AIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202

Centimeter

Inches

MANUFACTURED TO AIM STANDARDS
BY APPLIED IMAGE, INC.

1 of 1

DECLASSIFIED

HW-56323 RD

1

June 10, 1958

GENERAL ELECTRIC

HANFORD ATOMIC PRODUCTS OPERATION - RICHLAND, WASHINGTON

X

THIS DOCUMENT CONTAINS RESTRICTED DATA
DEFINED IN THE ATOMIC ENERGY ACT
AND ITS TRANSMISSION OR THE DISCLOSURE
OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED
PERSON IS PROHIBITED.

ION - RICHLAND, WASHINGTON
TITLE
RECORD CENTER FILE

SLUG TEMPERATURE AFTER H₂O
STOPPAGE

☐ OTHER OFFICIAL CLASSIFIED INFORMATION

THIS MATERIAL CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U. S. C. , SECS. 793 AND 794, THE TRANSMISSION OR REVELATION OF WHICH IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW.

S. S. Jones

W. F. Ecker

CIRCULATING COPY
RECEIVED 100. AREA

JUN 10 1958

RETURN TO

THIS DOCUMENT MUST NOT BE LEFT UNATTENDED OR WHERE AN UNAUTHORIZED PERSON ~~PERSON~~ ^{TECHNICAL INFORMATION FILES} MAY HAVE ACCESS TO IT. WHEN NOT IN USE, IT MUST BE STORED IN AN APPROVED LOCKED REPOSITORY WITHIN AN APPROVED GUARDED AREA. WHILE IT IS YOUR POSSESSION AND UNTIL YOU HAVE OBTAINED A SIGNED RECEIPT FROM CLASSIFIED FILES, IT IS YOUR RESPONSIBILITY TO KEEP IT AND ITS CONTENTS WITHIN THE LIMITS OF THIS PROJECT AND FROM ANY UNAUTHORIZED PERSON. ITS TRANSMITTAL TO, AND STORAGE AT YOUR PLACE OF RESIDENCE IS PROHIBITED. IT IS NOT TO BE DUPLICATED. IF ADDITIONAL COPIES ARE REQUIRED, OBTAIN THEM FROM THE RELATED ISSUING FILE. ALL PERSONS READING THIS DOCUMENT ARE REQUESTED TO SIGN IN THE SPACE PROVIDED BELOW.

[illegible]

A.E.C.-G.E.-RICHLAND, WASH.

(CLASSIFICATION)

DECLASSIFIED

TITLE: SLUG TEMPERATURE AFTER H₂O STOPPAGE

AUTHOR: S. S. Jones

DATE: June 10, 1958

This document consists of
34 pages, No. 1 of
1 copies.

Classification Cancelled and Changed To

DECLASSIFIED

By Authority of SE Gudeken

RLO-CG-4, 11-22-93

By DK Hanson, 12-17-93

Verified By Jenni Maley, 1-4-94

This document contains data as described in the Atomic Energy Act of 1946. It is not to be distributed or the contents of its content in any manner to an unauthorized person.

DECLASSIFIED

SYNOPSIS 825 RD 111
-2-
1. ~~CH G. Gager - W. Woods~~
2. RB Richards - PH Reinker 12-3-52
3. WK Alexander - MW Carbon

SLUG TEMPERATURE AFTER WATER FLOW FAILURE (7)

On the basis of numerous rough calculations it has generally been assumed that if the water flow to a tube were to stop, while pile operation continued, the tube central temperature would increase in a matter of seconds to dangerously high values. In several seconds the water around the central slugs would flash to steam, shortly thereafter the aluminum cans would melt and this would give good contact between the slug and the tube which would quickly melt. The bare uranium would react with the steam and possibly the pile gas atmosphere. Radioactive Xenon and fission products would be spread through the gas system, and the molten aluminum and uranium would fill up all of the cracks in the graphite and the tube would be impossible to discharge by all normal methods after the pile is shut down. If the pile were operated with this tube blocked off there would still be the problem of exceedingly high graphite temperatures around it, and the spread of contamination in the gas system. Because these problems are expected with an undetected water failure in a pile, where the operation is maintained, a program is underway to ensure proper and sufficient tube instrumentation to scram the pile before boiling starts in a tube.

A recent report of the Design Section⁽¹⁾ concluded that the uranium would not melt until 10 minutes after loss of water rather than the one minute previously expected. In this Design report a derivation is presented giving the increase in graphite bore temperature above the lattice boundary temperature during the unsteady state period of graphite temperature increase. This equation has been checked using a graphite thermal conductivity revised for the effect of increased temperature and a specific heat revised for the liberation of stored energy. Substantially the same results were obtained. One of the basic assumptions in this derivation was that of a homogeneous graphite medium around the metal. The actual condition of the graphite is shown in Figure 1. This indicates that there is a definite line of resistance and partial separation between the tube block and the

(1) Foresman, M.E., "An Analysis of the Economics and Hazards Associated with Process Tube Instrumentation", HW-29970, November 13, 1953.

DECLASSIFIED

surrounding filler blocks. Experimental tests of the heat transferred across blocks in good physical contact have given thermal conductances on the order of 150 Chu/hr, ft², °C(2,3) or if we wish to consider a gas gap, this corresponds to a gap of 0.2 mils with a CO₂ atmosphere and 2 mils with helium. It is probable that the actual average gas gap between the tube block and the filler block is larger than this 0.2 mils value.

