,4}\cos(A_{m,5}V) + A_{m,6}\exp(A_{m,7}V) + A_{m,8}V^5$ where V is x, y, or z.				
NOPARM (I9) Coefficient index, i	DUPMY (E9.8) Coefficient value, A _{m,i}	NOPAZM (I9) Coefficient index, i	DUPMY (E9.8) Coefficient value, A _{m,i}	NOTE: Can be repeated for up to 9 coefficients.		
NTM (I9) Time dependent function number. Maximum 20	NTMFP (I9) Number of pairs in table. Maximum 25	TIMEFN (E9.8) Time.	TIMEFN (E9.8) Factor.	TIMEFN(E9.8) Time.	TIMEFN (E9.8) Factor.	TIMEFN (E9.8) Time.
TIMEFN (E9.8) Time.	TIMEFN (E9.8) Factor.	NOTE: Can be repeated for up to 25 pairs. This establishes the time dependent function in				
NBDTP (I9) Boundary number. Maximum 50	NBDTYP (I9) Boundary Type. 1-surface to boundary 2-isothermal 3-surface to surface	NBDTWP (E9.8) Boundary temperature, T _n (Blank for type 3)	NBDTFN (I9) Boundary time dependent function number. (Card T) (Blank for type 3)	Boundary temperature will be established as $F_n(t) = T_n \cdot T_t(t)$ where T _t (t) is time dependent function.		
NBCOV (E9.8) Forced convection film coefficient, h _c	NBRAD (E9.8) Radiation coefficient, h _r = F·σ	NBNAT (E9.8) Natural convection coefficient, h _n	NBEXP (E9.8) Natural convection exponent, h _e	NFLUX (E9.8) Prescribed heat flux (positive if going to surface), where ΔT = T ₁ - T ₂ .	NOTE: The heat flux will be established $q'' = h_f + h_c \Delta T + h_r(T_1^4 - T_2^4)$	
RG (E9.8) Smallest X or R gross lattice line dimension.	RG (E9.8) Next X or R gross lattice line dimension.	RG (E9.8) Next X or R gross lattice line dimension.	Can be repeated for up to 50 gross lattice lines (but equal to entry one			
NDRG (I9) Number of DIVISIONS between corresponding X or R gross line and the following line.	NDRG (I9)	NDRG (I9)	Must have one less entry than in L1 cards (maximum of 100 fine lattice lines in direction).			
THG (E9.8) Y or 0	Same as L1 cards except for Y or 0 direction.					
NOTHG (I9) Y or 0	Same as N1 cards except for Y or 0 direction.					
ZG (E9.8) Z	Same as L1 cards except for Z direction.					
NDZG (I9) Z	Same as N1 cards except for Z direction.					
PRTIME (E9.8) First time print-out is desired.	PRTIME (E9.8) Second time print-out is desired.	PRTIME (E9.8) Third time print-out is desired.	Can be repeated for up to 100 printout times (but equal to entry six in C			

Job Description, Format 18A4

Columns 1-5	Columns 6-15	Columns 16-20	Columns 21-30	Columns 31-35	Columns 36-45	Columns 46-50	Columns 51-60
N(I5) Lattice point number.	T1(N) (D10.0) Specified initial temperature of that point.	N(I5) Lattice point number.	T1(N) (D10.0) Specified initial temperature of that point.	Can be repeated up to 1750 lattice points (but in Card 3).			

Blank card if additional problem follows.

Cards for additional problem if desired.

	D	Cards N.C. (J.S.7)
eat	S	

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Specific heat										
Position dependent function number in X or Y or Z direction. (Card P)	Position dependent function number in Y or Z direction. (Card P)	NOTE: The heat generation will be $q(x,y,z,t) = F_1(x) \cdot F_2(y) \cdot F_3(z) \cdot T_4(t)$ where $F_n(v)$ are position dependent functions, and $T_4(t)$ is 4th time dependent function.				G (3.5.8)				
Position dependent function number in Z direction. (Card P)	NOTE: The initial temperature will be $T_0(x,y,z) = F_1(x) \cdot F_2(y) \cdot F_3(z)$ where $F_n(v)$ are position dependent functions.				I (3.5.9)					
P1 and P2 establish the position dependent function in the form $F_n(v) = A_{n,1} + A_{n,2}v + A_{n,3}v^2 + A_{n,4}\cos(A_{n,5}v) + A_{n,6}\exp(A_{n,7}v) + A_{n,8}\sin(A_{n,9}v)$ where V is x, y, or z.								P1		Coupled (3.5.10)
								P2		
COEFFICIENT (E9.8)	COEFFICIENT (E9.8) value. $A_{n,i}$	NOTE: Can be repeated for up to 9 coefficients.						P2		Coupled (3.5.11)
TIME (E9.8)	TIME (E9.8) Factor.	TIME (E9.8) Time.	TIME (E9.8) Factor.	TIME (E9.8) Time.	TIME (E9.8) Factor.			T1		
Can be repeated for up to 25 pairs. This establishes the time dependent function in the form $T_4(t)$.								T2		Coupled (3.5.12)
BOUNDARY TIME (E9.8)	BOUNDARY TIME (E9.8) Boundary time dependent function number. (Card T) (Blank for type 3)	Boundary temperature will be established as $F_n(z) = T_n \cdot T_4(t)$ where $T_4(t)$ is time dependent function.						B1		
CONVECTION COEFFICIENT (E9.8)	NATURAL CONVECTION EXPONENT (E9.8)	NOTE: The heat flux will be established as: $q'' = h_f + h_c \Delta T + h_r (T_1^4 - T_2^4) + h_n \Delta T ^n (\Delta T)$ where $\Delta T = T_1 - T_2$.						B2		Coupled (3.5.13)
Can be repeated for up to 50 gross lattice lines (but equal to entry one in Card 2).								L1		(3.5.13)
Must have one less entry than in L1 cards (maximum of 100 fine lattice lines in each direction).								N1		(3.5.13)
Same as L1 cards except for Y or Z direction.								L2		(3.5.13)
Same as N1 cards except for Y or Z direction.								N2		(3.5.13)
Same as L1 cards except for Z direction.								L3		(3.5.13)
Same as N1 cards except for Z direction.								N3		(3.5.13)
TIME PRINT-OUT DESIRED (E9.8)	Can be repeated for up to 100 printout times (but equal to entry six in Card 4).							P		(3.5.14)

