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HANFORD ATOMIC PRODUCTS OPERATION - RICHLAND, WASHINGTON

July 18, 1958

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TITLE

C - PILE PIGTAIL FAILURE

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HW-56816-R1

C-File Pigtail Page 1

DISCUSSION

Failure

A. General

July 18, 1958

This document consists of
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Several important general conclusions can be made concerning inlet line (pigtail) rupture effects on Hanford reactors. These are as follows:

1. ~~There~~

1. During the ~~last~~ critical time period of 1 to 300 seconds after the water loss there is ~~very~~ little change in graphite temperature. This means that the graphite serves as an effective

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~~the~~ only a small fraction of the lattice heat can be transferred to adjacent channels. Consequently, there is ^{negligible} ~~little~~ difference in the graphite lattice heat sink for the cases of one tube, one cross-header, and all tubes losing their water supply.

2. There are two ~~important~~ manners in which the ~~the~~ water flow can be lost with quite a wide variation in the resulting charge temperatures:

- a) Instantaneous flow loss followed by boil out and film boiling (< 5 sec.)
- b) Gradual flow loss (> 1 hr.) in which the reactor power level drops off ~~to~~

flow and nucleate boiling, ~~results~~, if any, results in continued cooling of the charge.

The reason for the insulating or inertia action of the graphite is readily explained by an examination of the following equation:

$$\cancel{\frac{q_s}{A_s}} \cancel{A_s} \cancel{\frac{dt_s}{dt}} = \cancel{\frac{q_g}{A_g}} \cancel{A_g} \cancel{\left(\frac{dt_g}{dt} \right)}$$

Neglecting the process tube a generalized heat transfer equation between the fuel and the moderator is:

$$q_s - w_s \frac{dt_s}{dt} = \frac{\bar{t}_s - \bar{t}_g}{R_T} = -q_g + w_g \frac{dt_g}{dt}$$

Heat
Generated
in Fuel

Increase
in fuel
Sensible
Heat.

Heat Flow
to
Moderator

Heat
Generated
in
Moderator

Increase
in Mod.
Sensible
Heat.

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And substituting in the approximate values for C-Reactor we obtain:

$$.89_{\text{FT}} - .45 \frac{\Delta t_s}{\Delta \theta} = \frac{\bar{t}_s - \bar{t}_c}{1370} = -.29_{\text{FT}} + 11 \frac{\Delta t_c}{\Delta \theta}$$

$$9_{\text{FT}} \Delta \theta = 11 \Delta t_c + .45 \Delta t_s$$

Thus it can be shown that an increase in fuel temperature of 100°C is accompanied by an increase in moderator temperature of not over $\approx 4^\circ\text{C}$, and the moderator is very insensitive to ~~these~~ large fuel temperature changes in short time periods.

The significance of the two types of flow loss is best explained by reference to Figure 1. Consider the reactor operating at point 1, corresponding to the intersection of the supply and demand curves for 1000 Kw tube power. If the flow reduction is instantaneous then we would expect the flow to change ~~to~~ along the arrowed line 1-2-3-4. It would proceed to the low flow point 2 very quickly, and would end-up at 4 only after the heat generation had reduced by a factor of 100 and after

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the coolant had absorbed the accumulated sensible heat effects that had been generated during the very low flow conditions of points 2, and 3. During this period ~~the~~ the back flow cooling would be very low. This ~~and~~ probably would mean adequate cooling of the first third of the charge as the water boiled and negligible cooling of the rest, as the steam approached charge temperatures.

If the flow reduction is not instantaneous, ~~and~~

if the reactor is scrammed as

Then the reactor will be scrammed after a 5-10 percent

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[REDACTED] d-2

NW-56816 R.

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flow reduction and the flow will follow the path 1, 2a, 3a, 4. Under these conditions only minor boiling will occur, the flow will remain stable, and the charge will be adequately cooled at all times.

At the present time we ~~cannot~~ cannot be sure of the actual mechanism of the pretail failure at the C-Reactor. The actual flow decay ~~path~~ could have followed either path since we do not know the time properties of the failure.

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b. Fuel Temperatures

The fuel temperatures for the case of no reactor scram and a scram @ 2 seconds after the pigtail failure are shown in Figure 2. These curves do not have any allowance for back-flow cooling. However, initial calculations indicate two significant conditions.

(1) - If the reactor power level is low enough that only a fraction of the water is vaporized in flowing through the tube then considerable fuel cooling is obtained and

back flow would definitely
prevent burn-out.

(2) - At high reactor
power levels ≥ 4000 Kw/T
the water is vaporized
to 100% quality ~~and~~ in
the first ^{5-10%} ~~10-30%~~ of
the tube length and we
have only steam cooling
beyond this point. The
annular resistance
to ^{this} steam flow is very
high and there is a
reduction by a factor of > 10
in the back flow
through the tube. This
means that the last
~~half~~ to one third of
the charge has negligible

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cooling.

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EQUATIONS

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1. Pressures

$$p_H = \Delta p_d + \Delta p_{fe} + \Delta p_{TPF} + \Delta p_v + p_c$$

Rear = Press. Drop thru + Press. Drop. Lia. Press. Drop. Two Press. Drop Vapor Critical
 Header Drop thru + Header Drop. Lia. Header Drop. Two Header Drop Vapor Header Press.
 Pressure rear fittings rear fittings phase + phase + phase + phase + in after
 & dummy thru Act. thru Act. thru Act. Act. Clog. Venturi.
 charge charge charge charge

Where

$$\Delta p_d = 0.51 w^{1.86}$$

$$\Delta p_{fe} = .363 L_2 w^{1.86}$$

$$\Delta p_{TPF} = R \left[.363 L_{TPF} w^{1.86} \right] + 22.3 R_2 w^2$$

$$\Delta p_v = 6.98 \times 10^6 w^{2.45} \leftarrow L_v$$

And p_c is a function of q_T , t_i , and w

2. Temperatures:

Liquid Sect. Act. charge

$$L_c = \frac{(wc)_w (t_{ws} - t_i)}{h_c a (\bar{t}_{c_A} - \bar{t}_w)}$$

$$t_{c_{A2}} = \frac{\bar{F}(s)}{\beta} + e^{-\beta \Delta s} \left(t_{c_{A1}} - \frac{\bar{F}(s)}{\beta} \right)$$

$$\text{Where } \beta = \frac{h_c a}{(wc)_c}$$

$$\text{And } \bar{F}(s) = \frac{q_0 f_D + h_c a \bar{t}_w}{(wc)_c}$$

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(3)

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Using the integrating factor $e^{\beta\theta}$ equation (9) may be expressed as:

$$\frac{d(t e^{\beta\theta})}{d\theta} = F(\theta)$$

Since $F(\theta)$ is a function of (θ) we must integrate step wise within limits assuming $F(\theta)$ constant over the $\Delta\theta$ period. This gives us:

$$t_2 e^{\beta\theta_2} - t_1 e^{\beta\theta_1} = \frac{\bar{F}(\theta)}{\beta} (e^{\beta\theta_2} - e^{\beta\theta_1})$$

$$\therefore t_2 = t_1 \frac{e^{\beta\theta_1}}{e^{\beta\theta_2}} + \frac{\bar{F}(\theta)}{\beta} - \frac{\bar{F}(\theta)}{\beta} \frac{e^{\beta\theta_1}}{e^{\beta\theta_2}}$$

~~$$t_2 = \frac{\bar{F}(\theta)}{\beta} + e^{-\beta\Delta\theta} \left[t_1 - \frac{\bar{F}(\theta)}{\beta} \right]$$~~

And Finally

$$t_{A_2} = \frac{\bar{F}(\theta)}{\beta} + e^{-\beta\Delta\theta} \left(t_{A_1} - \frac{\bar{F}(\theta)}{\beta} \right)$$

~~And transforming to the original terms~~

~~$$t_{A_2} = f(\theta) + h_2 h_1 a t_1$$~~
~~$$t_{A_2} = (e^{-\beta\Delta\theta}) t_{A_1} + (t_{A_1} - f(\theta))$$~~

Where $\Delta\theta = \theta_2 - \theta_1$

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2. Heat Transfer(a) Charge cooled by Liquid:(1) coolant

$$(w c_p)_w (t_c - t_i) = h_c (l_c a) \left[\bar{t}_c - \frac{t_c + t_i}{2} \right] \quad (6)$$

Increase in coolant Enthalpy = Heat Transferred to coolant.