The simplified method used in this report is first compared with the method presented in the Design report to obtain a comparison of the two methods using the same assumptions. This is shown in Table I, and indicates that the approximate method agrees reasonably well with the more refined derivation. However, when the resistance between the tube block and the filler blocks is considered a much different result is obtained. In order for the heat to flow away from the tube block to the large graphite sink formed by the filler blocks, there must be an appreciable increase in the temperature of the tube block. This causes a large increase in the graphite tube block temperature and an even greater increase in the graphite bore temperature. This is shown in Table II. The derivation of the equations used in Table II are given as an appendix to this report. The results obtained in Table II show that the uranium slugs reach their melting point in less than a minute after water flow stops at an operating tube level of 650 KW/tube or an approximate pile level of 900 Megawatts.

It should be noted that the effect of the exothermic reaction that has been observed between uranium and steam has not been included, nor has the possible increase in slug temperature above that of the graphite bore. In a uniform graphite channel with no cracks or tube block separations the aluminum can, end caps, and tube will submerge the uranium slugs nearly completely in molten aluminum. However, the weep holes and any cracks or fissures will permit some or all of the molten aluminum to drain from around the slugs. This would cause the top of the slug to reach its melting point in a matter of about 20 seconds after the water flow stops, if all the aluminum drains from around the slugs. The proposed higher power levels would decrease the time before melting.

DECLASSIFIED

- (2) Kuniansky, S., "Compendium of Pile Data", TNX-5, October 12, 1943, page 1-201.
- (3) Fields, S.R., "Calculated Temperature Distributions in a Graphite Lattice - Report No. 1", HW-28725, July 15, 1953, page 4.

further.

Another consideration is that the use of enriched C and J slugs would reduce the melting temperature from 1100 C to close to 700 C, which means that the C and J slugs having an aluminum matrix would melt in a matter of 15 to 20 seconds after water flow failure.

A further argument for the necessity of prompt pile scram after water flow failures is the fact that we will probably have quite serious conditions produced several seconds after the aluminum melts. At this time the aluminum will flow into all the cracks and crevices and lock the charge into the graphite, while the exposed uranium will react vigorously with the steam and possibly the pile gas atmosphere. The uranium reacts with steam exothermically to form very fine particles of UO_2 , the majority of these are less than .0017 inch diameter and this highly radioactive material could easily be spread throughout the gas system and possibly the effluent water system.

The only conclusion that can be made from these calculations and estimations of the effects of increased levels and the decreased slug melting points in C and J slugs is that the problem of water flow failure to a tube is a very serious one and that we are justified in spending considerable time, money and effort in preventing such a condition from occurring.

Stephen S. Jones
PILE TECHNOLOGY SUB-SECTION
ENGINEERING DEPARTMENT

W. Ekern
PILE TECHNOLOGY SUB-SECTION
ENGINEERING DEPARTMENT

SS Jones:WF Ekern:msp

DECLASSIFIED

DECLASSIFIED

(I)

HW-56323 RD 000005

TABLE I
SLUG TEMPERATURE AFTER WATER FLOW FAILURE ASSUMING HOMOGENEOUS GRAPHITE

A. Constants

α^2 - Thermal Diffusivity ($k/\rho c_p = .049 \text{ ft}^2/\text{hr}$)

ρ - Graphite Density - 106 lbs/cu.ft

c_p - Graphite specific heat = .45 (Chu/lb, C)

k - Graphite thermal conductivity = 2.3 Chu/hr, ft², C (40 lb/ft)

q_T - Specific power of central tube = 76,000 Chu/hr, ft

w - Weight of graphite lattice of assumed radius = 4.18" = 38.8 lbs/ft

B. Theoretical Solution

$$\frac{t_i - t_a}{t_m - t_a} = 1 - 2 \sum_{n=1}^{\infty} \frac{J_0\left(\frac{\delta_n r_i}{r_a}\right) e^{-\left(\frac{\alpha \delta_n^2}{r_a^2}\right) \theta}}{\delta_n J_1(\delta_n)}$$

where t_m - ultimate bore temperature at infinite time = 7500 C.

δ_n - roots of J_0 Bessel's function

r_i - graphite bore radius = 0.87"

r_a - Lattice radius = 4.18"

$T_u = 4500$

Results

θ - minutes after Al melts*	5	10	15
t_i - gr. bore temperature, C	677	1054	1730

C. Approximate Solution

$$(t_i - t_a) = q_T / \left(\frac{w c_p}{2\theta} + \frac{\pi k}{\ln r_a/r_i} \right)$$

Results

θ - minutes after Al melts*	5	10	15
t_i - gr. bore temperature, C	860	1160	1460

2
825

* In the equations θ is in hours.

1130 1870 2440

1690 2300 2820 1015

DECLASSIFIED

TABLE II
SLUG TEMPERATURE AFTER WATER FLOW FAILURE
CONSIDERING THERMAL RESISTANCE BETWEEN TUBE AND FILLER BLOCKS

A. Constants

c_p - graphite specific heat, corrected, for release of graphite stored energy
 ($C_{p_a} = .2$: Tube Block) ($C_{p_c} = .3$: Filler Block)

h - thermal conductance between tube and filler blocks = 150 Chu/hr, ft², C

k - graphite thermal conductivity, corrected for effect of increased temperature

($K_a = 6$ tube block) ($k_c = 12$ filler blocks) 250°

q_t - specific power of central lattice - 76,000 Btu/hr, ft

w_a - Weight of graphite in one foot length of tube block - 11.2 lbs/ft

w_c - weight of surrounding filler blocks - 103 lbs/ft

q_b - heat flow from tube block to filler block.