Job Description, Format 18A4								IT1 (3.5.15)	
Columns 16-20	Columns 21-30	Columns 31-35	Columns 36-45	Columns 46-50	Columns 51-60	Columns 61-65	Columns 66-75	Columns 76-80	
IT2 (3.5.15)	T1(N) (D10.0) Specified initial temperature of that point.		Can be repeated up to 1750 lattice points (but equal to entry 5 in Card 3).						IT2 (3.5.15)
Blank card if additional problem follows.									
Cards for additional problem if desired.									

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Appendix D. Application of CHART to a Research or Production Type Reactor

In this application of the procedure for estimating the temperature distribution in a charcoal adsorber, a different type of reactor system is considered. The previous examples (Section V) were based on a pressurized-water power reactor but in this case we imagine a hypothetical reactor system which more nearly fits the specifications of research reactors or some of the production reactor systems. Two major differences are evident: first is the much lower reactor power and consequently less charcoal area in the adsorber and secondly, the latter type drives air continuously through the filters and out the stack rather than recirculating the exit air back into the containment building.

A second purpose of this application is to provide a step-by-step example of applying the calculational procedure which begins with the basic equation and ends with the data cards to be punched in order to run the program.

The two basic equations used in calculating the temperature distribution in the charcoal adsorber are:

$$\rho_b C_{p_b} \frac{\partial T_b}{\partial t} = k_b \left[\frac{\partial^2 T_b}{\partial x^2} + \frac{\partial^2 T_b}{\partial y^2} + \frac{\partial^2 T_b}{\partial z^2} \right] + q''' - H(T_b - T_g) \quad (D-1)$$

and

$$\rho_g C_{p_g} v_g \frac{\partial T_g}{\partial x} = H(T_b - T_g). \quad (D-2)$$

from which the value of t_g may be determined.

The heat generation term in Eq. (D-1) is developed on page 16 of the text and in the general form becomes:

$$q'''(x) = \frac{FP(t)}{V_b} (a_1 + fg_1) e^{-\lambda_1(t + tD)} \text{ Btu/min-in.}^3 \quad (D-3)$$

The heat generated by the decay of the iodine is considered in two parts; that generated by beta adsorption (a_1) and the gamma adsorption (g_1). Because of the penetration of the gamma rays the heat produced by their adsorption is considered to be uniform throughout the charcoal volume. Beta radiation, however, is adsorbed in the immediate vicinity

where it is produced. Most of the elemental iodine is deposited on the air inlet side of the bed and the part of the iodine which becomes CH_3I is less concentrated. For this reason the iodine deposit for beta heat generation must be considered in more detail as outlined on page 17 of the text. This is reflected in the following equation:

$$q_i'''(x,t) = \frac{F_1 P(t)}{v_b} \left[\left(\frac{\beta_1 b_1 \ell}{1 - e^{-b_1 \ell}} e^{-b_1 x} + \frac{\beta_2 b_2 \ell}{1 - e^{-b_2 \ell}} e^{-b_2 x} \right) a_i + F_2 g_i \right] e^{-\lambda_i(t+t_D)} \quad \text{Btu/min-in.}^3. \quad \text{D-4}$$

where the two terms in parentheses represent the location of the elemental methyl iodide, respectively. For any particular reactor system these terms are constant and are given the designation B_1 and B_2 . The terms are expressed here and are calculated for this particular problem on page 85.

$$B_1 = \frac{P(t) \ell \beta_1 b_1}{v_b (1 - e^{-b_1 \ell})}$$

$$B_2 = \frac{P(t) \ell \beta_2 b_2}{v_b (1 - e^{-b_2 \ell})}$$

The terms representing the gamma heat generation is

$$G = \frac{P(t)}{v_b} f$$

At this point q''' is calculated as a function of time and position in the charcoal. If we wish to include the practical consideration, that the iodine accumulates on the charcoal over a period of time depending on air flow rate we need to add a term which determines the fraction of the total iodine that has been adsorbed at any time (see page 18 of text).

$$\text{Fraction of total iodine adsorbed} = 1 - e^{-(aRT/V)}$$

Including this factor and summing the heat generation due to all the individual isotopes of iodine, we have:

$$q'''(x,t) = F_1 \left[(B_1 e^{-b_1 x} + B_2 e^{-b_2 x}) \sum_{i=1}^m a_i e^{-\lambda_i (t+t_D)} + G \sum_{i=1}^m g_i e^{-\lambda_i (t+t_D)} \right] (1 - e^{-(aR/vt)}) \quad (D-5)$$

where

$q'''(x,t)$ = heat generation rate per unit volume of charcoal bed,
 x = distance from front face of charcoal bed in direction of gas flow
 t = time elapsed from beginning of iodine adsorption by the charcoal bed

t_D = time delay between end of fissioning and beginning of iodine adsorption

a = fraction of iodine removed from the air as it passes through the charcoal (assumed here to be 0.9)

R = gas flow rate, ft^3/min

V = volume of containment vessel

b_1 = attenuation coefficient for iodine

b_2 = attenuation coefficient for methyl iodide

F_1 = fraction of total iodine adsorbed by the charcoal filter.