(b) Change in Charge Temp.

$$\bar{t}_c = \frac{t_{c1} + t_{c2}}{2} \quad (7)$$

~~and finally~~Charge temp. change

$$\frac{d t_c}{d \theta} = F(\theta) - h_c (l_c a) [t_c - t_w]$$

$$(w c_p)_c \frac{d t_c}{d \theta} = F(\theta) - h_c (l_c a) [t_c - t_w] \quad (8)$$

$$(w c_p)_c \frac{d t_c}{d \theta} = F(\theta) - h_c (l_c a) t_c + h_c l_c a t_w$$

Or expressed in simplified terms.

$$\frac{d t_c}{d \theta} + \beta t_c = F(\theta) \quad (9)$$

$$\text{Where } \beta = \frac{h_c (l_c a)}{(w c_p)_c l_c} = \frac{h_c a}{(w c_p)_c} \quad (10)$$

$$F(\theta) = \frac{\bar{q}(\theta) l_c + h_c l_c a t_w}{(w c_p)_c l_c} \quad (11)$$

EQUATIONS SUMMARY

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Pressures

$$p_H = \Delta p_d + \Delta p_e + \Delta p_{TPF} + \Delta p_v + p_c$$

p_H = Available rear header pressure

$$\Delta p_d = 0.51 w^{1.86}$$

$$\Delta p_e = .363 l_e w^{1.86}$$

$$\Delta p_{TPF} = R \left[.363 l_{TPF} w^{1.86} \right] + 22.3 n_2 w^2$$

$$= R l_{TPF} \Delta p_e / l_e + 22.3 n_2 w^2$$

$$\Delta p_v = \frac{6.9 \times 10^{-6} w^{2.45}}{1.83 \times 10^{-5} l_v w^{2.45}}$$

And p_c depends upon $\Sigma(q)$, w
and t_i

Temps

~~LiQ. sect. of charge~~ LiQ. sect. of charge

$$(wc)_w (t_s - t_i) = h_e l_e a (\bar{t}_{cA} - \frac{t_s + t_i}{2})$$

$$\bar{t}_{cA} = \frac{t_{cA1} + t_{cA2}}{2}$$

$$t_{cA2} = \frac{\bar{q}_0 \bar{f}_d + h_e a (t_s + t_i)/2}{(wc)_c} + e^{-\frac{h_e a}{(wc)_c}} \left[t_{cA1} - \frac{\bar{q}_0 \bar{f}_d + h_e a t_i}{(wc)_c} \right]$$

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FIGURE-1
C-PILE TUBE
LIQUID FLOW CHAR.
(Header to Header - 110°C)

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C- Pile Pigtail Failure
3-27-56

II - Theo. Temperatures :

1- C-Pile Properties

a- Operating Conditions
Tube - 3158

Power - 920 KW

Water Flow - 42.5 gpm

Temp. Incr. - 82°C , $t_i = 6$, $t_o = 88$

Gas Comp. - 71% He

Graphite Temp. - 440°C

Header Pressures

Before

After.

Front Rear

8.5 18.5 Psig
in Control At Riser
Room

~0
At Riser

Graphite Period

Rising - —

Falling. - 79 min.

Central Heat Generation $110,000^{105}$

Local Water Temp. 47°
hwt 9000 (OF) = 50

Slog. Surf. temp - 970 99

" Central Temp. - 546° 528 (STM - 445)

Avg Slog Temp. [REDACTED]

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3 - Physical and Geometric Properties

a. Inner Resistance
DRY TUBE

(Top of Slog to
Process Tube) *

$$R_{xz} = .052$$

$$R_{zy} (\text{Steam}) = 1.35$$

$$R_{zy} (\text{Ribs}) = .41$$

$$R_1 = R_{xz} + \frac{1}{\left(\frac{1}{R_{zyH_2O}}\right) + \left(\frac{1}{R_{zyRibs}}\right)}$$

$$R_1 = .052 + \frac{1}{\frac{1}{1.35} + \frac{1}{.41}} = .365 \quad \frac{^{\circ}\text{C, hr, ft}}{\text{Chu}} \quad \text{7 Nominal}$$

$$= 1310 \quad \frac{^{\circ}\text{C, sec, ft/Chu}}$$

b. Outer Resistance, tube to Graphite:
(Assume centered tube)

$$q_g \approx \frac{k_g A \Delta t_g}{l} = \frac{k_g (1.78\pi) \Delta t_g}{.007}$$

$$\Delta t_g (\text{max}) = .00214 q_g / k_g$$

$$\Delta r = 12$$

$$\Delta t_g (\text{min}) = .00089 q_g / k_g$$

$$\Delta r = 5$$

$$\frac{\Delta t_g}{\Delta r} = .00125 q_g / k_g$$

$$\Delta r = 7$$

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These various stages of the temperature calculation are presented in the following sections:

Operating Conditions
4. Given Data

Tube - 3158 : Exposure - 28 Days
Power - 920 Kw. Scram. Sh - 1900
Flow - 42.5 gpm
Temps. 88° outlet, 6° Inlet $\Delta T = 82^\circ C$

Graphite - Central Temp - 440°C
71% Helium Gas Comp.
79 min. Falling Period

Header Pressures		Front	Rear
Before	—		
After	psig	~0 psig	13.5

Calculated Operating Temps. (center of Tube)

Heat Generation at center of change 12
 $q_c = 920 \times \frac{3415}{1.8} \times \frac{1.43}{23.9} \times 1.08 \times .94 = 105,000 \text{ Ch/h ft}^2$

Local Water Temp. $t_e = 6 + \frac{82}{2} = 47^\circ C$

Water film coef $h_w = 7600 \text{ Ch/h ft}^2, ^\circ C$

Slug Surface Temp. $= t_e + \left(\frac{2.65}{h_w} \right) q_c = 84^\circ$

U - Surface Temp. $= t_{us} + (30020) q_c = 145^\circ$

U - Central Temp. (assume $k_u = 12$)
 $t_{uc} = t_{us} + \frac{.0727}{k} q_c = 53^\circ$

Avg U Temp $= t_u = t_{us} + .53 \Delta t_u = 330^\circ$
 $\therefore h_u = 18.1 \checkmark$

47
37

TOP SECRET

2

only be conjectured. Two extreme cases can be considered.

1. Immediate and complete water flow failure followed by reactor scram and reverse flow potential of 18 psi driving force.
2. Gradual reduction in water flow to about 80% of normal followed by a reactor scram and a complete flow reduction 4 minutes later. Again there will be a reverse flow potential represented by the 18 psi pressure differential from rear to front of this reactor tube.

An examination of the results obtained from the first type of failure clearly indicates that the second type would cause no excessive change or tube temperatures.

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b. Physical & Geometric Properties

1. Inner Resist.

$$R_{X2} (\text{across Slug}) = .052$$

$$R_{2T_1} (\text{across Stem}) = 1.35$$

$$R_{2T_2} (\text{Ribs} - (1 \text{ mil gap})) = 0.41$$

$$R_{2T} = \frac{1}{\frac{1}{1.35} + \frac{1}{.41}} = \underline{\underline{0.315}}$$

$$R_1 (\text{Slug to Process Tube}) = \underline{\underline{.37}} (1330)$$

2. Outer Resistance (assume centered tube)

$$R_2 = \frac{\Delta r}{k_g A} = \frac{(.008)}{k_g \pi (1.78)} = \frac{.00143}{k_g}$$

Temp	→	150°C	300	500
k_g	→	.058	.062	.079
R_2	→	.025	.023	.018
R_2		90	83	65

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2. Calculation of Theo. Temperatures:
a- Water Filled Tube

The heat to the water would be made up of the continued heat generation plus sensible heat from the charge as the heat generation & charge temperature decayed.

This can be approximated by the equation:

$$\Sigma(wc)(t_s - t_{s_0}) = .94 f_d q + wc_1 (T_{m_0} - T_{m_0})$$

Sensible heat Heat Heat Lib.
abs. by Fuel, H₂O, Tube gen. by Fuel

Where the third term will be 0 as long as the charge core temp is increasing.

b- Boiling $\Delta H_0 = \frac{1000 \times .1 (1.07)}{1.8}$ Cal/lb.

$$\frac{\Delta H_0}{\Delta t} = .94 f_d q$$

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(Assume 10% of H₂O boils and drives out rest)

SECRET ROUGH DRAFT

C. Dry Tube

Temp. change of Uranium

$$wc_1 \frac{dt_{u1}}{d\theta} = (q_1 - q_s) - \left(\frac{t_{u1} - t_c}{R_1} \right) \quad (1)$$

Sensible heat change in U Net heat Input Heat Loss to Process Tube

Temp. change of Process Tube

$$wc_2 \frac{dt_t}{d\theta} = \left(\frac{t_{u1} - t_c}{R_1} \right) - \left(\frac{t_t - t_c}{R_2} \right) \quad (2)$$

Sensible heat of Tube heat from chg. Heat to graphite

Assume $t_{c0} = 200^\circ = \text{constant}$

Initial Uranium (Dry Tube) Temp.

$$t_{u0} \approx \frac{2(404) + 171}{2} = 490^\circ$$

Heat generation in Tube

$$q_1 = .8 f_s q_0 \quad (\text{Assume } 1500 \text{ in scram})$$

Steam Cooling (q_s)

At 90 Kw/H $G = 1.3 \text{ Gpm}$ {18 psi Δ }
Assume 80% Quality.