B. Approximate Solution

a. Filler Block

$$\left[\frac{(w c_p)_c}{2\theta} + \frac{\pi k_c}{\ln(r_o/r_a)} \right] (t_b - t_c) = q_b$$

b. Resistance between Filler and tube Block

$$q_b = h \left(\frac{2\pi r_a}{12} \right) \left(\frac{t_a - t_b}{2} \right) = 92.7 (t_a - t_b)$$

c. Tube Block

$$(1.) \left[\frac{(w c_p)_a}{2\theta} + \frac{\pi k_a}{\ln(r_o/r_i)} \right] t_i + \left[\frac{(w c_p)_a}{2\theta} - \frac{\pi k_a}{\ln(r_o/r_i)} \right] t_a = q_T + \frac{(w c_p)_a}{\theta} t_c$$

$$(2.) q_b = \left[\frac{\pi k_a}{\ln(r_o/r_i)} \right] (t_i - t_a)$$

C. Results

TIME seconds after Al melts	GRAPHITE TEMPERATURE - °C			
	Bore 120	Tube t_a	Filler t_b	Boundary t_c
47	1100	565	459	450

[REDACTED]

DECLASSIFIED

APPENDIX

APPROXIMATE DETERMINATION OF SLUG TEMPERATURE AFTER WATER FLOW FAILURE

A. Nomenclature

A - area perpendicular to heat flow - sq. ft

C_p - heat capacity - Chu/lb, C

h - Coefficient of thermal conductance between graphite tube block and the filler blocks Chu/hr, ft, C

k_g - thermal conductivity of the graphite Chu/hr, ft, C

q_b - heat flow into the filler blocks Chu/hr, ft. of length

q_t - total heat generated in the tube lattice - Chu/hr, ft. of length

r_a - Radius of graphite cylinder having area equal to that of tube block - in.

r_c - Radius of graphite cylinder having area equal to that of the surrounding filler blocks - in. (See Figure 1)

t_a - temperature of graphite at edge of tube block - C

t_b - temperature of graphite filler blocks adjacent to tube block - C

t_c - temperature of graphite at outer edge of filler blocks - C

t_i - temperature of graphite tube block bore - C

w_a - weight of graphite in the tube block - 11.2 lbs/ft of length

w_c - weight of graphite in the surrounding filler blocks - 103 lbs/ft of length

θ - time after aluminum melts in hours (it will take about 5 seconds for the aluminum and tube to melt at a 40 kw/ft heat output)

δ_n - roots of the Bessel function

$J_0(x)$ - Bessel's function of the first kind, zero order

$J_1(x)$ - Bessels function of the first kind, first order

DECLASSIFIED

B. Case I. Homogeneous Graphite

The heat generated in the lattice including that in the uranium goes either to increase the lattice temperature or flows from the lattice to the surrounding lattices.

This is represented by the equation:

$$w c_p \frac{\Delta t}{\Delta \theta} + \frac{2 \pi k (t_i - t_a)}{\ln(r_o/r_i)} = q_T \quad (1)$$

Sensible heat absorbed
in the lattice

Heat flowing thru
the lattice

Total heat
generated in
the lattice

The lattice is assumed to be at a uniform temperature, t_a , at the time the aluminum melts and forms an excellent bond between the graphite and the uranium.

Equation (1) may be expanded to give the average conditions between time 0 and θ :

$$\frac{(w c_p) \left(\frac{t_i + t_a}{2} - t_a \right)}{\Delta \theta} + \frac{2 \pi k \left(\frac{t_i - t_a}{2} \right)}{\ln(r_o/r_i)} = q_T \quad (2)$$

and combining terms:

$$(t_i - t_a) = q_T / \left(\frac{w c_p}{2 \Delta \theta} + \frac{\pi k}{\ln(r_o/r_i)} \right) \quad (3)$$

In this equation the heat generated in the graphite is assumed to flow into it along with the heat produced in the uranium. Also the heat capacity and thermal conductivity of the graphite are assumed constant over the period 0 to θ .

DECLASSIFIED

CASE II. Graphite with Thermal Resistance between Tube Block and Filler Blocks

The physical representation of this problem is shown in Figure 1. The filler block layer is carried out to the adjacent tube blocks, and the square boundaries are represented by circles such that the circular area is equal to the square, i.e.,

$$\pi r^2 = s^2 \quad (4)$$

Using the preceding method adapted for the change in conditions we obtained the following equations:

1. Filler blocks

$$\frac{(wC_p)_c \left(\frac{t_b + t_c}{2} - t_c \right)}{s} + \frac{2\pi k_c \left(\frac{t_b - t_c}{2} \right)}{\ln(r_c/r_a)} = q_B \quad (5)$$

Sensible heat absorbed
in filler blocks
Heat flowing thru
filler blocks
Heat flowing
thru tube
block

and simplifying:

$$\left[\frac{(wC_p)_c}{2s} + \frac{\pi k_c}{\ln(r_c/r_a)} \right] (t_b - t_c) = q_B \quad (6)$$

2. Resistance between Filler and Tube Blocks

$$q_B = h A \left(\frac{t_a - t_b}{2} \right) = h \left(2\pi \frac{r_a}{12} \right) \left(\frac{t_a - t_b}{2} \right) \quad (7)$$

from references (2) (3) $h = 150$, Chu/hr. ft.² C; and the equivalent radius of the tube block is 2.36 inches. Therefore:

$$q_B = 92.7 (t_a - t_b) \quad (8)$$

where the equivalent radius of the tube block () is equal to 2.36 inches.