In order to calculate the constants needed for the heat generation part of the computer code the data listed in Table D-1 is required.

Table D-1. Data for Calculating the Temperature Distribution in the Charcoal Adsorber of the Hypothetical Production Reactor System

Specifications of the Reactor System

Reactor Power	350 Mw(t)
Charcoal Adsorber	
Area of charcoal	600 ft^2
Thickness of charcoal	2 in. (1)
Volume of charcoal	100 $\text{ft}^3 (1.7280 \times 10^5 \text{ in.}^3) (V_b)$
Normal air velocity	40 ft/min (R)
Containment volume	451,880 ft^3 (V)

Other Constants

$\beta_1 = 0.9$ (fraction of I_2)

$\beta_2 = 0.1$ (fraction of CH_3I)

$b_1 = 9.2104 \text{ 1/n}$ (I_2 attenuation coefficient)

$b_2 = 1.0234 \text{ 1/n}$ (CH_3I attenuation coefficient)

Time elapse between reactor shutdown and beginning of iodine adsorption = 10 min

$a = 0.99$ (fraction of iodine adsorbed as the air passes through the charcoal)

Calculation of Input Data for Computer Program

$$B_1 = \frac{P(t)}{V_b} \left(\frac{\beta_1 b_1 \ell}{1 - e^{-b_1 \ell}} \right) = \frac{350}{1.7280 \times 10^5} \times \frac{0.9 \times 9.2104 \times 2}{1 - e^{-(9.2104 \times 2)}} = 3.3578 \times 10^{-2}$$

$$B_2 = \frac{P(t)}{V_b} \left(\frac{\beta_2 b_2 \ell}{1 - e^{-b_2 \ell}} \right) = \frac{350}{1.7280 \times 10^5} \times \frac{0.1 \times 1.0234 \times 2}{1 - e^{-(1.0234 \times 2)}} = 4.7608 \times 10^{-4}$$

$$G = \frac{P(t)}{V_b} 0.5 = 1.0127 \times 10^{-3}$$

The terms a_i and g_i in Eq. (D-5) refer to the fraction of the decay power of the iodine which is due to beta and gamma, respectively. They are calculated for each isotope and the dimensions are Btu/min-Mw(t). A sample calculation for ^{131}I is as follows: (refer to Table D-2 for decay power of iodine isotopes at reactor shutdown).

$$a_i(^{131}\text{I}) = 118 \text{ watts/Mw(t)} \times 0.0569 \frac{\text{Btu/min}}{\text{watt}} (0.425) \text{ (fraction for beta)}$$

$$g_i(^{131}\text{I}) = 118 \text{ watts/Mw(t)} \times 0.0569 \frac{\text{Btu/min}}{\text{watt}} (0.0574) \text{ (fraction for gamma)}$$

$$= 3.8540 \frac{\text{Btu/min}}{\text{Mw(t)}} .$$

Corresponding values for all the isotopes and the decay constant are listed in Table D-3.

Table D-2. Constants for Iodine Isotopes Produced in a Reactor

Iodine Isotope	Decay Constant		Fraction of Decay Heat Due to		Watts/Mw(t) of Reactor Power		
	(sec ⁻¹)	(min ⁻¹)	Beta	Gamma	Discharge	From Beta	From Gamma
127					0.0		
128	4.62E-04	2.77E-02	0.827	0.173	1.99E-00		
129	1.29E-15	7.74E-14	1	0.0	5.37E-07	5.37E-07	
130m	1.26E-03	7.56E-02	1	0.0	2.34E-01	2.43E-01	
130	1.55E-05	9.30E-04	0.220	0.780	9.97E-00	2.19E 00	7.78E 00
131	9.97E-07	5.98E-05	0.426	0.574	1.18E 02	5.03E 00	6.77E 01
132	8.37E-05	5.02E-03	0.220	0.780	6.55E 02	1.44E 02	5.11E 02
133	9.17E-06	5.50E-04	0.490	0.510	3.50E 02	1.72E 02	1.79E 02
134	2.19E-04	1.31E-02	0.186	0.814	1.18E 03	2.19E 02	9.61E 02
135	2.87E-05	1.72E-03	0.160	0.840	6.45E 02	1.03E 02	5.42E 02
136	8.35E-03	5.01E-01	0.480	0.520	5.10E 02	2.45E 02	2.65E 02
137	3.06E-02	1.84E-00	1	0.0	5.43E 01	5.43E 01	
138	1.17E-01	7.02E-00	1	0.0	1.02E 03	1.02E 03	
139	3.47E-01	2.08E-01	1	0.0	4.91E 02	4.91E 02	
					5.04E 03	2.50E 03	2.53E 03