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$$\Delta H_0 = \left(\frac{1.3 \times 8.3}{60} \right) \left(\frac{1000}{1.8} \right) (1.8) \left(\frac{1.43}{2} \right) = 0.48 \text{ Chg/sec}$$

CALCULATION

(a) Time to Reach Boiling.

CASE	TIME AFTER WATER LOSS	TIME AFTER SCRAM	f_r	g	$f_r g$	$\Sigma w c$	Δt	(1) $\Delta \theta$ sec	t_w	T_{u_1}	T_{u_2}
I	0 1.6	0 0	1 1	29.2 29.2	29.2	.70	67	1.6	114	325	392
II	1.6	0						1.6	114	325	392
III	0 22	240 262	.003	29.2	3.0	.70	94	22 22	114 114	60	154
IV	22	262						22	114		154

(b) Time to Boil Dry.

CASE	TIME AFTER WATER LOSS	TIME AFTER SCRAM	f_r	g	$f_r g$	w_{sh}	f_w	$f_w w_{sh}$	$\Delta \theta$	T_{u_2}	T_{u_3}
I	1.6 2.0	0 0	1	29.2	29.2	104	0.1	10.4	0.4	392	392
II	2.0									392	392
III	22 30	262 270	.09	29.2	2.6	104	0.2	20.8	8	154	154
IV	30	270								154	154

(1) $\Delta \theta = \frac{\Sigma w c \Delta t}{f_r g}$

(2) $\Delta \theta = \frac{10.4}{f_r g}$

(2a) $\Delta \theta = \frac{20.8}{f_r g}$

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ELEVATIONS

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TABLE - VII CALCULATION OF CHARGE TEMPERATURES

①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪	⑫
TIME				HEAT GEN				FUEL TEMPS.			
CASE	AFTER SCRAM	AFTER H ₂ O LOSS	TIME INCRE- MENT Δt SEC.	DECAY FACT. f _D	HEAT GEN. f _g	STEAM COOL. HEAT REMOVAL f _s	NET HEAT ACCUM. f _N	T _U	T _D	ΔT _i	R _i
II	0	2	0								
	0	3	1	1	29.2	0	29.2	392	114	278	1310
	1	9	1	.19	5.57	0	5.33	451	132	319	
	3	6	2	.132	3.87	.7	3.87	460	149	311	
	6	9	3	.109	3.19		3.19	474	178	296	
	10	13	4	.11	2.77	.97	1.59	489	211	279	
	15	18	5	.109	2.35		1.18	501	239	262	
	20	23	5	.108	2.19		1.03	512	257	255	
	30	33	10	.107	1.93		0.76	522	263	259	
	50	53	20	.1055	1.55		0.38	536	270	266	
omit	100	103	30	.1041	1.198		0.08	556	267	284	
	200	203	100	.1036	1.051		-0.18	557	273	284	
	250	253	50	.1031	1.05		.07	534	280	254	
	75		25		1.28		0.0095	549	267	282	
	100	103	25	.1039	1.14		-0.04	550	276	274	
	150	153	50	.1034	0.99		-.18	550	284	286	
	200	203	50	.1032	0.935		-.232	534	270	284	
	250	253	50	.1031	0.905		-.255	514	269	255	
	300	303	50	.1030	1.020		-.151	533	270	263	

$$* f_N = f_{gc} - f_s - \frac{\Delta t_i}{R_i}$$

$$\begin{array}{r} 1.198 \\ .97 \\ \hline 2.28 \\ 22 \end{array}$$

$$\begin{array}{r} 1.198 \\ .97 \\ \hline 2.28 \\ 20 \end{array}$$

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TEMP.						PROCESS TUBE									
						(t_u, t_c)									
ΔT_1	R_1	$\frac{\Delta T_1}{R_1}$	W_{C1}	$\frac{dT_1}{d\theta}$	t_{u2}	t_{c1}	t_{c2}	ΔT_2	R_2	$\frac{\Delta T_2}{R_2}$	W_{C2}	$\left(\frac{\Delta T_1}{R_1} - \frac{\Delta T_2}{R_2}\right) \frac{dT_2}{d\theta} t_{c2}$			
78	1310	.21	.49	59	451	114	250	-136	94	-1.45	.09	1.66	18	132	
119		.244		8.85	460	132		-118		-1.255		1.499	16.65	149	
111		.238		7.1	474	199		-101		-1.075		1.313	14.6	178	
396		.226	.53	4.9	489	178		-72		-.766		.992	11	211	
79		.213		3.00	501	211		-39		-.415		.628	6.98	239	
62		.200		2.23	512	239		-11		-.117		.317	3.55	257	
55		.194		1.94	522	257		7		.0745		.119	1.27	263	
59		.198		1.43	536	264		14		.1375		.060	.67	270	
66		.202	.57	-.67	549	270		20		.224		-.012	-.13	267	
84		.22		.014	557	267		17		.181		.639	4.33	293	26
84		.22		-.765	551	289		39		.415		-.211	-2.35	280	
84				-7.65	496	54		-196		-2.08		2.446	27.7	1414	
82		.215	.57	.017	550	267	250	17		.181	.09	+.034	.38	276	
74		.210	.57	.007	550	267	250	17	94	.181	.09	+.03	.33	284	
66		.203		-.82	534	284	284	34		.36		-.11	-.11	270	
84		.201		-.90	514	272		22		.234				269	
85		.185		-.45	392	242	271	21		.223				268	
63		.201		2.65	520	270		-20		.213				267	

$t_{c2} = 250 + .072(t_{u2} - 250)$

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Time Required to sweep
Active zone free of water

Enter Power

500 900 1300

1. full power for 2.7 sec
after H₂O loss

1.7 sec 0.9 sec 0.3 sec

2. H₂O loss 30 sec after
shutdown

55 " 25 " 20 "

3. 30 min after shutdown

10 min 5 min 3.5 min

4. 24 hrs " "

4 hrs 1.3 hrs 40 "

Slug jacket activities

1. full power for 2.7 sec
after H₂O loss

2 hrs 29 sec 5 sec

2. H₂O loss 30 sec after shutdown

7 hrs 28 min 4 min

3. " " 30 min " "

18 " 3 hrs 30 "

4. " " 24 hrs " "

50 " 20 " 10 hrs

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42,000

STEAM COOLING
CALCULATIONS

Jim Ferguson
Hank Huber 4489

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[REDACTED]

$$WC_{gs} = x_{45} / 41$$

NW-56816 R
Page 27

Section	Distance from Rear Charge	F_x	$F_x F_G$	F_T	$CHU / ft. - sec$
A	0-4	131	$\frac{5}{4330}$ 5400	10 sec 2,960	$\frac{100 sec}{960}$
B	4-9	181	11,300 14,200	7700	2510
C	9-14	1	14,000 17,500	9,500	3100
D	14-19	181	11,300 14,200	7700	2510
E	19-23	131	4330 5400	2960	960
<u>Area / 12</u>		<u>total heat gen. CHU/sec</u>			
A	1.51	6.0	4.81	3.3	1.06
B	1.89	19.7	1570	10.7	3.50
C	1.89	24.3	19,410	13.2	4.32
D	1.89	19.7	1570	10.7	3.50
E	1.51	6.0	4.81	3.30	1.06

8
10
10
10

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[REDACTED]

3. Physical and Geometric Properties

a. Inner Resistance Dry Tube (Top of slug to Process Tube) * (3) *

$$R_{k2} = .052$$

$$R_{2r_s} (\text{steam}) = 1.35$$

$$R_{2r_k} (\text{Ribs}) = 0.41$$

$$R_A = R_{k2} + \frac{1}{\left(\frac{1}{R_{2r}}\right)_{H_2O} + \left(\frac{1}{R_{2r}}\right)_{Ribs}}$$

$$R_A = .052 + \frac{1}{\frac{1}{1.35} + \frac{1}{.41}} = .365 \frac{^{\circ}\text{C, h, ft}}{\text{chw}}$$

$$= \underline{\underline{1310^{\circ}\text{C, avg ft/chw}}}$$

b. Outer Resistance, Tube to Graphite: (Assume Centered Tube)

$$q_0 = \frac{h_g A \Delta t_0}{L} = \frac{h_g (1.78\pi) \Delta t_0}{1.007} \quad \frac{1.78\pi h_g}{1.007}$$

TABLE II: GRAPHITE BORE TEMPERATURES

HEAT Generation	Gas Annulus Δr (ft)	Gas Thermal Cond. k_g	Temp. Drop Δt_0	Local Water Temp. t_2	Graphite Bore Temp. t_{GBore}
6300	12	0.57	245	47	292
	5		99		146
	7		138		185
6300	12	0.61	221	47	268
	5	0.52	108		155
	7	.055	143		190

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Assume graphite tube block temperature is constant at 250°C , and $\Delta V = .008$.