3. Tube Block

$$\frac{(wC_p)_a \left(\frac{t_i + t_a}{2} - t_c \right)}{s} + \frac{2\pi k_a \left(\frac{t_i - t_a}{2} \right)}{\ln(r_a/r_i)} = q_T \quad (9)$$

Sensible heat absorbed
in the tube block
Heat flowing thru
the tube block
Total heat generated
in the lattice

DECLASSIFIED

000011

And rearranging:

$$\left[\frac{(wC_p)_a}{2\theta} + \frac{\pi k_a}{\ln(r_o/r_i)} \right] t_i + \left[\frac{(wC_p)_a}{2\theta} - \frac{\pi k_a}{\ln(r_o/r_i)} \right] t_a = q_T + \frac{(wC_p)_a}{\theta} t_c \quad (9)$$

This is three equations and four unknowns, (t_b , t_a , t_i , q_b). Equations 6 and 7 may be combined to eliminate q_b :

$$\left[\frac{(wC_p)_c}{2\theta} + \frac{\pi k_c}{\ln(r_c/r_a)} \right] (t_b - t_c) = 92.7(t_a - t_b) \quad (10)$$

And finally a fourth equation may be written that the heat flowing through the tube block must be equal to the heat flowing across the tube filler block resistance, (11).
Thus.

$$\left[\frac{\pi k_a}{\ln(r_o/r_i)} \right] (t_i - t_a) = 92.7(t_a - t_b) \quad (11)$$

This gives three equations and three unknowns that are most readily solved by a trial and error solution, assuming a value for t_b . Solve for t_a from equation (10).

4. Trial and Error Solution

Solve for t_a from equation (10):

$$t_a = \frac{\left[\frac{(wC_p)_c}{2\theta} + \frac{\pi k_c}{\ln(r_c/r_a)} \right] (t_b - t_c)}{92.7} + t_b$$

Then solving for t_i from equation (9)

$$t_i = \frac{q_T + \frac{(wC_p)_a}{\theta} t_c - \left(\frac{(wC_p)_a}{2\theta} - \frac{\pi k_a}{\ln(r_o/r_i)} \right) t_a}{\left[\frac{(wC_p)_a}{2\theta} + \frac{\pi k_a}{\ln(r_o/r_i)} \right]}$$

And finally checking the assumed value of t_b by equation (11)

$$t_b = t_a - \frac{\left(\frac{\pi k_a}{\ln(r_o/r_i)} \right) (t_i - t_a)}{92.7}$$

DECLASSIFIED

TABLE I: SLUG TEMPERATURE AFTER WATER FLOW FAILURE ASSUMING HOMOGENEOUS GRAPHITE¹

A- CONSTANTS

- α^2 - Thermal Diffusivity $\left(\frac{k}{\rho c_p}\right) = .049 \text{ ft}^2/\text{hr}$
 ρ - Graphite Density = 106 lbs/cu. ft.
 c_p - Graphite specific heat = .45 Chu/lb, °C
 k - Graphite thermal conductivity = 2.3 Chu/hr, ft², °C
 q_T - Specific Power of Central tube = 76,000 Chu/hr, ft
 w - Weight of graphite Lattice of assumed radius = 4.18" = 36.8 lbs/ft.

B- THEORETICAL SOLUTION

$$\frac{t_i - t_a}{t_m - t_a} = 1 - 2 \sum_{n=1}^{\infty} \frac{J_0\left(\delta_n \frac{r_i}{r_a}\right)}{\delta_n J_1(\delta_n)} e^{-\left(\frac{\alpha \delta_n}{r_a}\right)^2 \theta}$$

where

δ_n = roots of J_0 Bessel's function
 r_i = graphite bore radius = 0.87"
 r_a = Lattice radius = 4.18"

Results

θ - minutes after Al melts *	5	10	15
t_i - gr. bore temp. °C	677	1054	1730

C- APPROXIMATE SOLUTION

$$(t_i - t_a) = q_T / \left(\frac{w c_p}{2\theta} + \frac{\pi k}{\ln \frac{r_a}{r_i}} \right)$$

Results

θ - minutes after Al melts *	5	10	15
t_i - gr. bore temp. °C	1260	1560	1860

DECLASSIFIED

* In the equations θ is in hours.

000013

TABLE II: SLUG TEMPERATURE AFTER
WATER FLOW FAILURE, CONSIDERING
THERMAL RESISTANCE BETWEEN TUBE
AND FILLER BLOCKS

A - CONSTANTS

- C_p - Graphite specific heat, corrected for release of graphite stored energy (2)
($C_{pa} = .2$ Tube block) ($C_{pc} = .3$ Filler Block)
- h - Thermal conductance between tube and filler blocks = 150 Chu/hr, ft², °C
- k_e - Graphite Thermal conductivity, corrected for effect of increased temperature.
($k_{ea} =$) ($k_{ec} =$)
- q_T - Specific Power of central lattice = 76,000 Chu/hr, ft.
- w_a - Weight of graphite in one ft. length of tube block = 11.2 lbs/ft.
- w_c - Weight of surrounding filler block = 103 lbs/ft.
- q_B - Heat flow from tube block to filler block - Chu/hr, ft.

B - APPROXIMATE SOLUTION

(a) Filler Block

$$\left(\frac{(wC_p)_c}{2\theta} + \frac{\pi k_e}{\ln \frac{r_o}{r_a}} \right) (t_b - t_c) = q_B$$

(b) Resistance between Filler & Tube Block

$$q_B = h \left(\frac{2\pi r_a}{12} \right) (t_a - t_b) = 92.7 (t_a - t_b)$$

(c) Tube Block

$$(1) \left(\frac{(wC_p)_a}{2\theta} + \frac{\pi k_a}{\ln \frac{r_o}{r_i}} \right) t_i + \left(\frac{(wC_p)_a}{2\theta} - \frac{\pi k_a}{\ln \frac{r_o}{r_i}} \right) t_a = q_T + \frac{(wC_p)_a}{\theta} t_c$$

$$(2) q_B = \left(\frac{\pi k_a}{\ln \frac{r_o}{r_i}} \right) (t_i - t_a)$$

DECLASSIFIED

C. RESULTS

Seconds after t _i Al melts	46	Graphite Temp. °C	t _i Bore	t _a Tube Bl	t _b Filler	t _c Boundary
			1100	565	459	450

APPENDIX

APPROXIMATE DETERMINATION OF SLUG TEMPERATURE AFTER WATER FLOW FAILURE

A. Nomenclature

A - area perpendicular to heat flow - sq.ft.