Table D-3. Decay Power for the Iodine Isotopes

Iodine Isotope	a_i	g_i	λ_i
	Btu/min/Mw(t)	Btu/min/Mw(t)	Decay Constant, 1/min
128	0.0936	0.0196	2.7667×10^{-2}
130	0.1248	0.4425	9.2562×10^{-4}
131	2.8602	3.8540	5.9795×10^{-5}
132	8.1992	29.0702	5.0245×10^{-3}
133	9.7584	10.1569	5.5005×10^{-4}
134	12.4884	54.6539	1.3079×10^{-2}
135	5.8720	30.8284	1.7253×10^{-3}

The last term of Eq. (D-5), which determines the fraction of the total iodine adsorbed, is calculated by the computer using values of air velocity and time which are specified in the data cards. Therefore, the exponential is expressed in these terms by substituting for R:

$R = \text{air velocity (v) } \times \text{ area of charcoal bed}$
 so that we have: $1 - e^{-(a \times 600 \text{ vt/v})}$. Substituting values from Table D-1 gives

$$1 - e^{-\left[\frac{0.99 \times (600 \times 144) \text{ in.}^2 \text{ vt}}{451.880 \times 1728 \text{ in.}^3}\right]}$$

or

$$1 - e^{-1.0954 \times 10^{-4} \text{ vt}}$$

The figure 1.0954×10^{-4} is the first entry in data card (c) and is referred to as the buildup coefficient (BUCOEF). To assume instant loading of the iodine on the charcoal the factor 10^{-4} can be changed to 10^4 and the fraction will always be one.

The information needed to punch the cards for this problem is listed in Table C-1 (Appendix C). These cards are punched as indicated in Table D-4 and placed in the order listed at the end of the main deck. If it is desired to run more than one case, a second data deck is prepared with the necessary changes and placed after the first data deck with one blank card separating them. The last two cards shown on the Fortran Sheet (Table D-4) appear only once (after the last case).

Samples of the output for this problem are shown in Table D-5. Figure D-1 is a plot of maximum temperature vs time for air flows of 4, 20 and 40 ft/min. The temperature represented in this graph assumes that the available iodine is adsorbed immediately at time 0. Tables D-6 and D-7 are samples of the printout of variables that are associated with each problem.

Table D-4. Data Deck which was Used to Make the Calculation of Temperature Distribution with Instant Loading and Air Flow 4 ft/min.

CODED BY _____
DATE _____ REQUEST NO. _____

FORTRAN

PROBLEM _____
PROGRAM _____
PAGE _____ OF _____

STATEMENT						PAGE _____ OF _____																																																																																				
TYPE	NUMBER					CONT	FORTRAN STATEMENT																																																																										IDENTIFICATION									
	1	2	3	4	5		6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80									

3.3579D-02	4.7608D-04	1.0127D-03	9.2104D 00	1.0234D 00	0.2500D 00	A
0.0D 00	3.4722D-05	2.4000D-01	0.0625D 00			B
1.0954D 04	10.0D 00	18.0D 01	48.0D 01			C
9.3640D-02	1.9590D-02	2.7667D-02				D1
1.2480D-01	4.4249D-01	9.2562D-04				D2
2.8602D 00	3.8540D 00	5.9795D-05				D3
8.1992D 00	2.9070D 01	5.0245D-03				D4
9.7584D 00	1.0157D 01	5.5005D-04				D5
1.2488D 01	5.4654D 01	1.3079D-02				D6
5.8720D 00	3.0828D 01	1.7253D-03				D7

CHARCOAL ADSORBER TEMP. CALCULATION FOR 40 FT/MIN INSTANT LOADING

9	1	1	1	2	1	2
2						3
-1					48	4
	1	0.020	5	0.0	200.0	5
1	1	0.0	2.0			R1
1	CHAR	1.667D-04	2.026D-02			2
-1.0E+20	0.20	1.0E+20	0.20			
1		1				

Table D-4 (continued)

CODED BY _____		REQUEST NO. _____		PROBLEM _____	
DATE _____				PROGRAM _____	
				PAGE _____ OF _____	

FORTRAN

STATEMENT		FORTRAN STATEMENT																																																																						IDENTIFICATION									
TYPE	NUMBER																																																																																
1	2																																																																																

1	2										
1	1										
1	1.0										
2	1										
1	0.0										
0.0	2.0										
32											
0.0	2.0	4.0	6.0	8.0	10.0	12.0	14.0				
16.0	18.0	20.0	22.0	24.0	26.0	28.0	30.0				
32.0	34.0	36.0	38.0	40.0	42.0	44.0	46.0				
48.0	50.0	55.0	60.0	65.0	70.0	75.0	80.0				
90.0	100.0	110.0	120.0	130.0	140.0	150.0	160.0				
170.0	180.0	200.0									

/*
//

Table D-5. Printout of the Temperature Profile of the Charcoal Filter
8 min after Iodine was Deposited