Outer Resistance $R_0 = \frac{\Delta V}{h_g A} = \frac{.008}{(.055)\pi(1.78)} 3600 = .94 \frac{^{\circ}\text{C, h, ft}}{\text{chw}}$

(3) S.S. Jones "Technical Note Book" - HW-5475-T pg -148

(4) J.C. Fox "Private communication" - Range of values for actual central annulus at a pile

* Terms defined in Nomenclature on pg 1

4. Heat Transfer Equations

a. Heating to Boiling

Assume boiling press = $\frac{18}{2} = 9$ psig $\therefore t_b = 114^\circ\text{C}$

$$\sum (wc_p) \frac{dt}{d\theta} + \dot{q}_{\text{heat gener.}} = 0 \quad (1)$$

Total sensible heat ~~heat generation change~~

b. Boil Out Time

$$\frac{f_w \Delta h_o}{\Delta \theta} = f_r \dot{q} \quad (2)$$

Where the charge temperature is assumed constant during the boil out period

Note: Thermal Properties

TABLE III - Heat Capacities of Lath

Temperature	100°C	300°	500°
Heat Capacity	Chu/ft-°C or Btu/ft-°F		
Fuel	.42	.47	.57
Water	.19	—	—
Process Tube	.09	.10	

Latent Heat

Chu/lb 540

~~lb water/ft annulus .19~~

Effective Evaporation (.19 lb H₂O per ft of annulus and assume 10% of H₂O boils out forcing out the rest) 10.4 - Chu/ft

With small error it can be assumed that the fuel temperature remains constant during the boil out period, especially when the time required is very short.

Then equation (1) reduces to:

$$t_{t_2} = t_{t_1} + \Delta \theta \left[\frac{\Delta t_{RA} - \Delta t_{RB}}{wc_2} \right]$$

High Level Boil Out

$$\frac{10.4}{\Delta \theta} = f_r 29.2 \quad (3)$$

c. Heat Transfer from Dry Charge (Steam Envelope)

Fuel Temperature Change:

$$(wc_1) \frac{dt_1}{d\theta} = (q_1 - q_2) - \frac{t_{t_1} - t_{t_2}}{R_A} \quad (4)$$

Tube Temperature Change

$$t_{t_2} = t_{t_1} + \Delta \theta \left[\frac{q_2 - \Delta t_{RA}}{wc_1} \right] \quad (4a)$$

d. Steam Cooling

$$wc_2 \frac{dt_2}{d\theta} = \frac{t_{t_1} - t_{t_2}}{R_A} - \frac{t_{t_2} - t_{t_3}}{R_B} \quad (5)$$

According to crossheader pressure measurements there was a steam cooling driving force (rear C.H. to front face pressure) of about 18 psi.

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Insert

In Figure 2, data obtained experimentally from a full scale mockup of the C Pile annulus s been replotted to indicate the water flow that might be obtained through 3158 C after the pigtail failure. Curve I indicates the observed peak instability pressure drop across the tube for different levels of operation.

Curve II indicates the observed water flow into the tube under these heat flux and maximum pressure drop conditions. Curve III indicates the pressure drop ^{for} approximately 100% steam quality conditions and curve IV indicates the steam flow under these 100% quality conditions.

Thus, for the Δp driving force available in this problem the corresponding maximum tube power and steam flow would be 83 kw and 0.06 lbs. of steam per second. For the case in question this represents 9% of original tube power. This corresponds to a time delay after a scram of ~800 seconds.⁽⁵⁾ This heat output, however, corresponds to ~~azzim~~ ^{that} from a lattice unit fully cooled rather than the conditions of the pigtail failure where the lattice assembly is actually absorbing heat rather than giving it to the cooling water. The actual heat generation for a 1900 ih scram would be down to 9% in 10 seconds after the rod insertion.⁽⁶⁾ Therefore, the problem is to determine how much cooling occurs from water evaporation in the central portion of the tube.

critical flow thru venturi.

The calculations for no steam cooling consider the system to be effectively stagnant and only heat conduction is considered. ~~This is the worst possible case, as there is no steam cooling.~~ ^{When} ~~But when~~ steam cooling is assumed we have ~~the problem that this cooling may be so~~ ^{two general types of cooling}

in addition to heat conduction to the graphite. First: there is evaporative cooling as steam is formed along the charge length. Then, there is some cooling produced by superheating the steam as it flows by the heated charge surface.

- (5) P. C. Walkup, R. E. Hall, "Final Report PT-105-14-MR, and Process Test MR-105-30", HW-42964, May 15, 1956.
- (6) S. S. Jones, "Heat Generation and Total Heat Output from the Pile After Shutdown", HW-33870, November 23, 1954.

The cooling action of the steam evaporation is considerable both because of the high heat of vaporization and because the evaporating liquid forms a relatively constant temperature sink. The cooling action of the superheated steam is about ~~less than 1/100 that~~ of the evaporating water and would have little effect.

less than $\frac{1}{100}$ that of the evaporating water and in general affords little protection against burnout. Therefore it is important to ensure that steam evaporation is occurring over the central portion of the charge. Conservatively we will assume that the maximum steam quality of the exist coolant is 58%.

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7b

Then the total steam cooling based upon the flow ^{obtained} from Figure 2 would be:

$$Q_s = 540 (1.5) (w_s) = (270) (1.06) = 16.2 \text{ chm/sec}$$

And assuming further that the steam cooling along the charge length is proportional to the heat generation, then:

$$| \quad q_s = \frac{1.43}{23.5} Q_s = 0.97 \text{ chm/ft. sec} \quad (7)$$

We may conclude therefore that at 10 seconds or more after the reactor scram steam cooling was established in this tube.

One further verification should be made. The data ~~obtained~~ presented in Figure 2 is based on steam-water flow through a simulated ~~pipe~~ outlet system assembly while in this case the flow was through the inlet system including a 0.385 inch venturi. Using the critical flow chart

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Simplify

FIGURE-2

BOILING ΔP IN C-ANNULES

Ref: K.G. Topsy, R.F. Raul
HW-24903, 7-2-52

C-Annulus
Pressure
Drop
Psi.

lbs Steam/sec
1.0
0.7
0.5
0.4
0.3
0.2
0.1

TUBE POWER- Kw

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EUGENE DIETZEN CO.
MADE IN U.S.A.

NO. 341-L22 DIETZEN GRAPH PAPER
LOGARITHMIC-2 CYCLES X 2 CYCLES

~~22~~ P

developed by W. K. Woods (1) the total enthalpy of the fluid at the venturi is:

$$E = h_f + \frac{Q_s}{w_s} = 112 + \frac{1.8(16.2)}{.06} = 597 \text{ Btu}$$

And at 15 psia, ^{discharge pressure} the critical flow is ~~76 lbs/sec, sq. ft.~~ from Figure 11 in Woods' report is 76 lbs/sec, sq. ft. The flow assumed in this case was only .06/.00252 ~~24 lbs/sec~~ or 24 lbs/sec, sq. ft. ~~Consequently~~

This indicates that reverse flow through the front face ~~of the~~ fittings and pig tail ~~of the magnitude and~~ quality of .06 lbs per sec and 50% quality could occur without reaching critical flow in the system.

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9

5. Fuel and Tube Temperature Calculations

Based upon these considerations and the assumptions listed below a stepwise calculation was made of the uranium and process tube temperature elevations above the surrounding graphite temperature. These calculations were based upon equations (4) and (5) using the q_s value in case II of 0.97 Chu/ft-sec. The assumptions on which this method is based are:

1. The fuel rod temperature is uniform and is equal to the volume averaged temperature at the start of these calculations.
2. The graphite tube block temperature is constant over the time period ~~considered~~ at a value of 250°C

3.

a. Time to Reach Boiling

This is obtained from the simplified equation:

$$\Delta \theta = \frac{\Sigma(w c_p) \Delta t_w}{f_t f_c} \quad (8)$$

The pressure at the center of this tube is about $14.7 + 18/2 = 24$ psia. This corresponds to a boiling point of 114°C. Therefore:

$$\Delta \theta = \frac{.7(114 - 47)}{29} = 1.6 \text{ seconds}$$

During this time the tube and charge increase in temperature by $(114 - 47) = 67^\circ\text{C}$.

b. Time to Boil Dry

As a conservative assumption the tube is considered to be effectively dry after 10% of the water has boiled out. Therefore, the time required to boil dry at constant temperature is:

$$\Delta \theta = \frac{w \Delta h_v f_c}{f_t f_c} = \frac{104(11)}{29} = 0.4 \text{ sec} \quad (9)$$

c. Maximum Temperatures

The stepwise calculation of the temperatures reached in the cases of no steam cooling and steam cooling after 10 seconds are presented in the following tables.