C_p - heat capacity - Chu/lb, °C

h - Coefficient of thermal conductance between graphite tube block and the filler blocks
Chu/hr, ft², °C

k_g - Thermal conductivity of the graphite Chu/hr, ft, °C

q_b - Heat flow into the filler blocks Chu/hr, ft. of length.

q_t - Total Heat generated in the tube lattice - Chu/hr, ft of length

r_a - Radius of graphite cylinder¹ having area equal to that of tube block - in.

r_c - Radius of graphite cylinder¹ having area equal to that of the surrounding filler blocks. - (See figure 1.)
- in.

t_a - Temperature of graphite at edge of tube block - C

t_b - Temperature of graphite filler blocks adjacent to tube block - C

t_c - Temperature of graphite at outer edge of filler blocks - C

t_i - Temperature of graphite tube block bore - C

w_a - Weight of graphite in the tube block - 11.2 lbs/ft of length.

w_c - Weight of graphite in the surrounding filler blocks - 103 lbs/ft of length.

θ - Time after aluminum melts in hrs. (it will take about 5 seconds for the aluminum and tube to melt at a 40 Kw/ft. heat output.)

δ_n - J_0 roots of the Bessel function.

$J_0(x)$ - Bessel's function of the first kind, zero order.

$J_1(x)$ - " " " " " " first order

DECLASSIFIED

B. Case I, Homogeneous Graphite

The heat generated in the lattice including that in the uranium goes either to increase the lattice temperature or flows from the lattice to the surrounding lattices.

This is represented by the equation:

$$\boxed{w c_p \frac{\Delta t}{\Delta \theta} + \frac{2 \pi k \Delta t}{\ln r_o / r_i}} = q_T \quad (1)$$

Sensible Heat Increase in the lattice	Heat flow across the lattice	Total heat generation
---	------------------------------------	-----------------------------

The lattice is assumed to be at a uniform temperature, t_a , at the time the aluminum melts and forms an excellent bond between the graphite and the uranium.

Equation (1) may be expanded to give the average conditions between time 0 and θ :

$$\frac{w c_p \left(\frac{t_i + t_a}{2} - t_a \right)}{\Delta \theta} + \frac{2 \pi k \left(\frac{t_i - t_a}{2} \right)}{\ln r_o / r_i} = q_T \quad (2)$$

and combining terms:

$$(t_i - t_a) = q_T / \left(\frac{w c_p}{2 \theta} + \frac{\pi k}{\ln r_o / r_i} \right) \quad (3)$$

In this equation the heat generated in the graphite is assumed to flow into it along with the heat produced in the uranium. Also the heat capacity and thermal conductivity of the graphite are assumed constant over the period 0 to θ .

HW-56323 RD

Case II, Graphite with Thermal Resistance between Tube Block and Filler Blocks 000016

The physical representation of this problem is shown in Figure 1. The filler block layer is carried out to the adjacent tube blocks, and the square boundaries are represented by circles such that the circular area is equal to the square, i.e.,

$$\pi r^2 = A^2 \quad (4)$$

Using the preceding method adapted for the change in conditions we obtained the following equations:

1. Filler blocks

$$\frac{(wcp)_c \left(\frac{t_b + t_c}{2} - t_c \right)}{\Delta t} + \frac{2\pi k_c \left(\frac{t_b - t_c}{2} \right)}{\ln r_c/r_a} = q_B \quad (5)$$

Sensible heat absorbed Heat flowing through
in Filler blocks filler blocks

and simplifying:

$$\left(\frac{(wcp)_c}{2\Delta t} + \frac{\pi k_c}{\ln \frac{r_c}{r_a}} \right) (t_b - t_c) = q_B \quad (6)$$

2. Resistance between Filler and Tube Blocks

$$q_b = h A \left(\frac{t_a - t_b}{2} \right) = h \left(\frac{2\pi r_a}{12} \right) \left(\frac{t_a - t_b}{2} \right)$$

from () () $h \approx 150$, therefore:

$$q_b = 92.7 (t_a - t_b) \quad (7)$$

Where the (r_a) is the equivalent radius of the tube block equal to 2.36 inches.

3. Tube Block

$$\frac{(wcp)_a \left(\frac{t_i + t_a}{2} - t_c \right)}{\Delta t} + \frac{2\pi k_a \left(\frac{t_i - t_a}{2} \right)}{\ln r_a/r_i} = q_T \quad (8)$$

Sensible heat in the Heat flowing thru Total
tube block the tube block heat
generated

DECLASSIFIED

Rearranging:

$$\left(\frac{w c_p a}{2 \Delta \theta} + \frac{\pi k a}{\ln \frac{r_a}{r_i}} \right) t_i + \left(\frac{w c_p a}{2 \Delta \theta} - \frac{\pi k a}{\ln \frac{r_a}{r_i}} \right) t_a = q_T + \frac{w c_p a}{\Delta \theta} t_c \quad (11)$$

This is three equations and four (t_b, t_a, t_i, q_b) unknowns. Equations ⁶~~6~~ and ⁷~~6~~ may be combined to eliminate q_b :

$$\left(\frac{w c_p c}{2 \Delta \theta} + \frac{\pi k c}{\ln \frac{r_c}{r_a}} \right) (t_b - t_c) = 92.7 (t_a - t_b) \quad (10)$$