RESULTS FROM TRANSIENT CALCULATIONS
TIME = 8.085570 00 TIME STEPS COMPLETED = 39

LATTICE POINT POINT NO.	POINT INDICES I J K	TEMPERATURES POINT TEMPERATURE
1	1 1 1	110.99478
2	2 1 1	130.14768
3	3 1 1	138.93338
4	4 1 1	145.90100
5	5 1 1	150.29654
6	6 1 1	152.24003
7	7 1 1	151.69924
8	8 1 1	148.92993
9	9 1 1	142.92464
10	10 1 1	135.25836
11	11 1 1	126.20796
12	12 1 1	116.49096
13	13 1 1	106.79148
14	14 1 1	97.74760
15	15 1 1	89.89929
16	16 1 1	83.26878
17	17 1 1	78.00382
18	18 1 1	73.94074
19	19 1 1	70.90143
20	20 1 1	68.68409
21	21 1 1	67.09923
22	22 1 1	65.98222
23	23 1 1	65.20000
24	24 1 1	64.69049
25	25 1 1	64.29931
26	26 1 1	63.97496
27	27 1 1	63.76167
28	28 1 1	63.59864
29	29 1 1	63.47230
30	30 1 1	63.37992
31	31 1 1	63.30526
32	32 1 1	63.26141
33	33 1 1	63.24613

LATTICE POINT POINT NO.	POINT INDICES I J K	TEMPERATURES POINT TEMPERATURE
----------------------------	---------------------------	--------------------------------------

LATTICE POINT POINT NO.	POINT INDICES I J K	TEMPERATURES POINT TEMPERATURE
----------------------------	---------------------------	--------------------------------------

LATTICE POINT POINT NO.	POINT INDICES I J K	TEMPERATURES POINT TEMPERATURE
----------------------------	---------------------------	--------------------------------------

Note: Points 1 and 33 indicate the temperature
of the air inlet and outlet, respectively,
of the charcoal filter.

Table D-6. Variables which can be Changed without Altering the
Computer Code and Which are Printed out with Each Problem.

BIGB1 0.335790D-01	BIGB2 0.476080D-03	BIGG 0.101270D-02	SMLB1 0.921040E C1	SMLB2 0.102340D 01	ESCFCT 0.250000D 00
GIT 0.0	GDEN 0.347220D-C4	GSPH 0.240000D CC	DELX 0.625000E-C1	DIMA 0.0	DIMB 0.0
BUCDEF 0.109540D 05	TMDLAY 0.100000D C2	HGGVEL 0.480000D 02	ACGVEL 0.480000E 02	RGH 0.180763D-01	ACH 0.180763D-01
AA(I)		GG(I)	LAMBDA(I)		
0.936400D-01		0.195900D-01	0.276670D-01		
0.124800D 00		0.442490D 00	0.925620D-C3		
0.286020D 01		0.385400D 01	0.597950D-C4		
0.819920D 01		0.290700D 02	0.502450D-C2		
0.975840D 01		0.101570D 02	0.550050D-C3		
0.124800D 02		0.546540D 02	0.130790D-01		
0.587200D 01		0.308280D 02	0.172530D-02		

Table D-7. A Printout of Variables for the Heat Transfer Section of Computer Code.

THE HEATING CODE WITH TEMPERATURE-DEPENDENT THERMAL PROPERTIES AND
NON-LINEAR AND SURFACE-TO-SURFACE BOUNDARY CONDITIONS.

THIS VERSION OF HEATING CAN HANDLE A MAXIMUM OF 1750 LATTICE POINTS.

INPUT RETURN

JOB DESCRIPTION-- CHARCOAL ADSORBER--RECHECK OF DECK 4 FT/MIN FACTOR 20 12/2/73

GEOMETRY TYPE NO. 9

NUMBER OF REGIONS 1

NUMBER OF MATERIALS 1

NUMBER OF INITIAL TEMPERATURE FUNCTIONS 1

NUMBER OF GENERAL POSITION DEPENDENT FUNCTIONS 2

NUMBER OF HEAT GENERATION FUNCTIONS 1

NUMBER OF TIME DEPENDENT FUNCTIONS 0

TYPE OF OUTPUT DESIRED 0

NUMBER OF POINTS IN GROSS X OR R LATTICE 2

NUMBER OF POINTS IN GROSS Y OR THETA LATTICE 0

NUMBER OF POINTS IN GROSS Z LATTICE 0

NUMBER OF DIFFERENT KINDS OF BOUNDARIES 0

NUMBER OF LATTICE POINTS FOR WHICH THE INITIAL TEMPERATURES ARE ENTERED 0

PROBLEM TYPE NUMBER -1

MAXIMUM NUMBER OF STEADY-STATE ITERATIONS 0

NUMBER OF S-S ITERATIONS BEFORE CALC BETA 0

NUMBER OF S-S ITERATIONS BEFORE EXTRAPOLATION 0

NUMBER OF DELTAS PER MONITOR PRINT 0

NUMBER OF TRANSIENT PRINTOUTS SPECIFIED 0

THE CONDUCTIVITY, DENSITY, AND HEAT CAPACITY ARE TEMPERATURE DEPENDENT.