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TABLE V

TEMPERATURE OF
AFTER WATER
10 SECONDS AFTER

TIME AFTER WATER SCRAM LOSS		TIME INTER- MENT	HEAT GENERATION DECAY HEAT FACT GEN.		INITIAL COND. FUEL TUBE TEMP TEMP	
Sec.	Sec	Sec	f_z	$f_z q_c$ ($\frac{Ch_k}{Acc, ft.}$)	$t_{u,}$ °C	$t_{t,}$ °C
3	0	1	1	29.2	392	114
4	1	1	.19	5.57	451	132
7	3	2	.132	3.87	462	149
9	6	3	.109	3.19	478	178
13	10	4	.095	2.77	489	211
18	15	5	.081	2.35	501	239
23	20	5	.075	2.19	512	257
33	30	10	.066	1.93	522	263
53	50	20	.053	1.55	536	276
78	75	25	.044	1.28	549	272
103	100	25	.039	1.14	550	276
153	150	50	.034	0.99	550	284
203	200	50	.032	0.94	534	270
253	250	50	.031	0.91	514	268

* To avoid unduly small time
equation was used for t_{t_2} in
 $t_{t_2} = 250 +$

* see footnote Table

F FUEL AND TUBE SHUT OFF WITH STEAM COOLING TER SHUT DOWN

HEAT LOSS		HEAT ACCUMULATION		FINAL COND.	
TO TUBE	TO GRACH.	IN FUEL	IN TUBE	FUEL TEMP	TUBE TEMP
$\frac{\Delta t_A}{R_A}$	$\frac{\Delta t_B}{R_B}$	$(\frac{q}{c_p} - \frac{\Delta t_A}{R_A})$	$(\frac{\Delta t_A}{R_A} - \frac{\Delta t_B}{R_B})$	t_{u2}	t_{t2}
		$\frac{chu}{\text{sec. ft.}}$	$\frac{chu}{\text{sec. ft.}}$		
.21	-1.43	29.2	1.66	451	132
.24	-1.26	5.33	1.50	460	149
.24	-1.08	3.63	1.31	474	178
.23	-0.77	2.96	0.99	489	211
.21	-0.415	1.59	0.63	501	239
.20	-0.12	1.18	0.32	512	257
.19	+0.07	1.03	0.12	522	263
.19	+0.14	0.76	0.06	536	270
.20	+0.21	0.38	-0.012	549	272
.215	+0.18	0.080	— *	550	276 *
.21	+0.18	-0.004	—	550	284
.20	+0.36	-0.18	—	534	270
.20	+0.23	-0.23	—	514	269
.185	+0.21	-0.26	—	392	267

increments the following approximate
the rest of the calculations:

$$\frac{R_2}{R_1} (t_{u2} - t_{t2}) - R_2 w c_2 (t_{t2} - t_{t1}) = 250 + .072 (t_{u2} - 250)$$

IV

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TABLE - IV TEMPERATURE AFTER WATER :

TIME AFTER WATER LOSS		TIME INCREMENT SEC Δt	HEAT GENERATION		INITIAL CONDITIONS		HE. LOSS TO TUBE ($\Delta t/R_A$)
SEC.	SCRAM SEC		DECAY FACT. f_T	HEAT GEN. f_{gc} ($\frac{C_{H_2O}}{SEC. FT.}$)	FUEL TEMP	TUBE TEMP	
2	0	—	1	29.2	392	114	—
3	0	1	1	29.2	392	114	.21
4	1	1	.19	5.57	451	132	.24
7	3	2	.132	3.87	462	149	.24
9	6	3	.109	3.19	478	178	.23
13	10	4	.095	2.77	494	211	.21
18	15	5	.081	2.35	513	239	.21
23	20	5	.075	2.19	534	254	.21
33	30	10	.066	1.93	554	263	.22
53	50	20	.053	1.55	586	273	.24
78	75	25	.044	1.28	622	274	.27
103	100	25	.039	1.14	666	280	.29
153	150	50	.034	0.99	703	283	.32
203	200	50	.032	0.94	762	287	.36
253	250	50	.031	0.91	814	291	.40
303	5.1 300	50	.030	0.88	859	294	.43
403	400	100	.0275	0.805	899	297	.46
503	500	100	.0255	0.75	960	302	.50
703	700	200	.024	0.70	1004	304	.53
903	900	200	.023	0.67	1064	309	.58
1203	1200	300	.021	0.62	1096	311	.60
1503	1500	300	.020	0.59	1118	312	.61

* To avoid either unduly small time following approximation was used

$$t_{t_2} = 250 + \frac{R_B}{R_A}(t_{t_2} - t_{t_2}) - \frac{R_B w c_2 (t_{t_2} - t_{t_2})}{\Delta t}$$

E OF FUEL AND TUBE
HOT-OFF NO STEAM COOLING

HEAT LOSS TO GRAPHITE $\Delta t_1/P_B$	NET HEAT ACCUMULATION IN TUBE ($\Delta t_1/P_A - \Delta t_2/K_B$)	FINAL NET HEAT ACCUM IN FUEL	CONDITIONS TEMP. RISE IN FUEL IN TUBE °C/sec	FUEL TUBE TEMP. TEMP.
-1.45	1.66	29.2	59 18	451 132
-1.26	1.50	5.33	11 17	462 149
-1.08	1.31	3.63	7.9 15	478 178
-.77	0.99	2.96	5.6 11	494 211
-.42	0.64	2.55	4.1 7.1	513 239
-.12	0.33	2.14	4.0 3.6	534 254
+0.07	0.17	2.08	3.9 1.8	554 263
+0.14	0.08	1.71	3.2 0.9	574 272
+0.215*	—*	1.31*	2.3 —*	622 275*
—	—	1.01	1.77 —	666 280
—	—	0.85	1.49 —	703 283
—	—	0.67	1.78 —	762 287
—	—	0.60	1.05 —	814 291
—	—	0.51	0.90 —	859 294
—	—	0.45	0.79 —	899 297
—	—	0.35	0.61 —	960 302
—	—	0.25	0.44 —	1004 304
—	—	0.17	0.30 —	1064 309
—	—	0.09	0.16 —	1096 311
—	—	0.02	0.026 —	1108 312
—	—	-0.02	-0.035 —	1098 310

increments or wide fluctuations in tube temp. the

$$t_1 = 250 + 0.072(t_{u_2} - 250)$$

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Part on 12-7

1. LH McEwen
2. LP Bupp
3. JF Music
4. GC Fullmer
5. GL Locke
6. CW Botsford
7. NG Wittenbrock
8. JM Atwood
9. JA Berberet
10. CL Boyd
11. JJ Cadwell

June 12, 1956

~~L. H. McEwen
Head - Heat Transfer Unit
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FAILURE OF A C PILE PIGTAIL

SUMMARY

A Panellit scram occurred on a tube at C Pile operating at 920 kw. When the front assembly of this tube was examined 4 - 20 minutes later the pigtail was found to be broken at its sections to the crossheader. It cannot be definitely stated when the water flow to the tube actually stopped (i.e., reduced to that available from the rear face). The most probable condition, however, based upon the 400 psig line pressure and the type ^{of} fitting failure, was a prompt cracking of the Parker fitting nut and an immediate separation of the pigtail. Thus, the worst condition of sudden and complete water loss was assumed and resulting charge temperatures calculated for the cases of:

1. Cooling only to the graphite.
2. Combined steam cooling ^{PRODUCED BY WATER FLOW} from the rear face, and cooling to the graphite.

The changes in temperature of the central fuel rod and adjacent process tube are shown in Figure 1. The limiting conditions are summarized below:

TABLE I
PEAK TEMPERATURES OF TUBE AND CHARGE

Condition	Time After Reactor Scram Minutes	Central Fuel Rod Temperature °C	Central Temperature of Process Tube
Immediate Water Loss			
a.No Steam	1.3	689	282
	20	1118	312
	25	1111	311
b.Steam	1.7	550	270
Cooling	4.2	496 302	265

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The effectiveness of the steam cooling is difficult to determine but the 18 psi driving force between the pressurized rear crossheader and the opened front pigtail represents a possibility of about 0.7 gpm water flow under 90 - 100 percent steam quality conditions. (1)
It is believed that a conservative value of steam cooling was used.