And finally a third equation may be written that the heat flowing through the tube block must be equal to the heat flowing across the tube filler block resistance ⁹~~9~~. Thus:

$$\left(\frac{\pi k a}{\ln \frac{r_a}{r_i}} \right) (t_i - t_a) = 92.7 (t_a - t_b) \quad (11)$$

This gives three equations and three unknowns that are most readily solved by a trial and error solution, assuming a ^{value}~~value~~ for t_b . Solving for t_a from equation ^e~~(9)~~ (10)

$$t_a = \frac{\left(\frac{w c_p c}{2 \Delta \theta} + \frac{\pi k c}{\ln \frac{r_c}{r_a}} \right) + 92.7 t_b}{92.7} \quad (12)$$

Then solving for t_i from equation ⁽⁸⁾~~(8)~~ (9)

$$t_i = \frac{q_T + \left(\frac{w c_p a}{\Delta \theta} \right) t_c - \left(\frac{w c_p a}{2 \Delta \theta} - \frac{\pi k a}{\ln \frac{r_a}{r_i}} \right) t_a}{\left(\frac{w c_p a}{2 \Delta \theta} + \frac{\pi k a}{\ln \frac{r_a}{r_i}} \right)}$$

assumed value of t_b by equation (10)

And finally checking the ~~assumption by equation (10)~~

$$t_b = \frac{\left(\frac{\pi k a}{\ln \frac{r_a}{r_i}} \right) (t_i - t_a) + 92.7 t_a}{92.7}$$

DECLASSIFIED

Iⁿ Consider Joint Tube Block [REDACTED] 323 RD
 (N) Equivalent radius. same area as sq. block 000018

$$\pi r_a^2 = (4.188)^2$$

$$r_a = 2.36$$

(b) Assume $t_a = \text{constant} = 400^\circ\text{C}$

(c) Heat Capacity Metal $\approx 0.6 \text{ cal/in}^3/\text{ft}, ^\circ\text{C}$

(d) Heat Capacity Block

$$C_p = 0.5 \cdot 0.3 \cdot 0.2 \text{ cal/in}^3/\text{ft}, ^\circ\text{C}$$

$$\text{Volume} = \pi \left[(2.36)^2 - (0.87)^2 \right] (12) = 182 \text{ in}^3/\text{ft}$$

$$\text{Weight} = \frac{11.2(182)}{1000} = 0.0615 \text{ lbs/in}^2$$

$$W = 0.0615(182) = 11.2 \text{ lbs/ft}$$

$$W_{cp} = (0.2)(11.2) = 2.24$$

DECLASSIFIED

I

Assume uniform - metal temp, inside

at 700°C

$$\frac{w c_p}{2} \left(\frac{t_1 + t_2}{2} - t_a \right) + w q_m \left[t_1 - t_2 \right]$$

Tube block
Metal

$$+ 2\pi h_c \left(\frac{t_1 - t_2}{2} \right) = \frac{L_1}{r_a} \frac{r_1}{r_2} = \frac{2.36}{1.87} = 1.0$$

g_T

Assume $h_c = 4$ ($h_c = 2.5$ for tube block)

$$\frac{2.24}{2} (t_1 - t_2) + 0.6 \left[\frac{t_1 - t_2}{2} \right] + 1.12 (t_1 - t_2) / \Delta t + 0.6 \frac{\Delta t}{(t_1 - t_2)} = \frac{2.24}{2} (t_1 - t_2) + 0.6 \left[\frac{t_1 - t_2}{2} \right] + 1.12 (t_1 - t_2) / \Delta t + 0.6 \frac{\Delta t}{(t_1 - t_2)} = g_T$$

Example

$$\Delta t = \frac{68}{2} = 34 \text{ hys}, \quad g_T = 76,000 \text{ Ch/hys}$$

$$34 t_1 - 13600 + 18.1 t_1 - 12.6 t_1 + 12.6 t_1 - 540 = 76,000$$

$$64.6 t_1 = 167,200$$

$$t_1 = 1660^\circ C$$

DECLASSIFIED

$$h_c = 1.04 \left(\frac{t_1 + t_2}{2} \right) = 12.15 (1.04) (1230)$$

000019

NW56323R0

I

Example 2nd Trial (2 minutes)

Assume $T_0 = 7$

$$34 t_1 - 13,600 + 18 t_1 - 12,600 + 22 t_1 - 8,800 = 76,000$$

$$74 t_1 = 117,200$$

$$t_1 = 1580^\circ \text{C}$$

Heat Flowing out of tube block,

$$= 22(1610 - 400) = 26,600 \text{ Chu/hr. ft.}$$

As compared with normal lattice
flow of $\frac{.05}{.94}(76,000) = \underline{4,050}$

From this it is obvious that the
assumption of constant T_a is
incorrect.

DECLASSIFIED

Ia solve for variable r_a

$$\begin{aligned}
 a - (w c_p) \frac{\Delta t}{\rho \Delta \theta} &= \frac{(1.2)(\pi)(r_a^2 - .17^2)(12)(.0615)(\frac{t_1 + t_a}{2} - t_a)}{\Delta \theta} \\
 &= \frac{(.463 r_a^2 - .35)(t_1 - t_a)}{\Delta \theta} \\
 &= \frac{(.231 r_a^2 - .18)(t_1 - t_a)}{\Delta \theta}
 \end{aligned}$$

$$b - (w c_p)_m \frac{\Delta t}{\Delta \theta} = \frac{0.3(t_1 - t_a - 300)}{\Delta \theta}$$

$$c - 2\pi k_G \frac{dl}{dx} = \frac{2\pi k_G(t_1 - t_a)}{\frac{\ln \frac{r_1}{.17}}{2}} = \frac{22(t_1 - t_a)}{\ln \frac{r_a}{.17}}$$

$$\therefore \frac{(.231 r_a^2 - .18)(t_1 - t_a)}{\Delta \theta} + \frac{0.3(t_1 - t_a - 300)}{\Delta \theta} + \frac{22(t_1 - t_a)}{\ln \frac{r_a}{.17}} = \dot{q}_T$$