CONVERGENCE CRITERION 0.0

INITIAL BETA 1.65599962

TIME INCREMENT 3.5000000E-02

NUMBER OF STABLE TIME STEPS UNTIL MODIFIED EXPLICIT METHOD IS ACTIVATED 20

INITIAL TIME 0.0

FINAL TIME 1.40000000 01

Figure D-1. Max Temperature vs Time For Various Air Flow Rates

Appendix E. STACK: An XTRAN Computer Program for Calculating Stack
Parameter vs Fraction of Decay Heat Removed from Charcoal
Adsorbers.

```

WRITE (1,99)
99 F'T(10/,SPRØGRAM STACK, REVISED 10/01/70$)
WRITE (1,100)
100 F'T($STACK DIAS. (FEET), MIN,MAX,INCRIMENT = $,Z)
A'T D1,D2,D3
WRITE (1,101)
101 F'T($STACK HEIGHTS (FEET) MIN, MAX,INCRIMENT = $,Z)
A'T Z1,Z2,Z3
WRITE (1,102)
102 F'T($CONTAINMENT AMB. TEMP. (DEG F) MIN,MAX,INC = $,Z)
A'T T1,T2,T3
WRITE (1,103)
103 F'T($TOTAL HEAT IN CHARCOAL BED (KW) = $,Z)
A'T QT
DISPLAY /,/,/,/,/,/
WRITE (1,215)
WRITE (1,216)
WRITE (1,217)
WRITE (1,218)
215 F'T($AMB.    DIAMET    HEIGHT    BED          STACK      STACK
      FRACTIONS)
216 F'T($TEMP    STACK    STACK    VELOCITY    VELOCITY    DP
      OF HEATS)
217 F'T($DEGF    FEET     FEET     FEET/MIN    FEET/MIN    IN
/H2O    (RATIO)$)
218 F'T($****    *****    *****    *****    *****
      *****    *****$)
DISPLAY /
DØ 18 TA=T1,T2,T3
DØ 16 DS=D1,D2,D3
DØ 17 Z=Z1,Z2,Z3
G = QT*3413.
DA = 39.675/(TA+460.)
TAVG = 0.5*(475. + TA)
DAVG = 39.675/(TAVG + 460.)
DPC = (DA-0.042433)*Z/5.1972
CU = 0.0
C = -.1
4 C = C + 0.1
5 CONTINUE
CALL SPH (TAVG,CPA)
W = C*Q/(CPA*(475.-TA))
C5 = 168000.*DAVG*CPA*(475.-TA)
VB = C*Q/C5
VS = (.500095*W)/(DS*DS)
VD=207.4074*VB
CALL REYN(TAVG,DAVG,VD,RED)
RED=0.947*RED
CALL REYN(TAVG,DAVG,VB,REB)
RES = 38.3836*VS*DS

```

```

IF(RED.LT.1500.) FD=16./RED
IF(RED.GT.1500..AND.RED.LE.3000.)FD= .011
IF(RED.GT.3000.)FD=.0014+.125/(RED*.32)
DPD= .00002325*FD*VD*VD*DAVG
IF(RES.LE.1500.) FS = 16./RES
IF (RES.GT.1500..AND.RES.LE.3000.) FS = .011
IF (RES.GT.3000.) FS = .0014 + .125/(RES*.32)
DPS =( 1.4104E-7*VS*VS*Z*FS/DS) + ( 5.2882E-8*VS*VS)
IF(REB.LE.400.) FB = 2400./REB
IF(REB.GT.400..AND. REB.LE.3000.) FB = 2601.75/(REB*.629)
IF(REB.GT.3000.) FB = 99.375/(REB*.225)
DPB = .00010692*FB*VB*VB*DAVG + .00002704*VB*VB*DAVG
DPT = DPB + DPS + DPD
IF(DPT.GT.DPC) GO TO 6
CL = C
DPTL =DPT
IF(CJ.EQ.0.0) GOT0 4
GO TO 7
6 CU = C
DPTU = DPT
7 FR = (ABS(DPT-DPC))/DPC
IF(FR.LT.0.000001) GO TO 25
C = (CU + CL)/2.
GO TO 5
25 WRITE(1,205) TA,DS,Z,VB,VS,DPT,C
205 F'T(1X,I3,3X,F6.3,3X,F6.2,3X,F8.3,3X,F8.3,3X,F6.4,3X,F6.4)
17 CONTINUE
16 CONTINUE
18 CONTINUE
END
SUBROUTINE REYN(X,DAVG,VB,REB)
IF(X.LE.0.0) VIS = .03939
IF((X.GT.0.0).AND.(X.LE.100.)) VIS=.03939 + .0000655*(100.-X)
IF((X.GT.100.).AND.(X.LE.200.)) VIS= .04594 +
.0000599*(200.-X)
IF((X.GT.200.).AND.(X.LE.300.))
VIS = .05193 + .0000555*(300.-X)
IF((X.GT.300.).AND.(X.LE.400.))
VIS = .05748 + .0000518*(400.-X)
IF((X.GT.400.).AND.(X.LE.475.))
VIS = .06266 + .000048933*(475.-X)
IF(X.GT.475.) VIS = .06633
IF(X.GT.475.) WRITE (1,295)
295 F'T($$STUPID, YOUR AMBIENT TEMP IS GREATER THAN THE
IGNITION TEMP JF YOUR CHARCOAL BEDS)
DB= .00517
REB = DB*2880.*VB*DAVG/VIS
RETURN
END
SUBROUTINE SPH (Y,CPA)
IF(Y.LE.100.) CA = .2406
IF((Y.GT.100.).AND.(Y.LE.200.)) CPA=.2406 + .000009*(Y-100.)
IF((Y.GT.200.).AND.(Y.LE.300.)) CPA=.2415 + .000016*(Y-200.)
IF((Y.GT.300.).AND.(Y.LE.400.)) CPA=.2431 + .000021*(Y-300.)
IF((Y.GT.400.).AND.(Y.LE.475.)) CPA=.2452 + .000025*(Y-400.)
RETURN
END
*?