The effectiveness of this cooling is very pronounced and probably accounts for the lack of damage observed in the tube and charge that were discharged from this channel soon after the reactor was shut down.

DISCUSSION

General

On March 27, 1956 C reactor was shut down by a Panellit scram of tube 3158. After preliminary scram procedures the front face was examined (⁴ to 20 minutes later according to the Log and other sources) and the pigtail of this tube was found to be separated from its connection to the inlet crossheader. In addition to a high velocity column of water streaming out the crossheader opening, water flow from the pigtail was reported. This meant a reverse flow through the tube. The exact method of flow failure can only be conjectured. Two extreme cases can be considered:

1. Immediate and complete water flow failure followed by reactor scram and reverse flow potential of 18 psi driving force.
2. Gradual reduction in water flow to about 80% of normal followed by a reactor scram and a complete flow reduction 4 minutes later. Again there will be a reverse flow potential represented by the 18 psi pressure differential from rear to front of this reactor tube.

An examination of the results obtained from the first type of failure clearly indicates that the second type would cause no excessive charge or tube temperatures.

Calculation of Maximum Charge and Tube Temperatures

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The worst situation that could have occurred is the sudden and complete loss of water to this tube. It is ~~quite~~ quite probable that the water loss closely approached this kind of

(1) K. G. Toyoda and R. F. Recht, "Test Results", HW-24903, July 2, 1952

[REDACTED]

a change. The line pressure was 400 psig and the Parker fitting follower nut sheared in two. This follower nut shearing and subsequent separation of the pigtail from the header would probably be a very rapid occurrence at 400 psig line pressure. The various phases of the temperature calculation assuming immediate water flow failure are presented in the following sections. Arbitrarily, the graphite is assumed to be a constant temperature sink at a temperature somewhat higher than normal tube block temperatures. Also the uranium is assumed to be at a constant temperature equal to its average radial temperature.

1. Given Data

Tube NUMBER - 3158
~~XXXX~~ 3158

Exposure - 28 days

Power - 920 kw

Scram ~~1.5~~ ^{STRENGTH} - 1900 ih

Flow - 42.5 gpm

Temperatures - 88° outlet, 6° inlet, 82°C = Δt_w

Graphite - Central temperature 440°C

71% helium gas composition

79 min. falling period (GRAPHITE TEMPERATURE)

Header pressures psig	Front	Rear
Before	415	19
After	0	18.5

2. Calculated Operating Temperatures (Center of Tube)

Heat generation at center of charge

$$q_c = 920 \times \frac{3415}{1.8} \times \frac{1.43}{23.9} \times 1.07 \times .94 = 105,000 \text{ Chu/hr-ft}$$

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Local water temperature - $T_c = 6 + 41 = 47^\circ\text{C}$

Water film coefficient - $h_w = 7600 \text{ Chat hr, ft}^2, a^{(2)}$

Slug Surface Temperature - $T_s = T_c + (2.65/h_w) q_c = 84^\circ\text{C}$

U surface temperature - $T_{Us} = T_s + (.0002) q_c = 105^\circ\text{C}$

U central temperature (assume $k_w = 18$) - $T_c = T_{Us} + .0727 q_c/K = 531^\circ\text{C}$

Average U temperature - $T_u = T_{Us} + .53 (T_c - T_{Us}) = 330^\circ\text{C}$

(2) S.S. JONES "HEAT TRANSFER DATA BOOK, WATER FILM COEFFICIENTS" - TO BE ISSUED

3. Physical and Geometric Propertiesa. Inner Resistance Dry Tube (TOP OF SLUG TO PROCESS TUBE) (3)

$$R_{XZ} = .052$$

$$R_{ZY} \text{ (STEAM)} = 1.35$$

$$R_{ZY} \text{ (RIBS)} = 0.41$$

$$R_i = R_{XZ} + \frac{1}{\left(\frac{1}{R_{ZY}}\right)_{H_2O} + \left(\frac{1}{R_{ZY}}\right)_{RIBS}}$$

$$R_i = .052 + \frac{1}{\frac{1}{1.35} + \frac{1}{.41}} = .365 \text{ } ^\circ\text{C, hr, ft} / \text{chw} \\ = \underline{1310} \text{ } ^\circ\text{C, sec, ft} / \text{chw}$$

b. Outer Resistance, Tube to Graphite: (Assume Centered Tube)

$$q_{G1} = \frac{R_g A \Delta T}{L} = \frac{R_g (1.78\pi)}{.007} \Delta T_g$$

TABLE II: GRAPHITE BORE TEMPERATURES

HEAT GENERATION	GAS ANNULUS	GAS THERMAL COND.	TEMP. DROP	LOCAL WATER TEMP	GRAPHITE BORE TEMP.
q_{G1}	$\Delta r^{(4)}$	$\frac{kg}{g}$	ΔT_g	t_{B2}	t_{Bore}
6300	12	0.57	245	47	292
	5		99		146
	7		138		185
6300	12	0.61	221	47	268
	5	0.52	108		155
	7	.055	143		190

Assume graphite tube block temperature is constant at 250°C , AND $\Delta V = .008$

$$\text{Outer Resistance } R_2 = \Delta V / h_g A = \left[\frac{.008}{(.055) \pi (1.78)} \right] 3600 = 94 \text{ } ^\circ\text{C, sec, ft} / \text{chw}$$

(3) J.S. JONES "TECHNICAL NOTE BOOK" - HW-5475-T, p. 148

(4) J.C. FOX "PRIVATE COMMUNICATION" - RANGE OF VALUE FOR ACTUAL CENTRAL ANNULUS AT C-PILE.

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4. Heat Transfer Equations

a. Heating to Boiling

Assume boiling press = $\frac{18}{2} = 9$ psig $\therefore T_b = 114^\circ\text{C}$

$$\sum (w c_p) \frac{dT}{d\theta} + f_t q = 0 \quad (1)$$

Total sensible heat ~~heat generation~~ ^{HEAT GENER.}

b. Boil Out Time

$$\frac{f_a w_g \Delta h_g}{\Delta \theta} = f_t q \quad (2)$$

Where the charge temperature is assumed constant during the boil out period

Note: Thermal Properties

TABLE III - HEAT CAPACITIES OF LATTICE

Temperature	100°C	300°	500°
Heat Capacity	Chu/ft-°C or Btu/ft-°F		
Fuel	.42	.47	.57
Water	.19	—	—
Process Tube	.09	.10	—
Latent Heat			
Chu/lb	540	—	—

Effective Evaporation (1.19 lb. H₂O PER FT. OF ANNULUS AND 10% OF H₂O BOILS OUT FORCING OUT THE REST.
10.4 - Chu/ft.

With small error it can be assumed that the fuel temperature remains constant during the boil out period, especially when the time required is very short.

Then equation (1) reduces to:

$$\text{High Level Boil Out} \quad \frac{10.4}{\Delta \theta} = f_t 29.2 \quad (3)$$

c. Heat Transf from Dry Charge (Steam Envelope)

Fuel Temperature Change:

$$w_c \frac{dT_1}{d\theta} = (q_1 - q_s) - \frac{T_u - T_e}{R_1} \quad (4)$$

Tube Temperature Change $T_{u2} = T_{u1} + \Delta \theta \left[\frac{q_N - \Delta T_c / R_1}{w_c} \right]$

$$\text{d. Steam Cooling} \quad \left[w_{c2} \frac{dT_2}{d\theta} = \frac{T_u - T_v}{R_1} - \frac{T_b - T_g}{R_2} \right] \quad (5)$$

According to crossheader pressure measurements there was a steam cooling driving force (rear C.H. to front face pressure) of about 18 net

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$\left[\frac{\Delta T_c / R_1 - \Delta T_v / R_2}{w_{c2}} \right]$
 $T_{u2} = T_{u1} + \Delta \theta \left[\frac{\Delta T_c / R_1 - \Delta T_v / R_2}{w_{c2}} \right]$
 INSERT

In Figure 2, data obtained experimentally from a full scale mockup of the C Pile annulus has been replotted to indicate the water flow that might be obtained through 3158 C after the pigtail failure. Curve I indicates the observed peak instability pressure drop across the tube for different levels of operation.

Curve II indicates the observed water flow into the tube under these heat flux and maximum pressure drop conditions. Curve III indicates the pressure drop ^(x10) approximately 100% steam quality conditions and curve IV indicates the steam flow under these 100% quality conditions.