DECLASSIFIED

Ia) cont.Set $\Delta t = 2$ minutes (0.33 hrs)Then

$$\left[(7r_0^2 - 5.45) + \frac{22}{\ln \frac{r_0}{1.87}} + 9.1 \right] (t_1 - t_a) = 78,700$$

$$\left[7r_0^2 + \frac{22}{\ln \frac{r_0}{1.87}} + 3.6 \right] (t_1 - t_a) = 78,700$$

r_0	r_0^2	$7r_0^2$	$\ln \frac{r_0}{1.87}$	$\frac{22}{\ln \frac{r_0}{1.87}}$	$\sum (t_1 - t_a)$	% FL	
1	1	7	.14	156	167	470	93
1.5	1	15.2	.54	141	.61	1290	67
3	9	63	1.24	18	85	930	21
5	25	175	1.75	12.6	204	386	6.2
7	49	343	2.08	10.6	357	220	3
12	144	1008	2.62	8.4	1020	77	0.8

t

For $\theta = 2$ min

DECLASSIFIED

Temp Drop Across Graphite

Assuming all heat generated in graphite to flow from t_i to t_o i.e. $q_o = 0$ then

$$w c_p \frac{dt}{ds} = -k \left[\frac{\partial^2 t}{\partial r^2} + \frac{1}{r} \frac{\partial t}{\partial r} \right]$$

$$\frac{dt}{ds} = - \frac{k}{w c_p} \left[\right] = -\alpha \left(\frac{\partial^2 t}{\partial r^2} + \frac{1}{r} \frac{\partial t}{\partial r} \right)$$

DECLASSIFIED

Let $t = T R$ where T is independent of R
 R " " " T

$$R \frac{dT}{ds} = -\alpha T \left(\frac{d^2 R}{dr^2} + \frac{1}{r} \frac{dR}{dr} \right)$$

$$\frac{1}{T} \frac{dT}{ds} + \frac{\alpha}{R} \left(\frac{d^2 R}{dr^2} + \frac{1}{r} \frac{dR}{dr} \right) = -\mu^2 = \text{separation constant}$$

DECLASSIFIED

$$t_{0B} - t_0 = \frac{3kH}{g_s}$$

(b) Return temperature at t_0

$$g_s = g_T - w_p \left(\frac{t_i + t_0}{2} - t_0 \right) \Delta \theta$$

(a) Heat flow to surrounding tubes.

4. Additional conditions not used for solution.

$$\left(\frac{dT}{d\theta} \right)_{r=r_1} = -m g_T$$

3. At $\left(\frac{dT}{d\theta} \right)_{r=r_1} = \text{constant}$ proportional to the heat flow through graphic.

2. At $t(r_0, \theta) = t_0 = \text{const.}$

1. At $\theta = 0$, $t_{r_1-r_0} = t_0 = \text{const.}$

Boundary conditions

$$t = A' e^{\mu \theta} J_0(\mu r) + B' e^{-\mu \theta} J_0(\mu r) + C' e^{-\mu \theta} J_1(\mu r) + D' e^{-\mu \theta} J_2(\mu r)$$

$$T = A e^{\mu \theta} + B e^{-\mu \theta}$$

$$\frac{dT}{d\theta} - \mu^2 T = 0$$

$$R = C_1 J_0(\mu r) + C_2 J_1(\mu r)$$

$$\frac{d^2 R}{dr^2} + \frac{1}{r} \frac{dR}{dr} + \mu^2 R = 0$$

000024

HW-RE-3-22-80

The equation solution is:

$$\frac{t_i - t_0}{t_m - t_0} = 1 - 2 \sum_{n=1}^{\infty} \frac{J_0\left(\frac{\delta_n}{r_0} r_i\right) e^{-\left(\frac{\alpha \delta_n}{r_0}\right)^2 \theta}}{\delta_n J_1(\delta_n)}$$

5-0

Where t_i = Graphite bore temp. at time θ
 t_0 = initial graphite temp.
 after Aluminum has melted
 = 400°C

t_m = Maximum graphite bore temp
 at time ∞

$$q_T = 2\pi h_c \frac{(t_m - t_0)}{\ln(r_0/r_i)}$$

r_i = inner radius = 0.0726"

r_0 = effective outer radius = 0.76"

δ_n = roots of J_0 =

$$\alpha^2 = \frac{h_c}{\rho c}$$

assume $h_c = 5$

$$\rho = 1.6 \times 62.4 = 100$$

$$c_p = 0.3$$

$$\rightarrow \alpha^2 = 0.167 \quad (h_c = 5)$$

$$\alpha^2 = 0.334 \quad (h_c = 10)$$

DECLASSIFIED

$$\alpha^2 = 0.167 \quad \eta_1 = .0726 \quad r_0 = .78$$

n	f _n	A		B		C		D		$\frac{B}{f_n A D}$
		J _i ()	$f_n \frac{r_i}{r_0}$	J ₀ ()	$\frac{f_n}{r_0}$	$(\alpha \frac{f_n}{r_0})^2$	A' θ	C θ	e ^{Cθ}	
							sec	hr.		
1	2.4048	+519	.224	.987	3.08	.158	10	.00028	.00004	+791
2	5.5201	-340	.514	.935	7.09	.839			.00024	1.0003 -497
										.294
3	8.6537	+272	.806	.844	11.1	2.05			.00057	1.0006 +358
										.652
4	11.7915	-23	1.098	.72	15.1	3.81			.0010	1.0011 -265
										.387
5	14.9309	+21	1.392	.57	19.1	6.1			.0017	1.0018 +184
										.571
6	18.0711	-19	1.68	.41	23.1	8.9			.0025	1.003 -119
										.452
7	21.212	+17	1.97	.24	27.2	12.3			.0035	1.004 +066
										.518
8	24.353	-16	2.26	.08	31.2	16.2			.0044	1.005 -.02
										.50
9	27.494	+15	2.56	-.07	35.3	20.8			.0058	1.006 -.02
										.48
10	30.635	-144	2.85	-.201	39.2	25.7			.0072	1.008 +045
11	33.776	+130	3.14	-.304	43.2	31.2			.0088	1.009 -