```

PROGRAM STACK, REVISED 10/01/70

STACK DIAS. (FEET), MIN,MAX,INCRIMENT = 1 4 0.5

STACK HEIGHTS (FEET) MIN, MAX,INCRIMENT = 5 100 5

CONTAINMENT AMB. TEMP. (DEG F) MIN,MAX,INC = 100 100 0

TOTAL HEAT IN CHARCOAL BED (K.W) = 732

AMB. TEMP DEGF ****	DIAMET STACK FEET *****	HEIGHT STACK FEET *****	BED VELOCITY FEET/MIN *****	STACK VELOCITY FEET/MIN *****	STACK DP IN/H2O *****	FRACTION OF HEAT (RATIO) *****
100	1.000	5.00	0.151	672.618	0.0273	0.0490
100	1.000	10.00	0.208	929.459	0.0547	0.0678
100	1.000	15.00	0.249	1110.755	0.0820	0.0810
100	1.000	20.00	0.281	1252.407	0.1093	0.0913
100	1.000	25.00	0.307	1368.683	0.1367	0.0998
100	1.000	30.00	0.329	1467.040	0.1640	0.1070
100	1.000	35.00	0.348	1551.969	0.1914	0.1131
100	1.000	40.00	0.365	1626.419	0.2187	0.1186
100	1.000	45.00	0.380	1692.455	0.2460	0.1234
100	1.000	50.00	0.393	1751.581	0.2734	0.1277
100	1.000	55.00	0.405	1804.933	0.3007	0.1316
100	1.000	60.00	0.416	1853.393	0.3280	0.1351
100	1.000	65.00	0.426	1897.654	0.3554	0.1383
100	1.000	70.00	0.435	1938.281	0.3827	0.1413
100	1.000	75.00	0.443	1975.734	0.4101	0.1440
100	1.000	80.00	0.451	2010.391	0.4374	0.1466
100	1.000	85.00	0.458	2042.571	0.4647	0.1489
100	1.000	90.00	0.465	2072.547	0.4921	0.1511
100	1.000	95.00	0.471	2100.546	0.5194	0.1531
100	1.000	100.00	0.477	2126.765	0.5467	0.1551
100	1.500	5.00	0.333	660.022	0.0273	0.1083
100	1.500	10.00	0.470	932.329	0.0547	0.1529
100	1.500	15.00	0.570	1130.535	0.0820	0.1854
100	1.500	20.00	0.651	1289.722	0.1093	0.2116
100	1.500	25.00	0.718	1423.714	0.1367	0.2335
100	1.500	30.00	0.777	1539.686	0.1640	0.2526
100	1.500	35.00	0.828	1641.965	0.1914	0.2693
100	1.500	40.00	0.875	1733.402	0.2187	0.2843
100	1.500	45.00	0.916	1816.004	0.2460	0.2979
100	1.500	50.00	0.954	1891.239	0.2734	0.3102
100	1.500	55.00	0.989	1960.227	0.3007	0.3215
100	1.500	60.00	1.021	2023.836	0.3280	0.3320
100	1.500	65.00	1.051	2082.799	0.3554	0.3417
100	1.500	70.00	1.079	2137.658	0.3827	0.3507
100	1.500	75.00	1.104	2188.877	0.4101	0.3591
100	1.500	80.00	1.129	2236.857	0.4374	0.3669
100	1.500	85.00	1.151	2281.925	0.4647	0.3743
100	1.500	90.00	1.173	2324.371	0.4921	0.3813
100	1.500	95.00	1.193	2364.434	0.5194	0.3879

100	1.500	100.00	1.212	2402.333	0.5467	0.3941
100	2.000	5.00	0.568	633.160	0.0273	0.1846
100	2.000	10.00	0.817	911.185	0.0547	0.2657
100	2.000	15.00	1.002	1117.215	0.0820	0.3258
100	2.000	20.00	1.153	1285.337	0.1093	0.3748
100	2.000	25.00	1.282	1428.773	0.1367	0.4167
100	2.000	30.00	1.394	1554.453	0.1640	0.4533
100	2.000	35.00	1.495	1666.570	0.1914	0.4860
100	2.000	40.00	1.586	1767.892	0.2187	0.5156
100	2.000	45.00	1.669	1860.360	0.2460	0.5425
100	2.000	50.00	1.745	1945.401	0.2734	0.5673
100	2.000	55.00	1.816	2024.104	0.3007	0.5903
100	2.000	60.00	1.881	2097.320	0.3280	0.6116
100	2.000	65.00	1.943	2165.731	0.3554	0.6316
100	2.000	70.00	2.000	2229.894	0.3827	0.6503
100	2.000	75.00	2.054	2290.270	0.4101	0.6679
100	2.000	80.00	2.105	2347.245	0.4374	0.6845
100	2.000	85.00	2.154	2401.150	0.4647	0.7002
100	2.000	90.00	2.200	2452.262	0.4921	0.7151
100	2.000	95.00	2.243	2500.835	0.5194	0.7293
100	2.000	100.00	2.285	2547.074	0.5467	0.7428
100	2.500	5.00	0.835	595.545	0.0273	0.2714
100	2.500	10.00	1.226	875.055	0.0547	0.3987
100	2.500	15.00	1.521	1085.045	0.0820	0.4944
100	2.500	20.00	1.763	1257.893	0.1093	0.5732
100	2.500	25.00	1.971	1406.590	0.1367	0.6409
100	2.500	30.00	2.155	1537.905	0.1640	0.7008
100	2.500	35.00	2.321	1655.912	0.1914	0.7545
100	2.500	40.00	2.471	1763.300	0.2187	0.8035
100	2.500	45.00	2.610	1861.952	0.2460	0.8484
100	2.500	50.00	2.733	1953.255	0.2734	0.8900
100	2.500	55.00	2.857	2038.263	0.3007	0.9288
100	2.500	60.00	2.968	2117.804	0.3280	0.9650
100	2.500	65.00	3.073	2192.541	0.3554	0.9990
100	2.500	70.00	3.172	2263.013	0.3827	1.0312
100	2.500	75.00	3.265	2329.670	0.4101	1.0615
100	2.500	80.00	3.354	2392.891	0.4374	1.0903
100	2.500	85.00	3.438	2452.994	0.4647	1.1177
100	2.500	90.00	3.518	2510.254	0.4921	1.1438
100	2.500	95.00	3.595	2564.912	0.5194	1.1687
100	2.500	100.00	3.668	2617.179	0.5467	1.1925
100	3.000	5.00	1.111	550.707	0.0273	0.3613
100	3.000	10.00	1.672	828.413	0.0547	0.5436
100	3.000	15.00	2.097	1039.074	0.0820	0.6818
100	3.000	20.00	2.450	1213.824	0.1093	0.7964
100	3.000	25.00	2.755	1365.143	0.1367	0.8957
100	3.000	30.00	3.026	1499.556	0.1640	0.9839
100	3.000	35.00	3.272	1620.998	0.1914	1.0636
100	3.000	40.00	3.496	1732.072	0.2187	1.1365
100	3.000	45.00	3.703	1834.599	0.2460	1.2038
100	3.000	50.00	3.895	1929.922	0.2734	1.2663
100	3.000	55.00	4.075	2019.061	0.3007	1.3248
100	3.000	60.00	4.244	2102.819	0.3280	1.3798
100	3.000	65.00	4.403	2181.838	0.3554	1.4316