Thus, for the Δp driving force available in this problem the corresponding maximum tube power and steam flow would be 83 kw and 0.06 lbs. of steam per second. For the case in question this represents 9% of original tube power. This corresponds to a time delay after a scram of ~ 800 seconds. ⁽⁵⁾ This heat output, however, corresponds to ~~that~~ ^{that} from a lattice unit fully cooled rather than the conditions of the pigtail failure where the lattice assembly is actually absorbing heat rather than giving it to the cooling water. The actual heat generation for a 1900 ih scram would be down to 9% in 10 seconds after the rod insertion. ⁽⁶⁾ Therefore, the problem is to determine how much cooling occurs from water evaporation in the central portion of the tube.

~ from heat flow to steam?

The calculations for no steam cooling consider the system to be effectively stagnant and only heat conduction is considered. This is the worst possible case as there is no steam cooling. But when steam cooling is assumed we have the problem that this cooling may be so good in the front portion of the tube that 100% steam is formed and there is only the cooling of super heated steam over the rest of the charge. This could result in excessive charge temperatures. However, if we conservatively assume 50% quality steam then the effective steam cooling would be:

$$Q_s = 540 (.5) (\dot{w}_s) = 16.2 \text{ ch/sec} \quad (6)$$

- () P. C. Walkup, R. E. Hall, "Final Report PT-105-14-MR, and Process Test MR-105-30", HW-42964, May 15, 1956.
(6) S. S. Jones, "Heat Generation and Total Heat Output from the Pile After Shutdown", HW-33870, November 23, 1954.

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[REDACTED]

And assuming further that the steam cooling along the charge length is proportional to the heat generation, then:

$$q_s = \frac{1.43}{23.5} Q_s = 0.97 \text{ Chu/ft. sec.} \quad (7)$$

We may conclude therefore that at 10 seconds or more after the reactor scram steam cooling was established in this tube.

5. Fuel and Tube Temperature Calculations

Based upon these considerations and the assumptions listed below a stepwise calculation was made of the uranium and process tube temperature elevations above the surrounding graphite temperature. These calculations were based upon equations (4) and (5) using the q_s value in case II of 0.97 Chu/ft-sec. The assumptions on which this method is based are:

1. The fuel rod temperature is uniform and is equal to the volume averaged temperature at the start of these calculations.
2. The graphite tube block temperature is constant over the time period considered at a value of 250°C

3.

a. Time to Reach Boiling

This is obtained from the simplified equation

$$\Delta \theta = \frac{\sum (w c_p) \Delta t_w}{f_T q_c} \quad (8)$$

The pressure at the center of this tube is about $14.7 + 18/2 = 24$ psia. This corresponds to a boiling point of 114°C. Therefore:

$$\Delta \theta = \frac{.7(114 - 97)}{29} = 1.6 \text{ SECONDS}$$

During this time the tube and charge increase in temperature by $(114 - 97)^\circ\text{C}$.

b. Time to Boil Dry

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As a conservative assumption the tube is considered to be effectively dry after 10% of the water has boiled out. Therefore, the time required to boil dry at constant temperature is:

$$\Delta \theta = \frac{w \Delta h_{v f v}}{f_T q_c} = \frac{104(.1)}{29} = 0.4 \quad (9)$$

c. Maximum Temperatures

The stepwise calculation of the temperatures reached in the cases of no steam cooling and steam cooling after 10 seconds are presented in the following tables.

TABLE - IV TEMPERATURE
AFTER WATER

TIME AFTER WATER LOSS SEC.	SCRAM SEC.	TIME INCRE- MENT SEC Δt	HEAT GENERATION		INITIAL CONDITIONS		
			DECAY FACTOR f_T	HEAT GEN f_{gc}	FUEL TEMP	TUBE TEMP	HE TO FUEL TEMP ($^{\circ}\text{C}/^{\circ}\text{R}$)
2	0	—	1	29.2	392	114	226
3	0	1	1	29.2	392	114	328
4	1	1	.19	5.57	451	132	.29
7	3	2	.132	3.87	462	149	.24
9	15	3	.109	3.19	478	170	.215
13	19	4	.095	2.77	494	211	.21
18	30	5	.081	2.35	504	239	.21
23	20	5	.075	2.19	534	254	.27
33	55	10	.066	1.93	554	263	.24
53	50	20	.053	1.55	586	273	.24
78	1,3	25	.044	1.28	622	274	.27
103	100	25	.039	1.14	666	280	.29
153	2,55	50	.034	0.99	703	283	.32
203	200	50	.032	0.94	762	287	.36
253	4,2	50	.031	0.91	814	291	.40
303	5,05	50	.030	0.88	859	294	.43
403	6,7	100	.0275	0.805	899	297	.46
503	500	100	.0255	0.75	960	302	.50
703	10,7	200	.024	0.70	1004	304	.53
903	900	200	.023	0.67	1064	309	.58
1203	1200	300	.021	0.62	1096	311	.60
1503	1500	300	.020	0.59	1118	312	.61

* SEE FOOT.

OF FUEL AND TUBE

SHUT-OFF

NO STEAM COOLING

NET HEAT ACCUMULATION IN TUBE ($\Delta t_1/\rho_1 - \Delta t_2/\rho_2$)	FINAL CONDITIONS HEAT ACCUM IN FUEL	TEMP. RISE IN FUEL °C/sec	TEMP. RISE IN TUBE °C/sec	FINAL TUBE TEMP. TEMP.
-1.66	29.2	59	18	451 132
-1.50	5.33	11	17	462 149
-1.31	3.63	7.9	15	478 178
-0.99	2.96	5.6	11	484 211
-0.64	2.55	4.8	9.4	513 239
-0.32	2.14	4.0	8.8	534 254
-0.17	2.08	3.9	8.9	554 263
-0.08	1.71	3.2	0.9	588 272
0.00 *	1.21	2.3	— *	622 275
—	1.01	1.77	—	666 280
—	0.85	1.49	—	703 283
—	0.67	1.78	—	762 287
—	0.60	1.05	—	814 291
—	0.51	0.90	—	859 294
—	0.45	0.79	—	899 297
—	0.35	0.61	—	960 302
—	0.25	0.44	—	1004 304
—	0.17	0.30	—	1064 309
—	0.09	0.16	—	1096 311
—	0.08	0.036	—	1108 312
—	-0.02	-0.035	—	1098 310

NOTE TABLE II

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TABLE V

TEMPERATURE OF
AFTER WATER
10 SECONDS AIR

TIME AFTER WATER CERM LOSS		TIME INCR. MINT	HEAT GENERATION DECAT HEAT FACT GEN.		INITIAL COND. FUEL TUBE TEMP TEMP	
Sec	Sec	Sec	f_r	$f_r q_c$ ($\frac{C_{H_2O}}{DCC, H_2O}$)	$T_{u,}$ °F	$T_{c,}$ °C
2	0	—				
3	0	1	1	29.2	392	114
4	1	1	.19	5.57	451	132
7	3	2	.132	3.87	462	144
9	6	3	.109	3.19	478	178
13	10	4	.095	2.77	469	211
18	15	5	.081	2.35	501	239
23	20	5	.075	2.19	512	257
33	30	10	.066	1.93	522	263
52	50	20	.053	1.55	536	270
78	75	25	.044	1.28	549	272
103	100	25	.039	1.14	550	276
153	150	50	.034	0.99	550	284
203	200	50	.032	0.94	534	270
253	250	50	.021	0.91	514	268

*

TO AVOID UNDOLY SMALL TIME INC.
EQUATION WAS USED FOR T_{T_2} IN THE RES

$$T_{T_2} = 250. + \frac{R}{R}$$

FUEL AND TUBE

SHUT OFF WITH STEAM COOLING
FOR SHUT DOWN

T ₁ - T ₂ °F	HEAT ACCUMULATION		FINAL COND.	
	IN FUEL FUEL	IN TUBE TUBE	FUEL TEMP TEMP	TUBE TEMP TEMP
$\frac{\Delta T_1}{R_1}$ $\frac{\Delta T_2}{R_2}$	$\frac{1}{2} \rho c_p \frac{\Delta T}{\Delta t} = \frac{\Delta T}{R_1} \left(\frac{\Delta T_1}{R_1} - \frac{\Delta T_2}{R_2} \right)$		t_{12}	t_2
	Ch. Sec. ft.	Ch. Sec. ft.		
1 - 1.4	29.2	1.56	451	132
2 - 1.26	5.33	1.50	460	149
3 - 1.05	3.87	1.31	474	178
4 - .77	3.19	0.99	484	211
5 - .415	1.59	0.63	501	234
6 - .12	1.18	0.32	512	257
7 - .07	1.03	0.12	522	263
8 - .14	0.76	0.06	536	270
9 - .21	0.38	-0.012	549	272
10 - .16	0.080	—	550	276
11 - .15	-0.004	—	550	274
12 - .16	-0.18	—	534	270
13 - .22	-0.23	—	514	269
14 - .21	-0.26	—	392	267