TIME	θ	f _n	A	B	C	C θ	D	$(\frac{B}{f_n A})$	$\frac{B}{f_n A D}$
60sec	0.167	2.405	+519	.987	.153	.0026	1.003	+790	+790
		5.52	-340	.935	.839	.014	1.02	-497	-495 .302
		8.65	+272	.844	2.05	.034	1.04	+359	+345 .647
		11.79	-23	.72	3.81	.063	1.06	-266	-251 .596
		14.93	+21	.57	6.1	.102	1.11	+182	+163 .549
		18.07	-19	.41	8.9	.149	1.16	-119	-103 .446
		21.21	+17	.24	12.3	.206	1.23	+067	+154 .530

DECLASSIFIED

Maximum flow temp. (°C)

600 Kuf Tube (27 gpm) $\Delta T = 840^\circ\text{C}$

$$T_c = 10 + 42 = 52^\circ\text{C}$$

$$q_m = (31.2)(27)(54) = 70,800 \text{ Cal/hr}$$

Grappled heat generation

$$q_g = \frac{(106)(70,800)}{12[(8.375)^2 - \pi(8.72)^2]} = 5.22 \text{ Cal/hr}$$

$$q_t = 70,800 + (16.7)^2(5.2)(12) = 54,300$$

$$T_{300} = \frac{2\pi(10)(T_m - 400)}{(L_1 \frac{9.4}{2.38})} = 3660^\circ\text{C}$$

$$T_m = 400 + (16.7)(5.2)(12) = 2040^\circ\text{C}$$

$$(3)(.015) =$$

$$T_m = 7280^\circ\text{C}$$

$$= 5120^\circ\text{C}$$

DECLASSIFIED

$$\bar{h}_G = 10$$

$$\bar{h}_G = 12$$

NOTE - $\frac{h_{G_s}}{h_{G_0}} = (1.04) \left[\frac{t_m + t_0}{2} / t_0 \right]$

$$h_{G_s} = \frac{(1.04) [2740] \cdot 4}{400} = 28.3$$

$$= 21.3$$

$$\bar{h}_G = \frac{28.3 + 4}{2} = \underline{\underline{16.2}}$$

$$= \underline{\underline{12.5}}$$

Graphite Heat Capacity

Average value including Stored E.
 $= 0.3 \text{ calin/lb, } ^\circ\text{C}$

$$W = \frac{(1.69)(62.4)}{1728} = \underline{\underline{0.061 \text{ \#/in}^3}}$$

$$W = (0.061)(16.7)^2(12) = 206 \text{ \#}$$

$$W_G = \underline{\underline{6.2}} \text{ Btu / ft, } ^\circ\text{C}$$

DECLASSIFIED

$$\alpha^2 = 0.334$$

TIME	θ	E $J_0\left(\frac{c_n r_n}{a}\right)$	C $\left(\alpha \frac{d_n}{r_n}\right)^2$	$C\theta$	D $\frac{D}{C\theta}$	E/D	Σ
2min	.0333	$c_n J_0$					
		1, +.790	3.08 3.17	.106	1.11	+.78	
		2, -.497	7.59 16.8	.56	1.75	-.28	.43
		3, +.359	11.1 41.2	1.37	3.94	+.09	.52
		4, -.266	15.1 76.2	2.54	12.7	-.02	.50
		5, +.182	19.1 122	4.07	59.7		
		6, -.119	23.1 179	5.97	365		
		7, +.067	27.2 247	8.22	3640		
		-					
10min	.167		3.16	.53	1.70	+.46	
			16.8	2.81	16.6	-.03	.43
			41.2	6.9	992	+	
			76.2	12.7			
5min	.0833			.264	1.30	+.607	
				1.4	4.055	-.123	.484
				3.43	30.88	+.012	.496
				6.35	570	-.001	.495

DECLASSIFIED

DECLASSIFIED

[REDACTED]

$$g_s = 86,000 - 11200 =$$

$$g_s = 86,000 - (62)(40,600)$$

$$T_1 = 830^\circ C$$

$$T_1 = 400 + (3080)(1 - .82)$$

10 minutes

$$\Delta T_g = 31^\circ C$$

$$T_1 = 400 + (3080)(1 - .990)$$

5 minutes

HW56323 RD
000030

[REDACTED]

DECLASSIFIED

17M
 0000681

HN 56323 KU
 000030

DECLASSIFIED

HW-5632-10
000033

WATER FILM COEFFICIENT
OF HEAT TRANSFER

WATER FILM
COEFFICIENT
h_w
(5160 SURFACE)
Chilling at 2°C

KEUFFEL & ESSER CO., N. Y. NO. 358-14
Manufactured in U.S.A. and England for the Navy.

DECLASSIFIED

5-30-2005
11-1-58

RELATIVE WATER VELOCITY - FT/SEC

DECLASSIFIED

DATE

FILMED

8/17/94

END