100	3.000	70.00	4.554	2256.638	0.3827	1.4807
100	3.000	75.00	4.698	2327.659	0.4101	1.5273
100	3.000	80.00	4.834	2395.264	0.4374	1.5716
100	3.000	85.00	4.964	2459.764	0.4647	1.6140
100	3.000	90.00	5.089	2521.430	0.4921	1.6544
100	3.000	95.00	5.208	2580.491	0.5194	1.6932
100	3.000	100.00	5.322	2637.152	0.5467	1.7304
100	3.500	5.00	1.379	502.054	0.0273	0.4484
100	3.500	10.00	2.126	773.898	0.0547	0.6912
100	3.500	15.00	2.699	982.564	0.0820	0.8775
100	3.500	20.00	3.178	1156.939	0.1093	1.0333
100	3.500	25.00	3.595	1308.805	0.1367	1.1689
100	3.500	30.00	3.968	1444.370	0.1640	1.2900
100	3.500	35.00	4.306	1567.402	0.1914	1.3998
100	3.500	40.00	4.616	1680.390	0.2187	1.5007
100	3.500	45.00	4.904	1785.082	0.2460	1.5942
100	3.500	50.00	5.172	1882.773	0.2734	1.6815
100	3.500	55.00	5.424	1974.443	0.3007	1.7634
100	3.500	60.00	5.661	2060.865	0.3280	1.8405
100	3.500	65.00	5.886	2142.656	0.3554	1.9136
100	3.500	70.00	6.099	2220.321	0.3827	1.9829
100	3.500	75.00	6.303	2294.280	0.4101	2.0490
100	3.500	80.00	6.496	2364.886	0.4374	2.1121
100	3.500	85.00	6.682	2432.439	0.4647	2.1724
100	3.500	90.00	6.860	2497.198	0.4921	2.2302
100	3.500	95.00	7.031	2559.389	0.5194	2.2858
100	3.500	100.00	7.195	2619.205	0.5467	2.3392
100	4.000	5.00	1.622	451.964	0.0273	0.5272
100	4.000	10.00	2.563	714.353	0.0547	0.8333
100	4.000	15.00	3.295	918.471	0.0820	1.0714
100	4.000	20.00	3.912	1090.363	0.1093	1.2719
100	4.000	25.00	4.452	1240.914	0.1367	1.4475
100	4.000	30.00	4.937	1375.932	0.1640	1.6050
100	4.000	35.00	5.378	1498.960	0.1914	1.7485
100	4.000	40.00	5.785	1612.356	0.2187	1.8808
100	4.000	45.00	6.163	1717.780	0.2460	2.0038
100	4.000	50.00	6.517	1816.460	0.2734	2.1189
100	4.000	55.00	6.851	1909.333	0.3007	2.2272
100	4.000	60.00	7.166	1997.132	0.3280	2.3296
100	4.000	65.00	7.465	2080.453	0.3554	2.4268
100	4.000	70.00	7.749	2159.776	0.3827	2.5193
100	4.000	75.00	8.021	2235.502	0.4101	2.6077
100	4.000	80.00	8.281	2307.971	0.4374	2.6922
100	4.000	85.00	8.530	2377.468	0.4647	2.7733
100	4.000	90.00	8.770	2444.244	0.4921	2.8512
100	4.000	95.00	9.001	2508.511	0.5194	2.9261
100	4.000	100.00	9.223	2570.460	0.5467	2.9984
100	1.000	5.00	0.151	672.618	0.0273	0.0490
100	1.000	10.00	0.208	929.459	0.0547	

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