PRESENTS THE FOLLOWING APPROXIMATE
OF THE CALCULATIONS :

$$(T_{12} - T_2) = \frac{R_2 W_{O_2} (T_{12} - T_2)}{\Delta Q} = 50 + .072 (T_{12} - 250)$$

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NOMENCLATURE

A	Area perpendicular to heat flow
Q_{sq}	Total heat absorbed by steam formation in tube - Chu/sec
R_A	Overall heat transfer resistance in dry tube, top of slug to tube - °C,ft,sec/Chu
R_B	Overall heat transfer resistance tube to graphite - °C,ft,sec/Chu
R_{xz}	Resistance - Across slug °C,ft,hr/Chu
R_{zy_s}	Resistance - Across steam annulus - °C,ft,hr/Chu
R_{xz_s}	Resistance - Across ribs - °C,ft,hr/Chu
O	Time after water shutoff - seconds
f_x	Fraction of original heat generation
f_v	Fraction of water in annulus converted to steam
h_w	water film coefficient, Chu/hr,ft ² ,°C
h_v	Heat of vaporization - Chu/lb
k_g	Thermal conductivity of pile gas Chu/hr,ft,°C
k_u	Thermal conductivity of uranium, Chu/hr,ft,°C
q_c	Heat generation at center of charge, Chu/sec,ft
q_n	Net heat accumulation in the fuel rod - Chu/sec,ft
q_s	Heat removed by the steam - Chu/sec,ft
r	Radial heat conduction path, ft
t_c	Core temperature at the center of charge - °C
t_g	Graphite bore temperature - °C
t_l	Local water temperature - °C
t_s	Charge surface temperature - °C
t_t	Process tube average temperature - °C
t_{us}	Uranium surface temperature - °C
t_A	temperature drop top of slug to process tube - °C = $t_u - t_t$
t_b	temperature drop across process tube to graphite - °C = $t_t - t_g$
t_w	increase in local water temperature from equilibrium temp to boiling point °C
	average heat capacity of the fuel Chu/ft,°C
	average heat capacity of the process tube Chu/ft,°C
	steam flow lbs/sec

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NW-56816 RD
Page 49 P - 10
May 28, 1956

TO: Steve Jones
John Batch
George Toyoda

FROM: Larry McEwen

SUBJECT: Thermal Transients - Pigtail Failure - 3158 C

Steve Jones has made an analysis of expected slug jacket and tube temperatures following a sudden total front pigtail failure followed by reverse flow. This is important from two standpoints. One, the study is to be written up and distributed off-site. Two, past power level limits at K were set very conservatively by not taking steam cooling into account.

This is the first analytical attempt I know of to try to characterize the steam cooling effect. It is not easy.

Therefore, I am asking Steve to work up his calculations on this particular situation in a little more elegant form, and for George to dig hard at the results of the recent transient instability runs. Next, if all three of you will put your heads together and mull over the overall situation, we should come up with any analytical-empirical procedure, in accord with theory, which will enable approximate handling of similar problems until even better techniques are available.

The present technique of Steve's, while plenty adequate at the time, can probably benefit by some "hindsight" analysis from the transient tests to firm-up some of the assumptions, etc. In any event, the Jones technique tried on one of our transient runs should give a good indication of validity of key assumptions. This is the only way I know of getting a good focus on the accuracy of the computed temperatures.

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HW-56816 RD
Page 5

1. LH McEwen
2. LP Bupp
3. JF Music
4. GC Fullmer
5. GL Locke
6. CW Botsford
7. NG Wittenbrock
8. JM Atwood
9. JA Berberet
10. CL Boyd
11. JJ Cadwell

June 12, 1956

R. L. Dickman
Pound
S. S. Jones

L. H. McEwen
Head - Heat Transfer Unit
Pile Technology Section
ENGINEERING DEPARTMENT

FAILURE OF A C PILE PIGTAIL

SUMMARY

A Panellit scram occurred on a tube at C Pile operating at 920 kw. When the front assembly of this tube was examined 4 - 20 minutes later the pigtail was found to be broken at its connections to the crossheader. It cannot be definitely stated when the water flow to the tube actually stopped (i.e., reduced to that available from the rear face). The most probable condition, however, based upon the 400 psig line pressure and the type^{of} fitting failure, was a prompt cracking of the Parker fitting nut and an immediate separation of the pigtail. Thus, the worst condition of sudden and complete water loss was assumed and resulting charge temperatures calculated for the cases of:

1. Cooling only to the graphite.
produced by water flow
2. Combined steam cooling from the rear face, and cooling to the graphite.

The changes in temperature of the central fuel rod and adjacent process tube are shown in Figure 1. The limiting conditions are summarized below:

TABLE I
PEAK TEMPERATURES OF TUBE AND CHARGE

Condition	Time After Reactor Scram Minutes	Central Fuel Rod Temperature °C	Central Temperature of Process Tube
Immediate Water Loss			
a.No Steam	1.3	689	282
	20	1118	312
	25	1111	311
b.Steam	1.7	550	270
Cooling	4.2	406 392	265

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S.S. Jones
5-24-54

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The effectiveness of the steam cooling is difficult to determine but the 18 psi driving force between the pressurized rear crossheader and the opened front pigtail represents a possibility of about 0.7 gpm water flow under 90 - 100 percent steam quality conditions. (10) It is believed that a conservative value of steam cooling was used.

The effectiveness of this cooling is very pronounced and probably accounts for the lack of damage observed in the tube and charge that were discharged from this channel soon after the reactor was shut down.

DISCUSSION

General

On March 27, 1956 C reactor was shut down by a Panellit scram of tube 3158. After preliminary scram procedures the front face was examined (⁴ to 20 minutes later according to the Log and other sources) and the pigtail of this tube was found to be separated from its connection to the inlet crossheader. In addition to a high velocity column of water streaming out the crossheader opening, water flow from the pigtail was reported. This meant a reverse flow through the tube. The exact method of flow failure can only be conjectured. Two extreme cases can be considered:

1. Immediate and complete water flow failure followed by reactor scram and reverse flow potential of 18 psi driving force.
2. Gradual reduction in water flow to about 80% of normal followed by a reactor scram and a complete flow reduction 4 minutes later. Again there will be a reverse flow potential represented by the 18 psi pressure differential from rear to front of this reactor tube.

An examination of the results obtained from the first type of failure clearly indicates that the second type would cause no excessive charge or tube temperatures.

Calculation of Maximum Charge and Tube Temperatures

The worst situation that could have occurred is the sudden and complete loss of water to this tube. It is ~~also~~ quite probable that the water loss closely approached this kind of

(1) K. G. Toyoda and R. F. Recht, "Test Results", HW-24903, July 2, 1952

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a change. The line pressure was 400 psig and the Parker fitting follower nut sheared in two. This follower nut shearing and subsequent separation of the pigtail from the header could probably be a very rapid occurrence at 400 psig line pressure. The various phases of the temperature calculation assuming immediate water flow failure are presented in the following sections. Arbitrarily, the graphite is assumed to be a constant temperature sink at a temperature somewhat higher than normal tube block temperatures. Also the uranium is assumed to be at a constant temperature equal to its average radial temperature.

1. Given Data

Tube Number - 3158

~~RAWAX 3158~~

Exposure - 28 days

Tube Power - 920 kw →

Scram ^{Strength} ~~in~~ - 1900 ih

Flow - 42.5 gpm

Temperatures - 88° outlet, 6° inlet 82°C = Δt_w

Graphite - Central temperature 440°C

71% helium gas composition

79 min. falling period (Graphite temperature)

Header pressures psig	Front	Rear
Before	415	19
After	0	18.5

2. Nomenclature

3. Calculated Operating Temperatures (Center of Tube)

Heat generation at center of charge

$$q_c = 920 \times \frac{3415}{1.8} \times \frac{1.43}{23.9} \times 1.07 \times .94 = 105,000 \text{ Chu/hr-ft}$$

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Local water temperature - $t_e = 6 + 41 = 47^\circ\text{C}$

Water film coefficient - $h_w = 7600 \text{ Chu/hr-ft}^2, ^\circ\text{C}^{(2)}$

Slug Surface Temperature $t_s = t_e + (2.65/h_w) q_c = 84^\circ\text{C}$

U surface temperature $t_{us} = t_s + (0.0002) q_c = 105^\circ\text{C}$

U central temperature (assume $k_u = 18$)

$$t_c = t_{us} + .0727 q_c / k_u = 511^\circ\text{C}$$

Average U temperature

$$T_u = t_{us} + .53 (t_c - t_{us}) = 330^\circ\text{C}$$

(2) S.S. Jones "Water

Film Coefficients" - to be issued

NOMENCLATURE

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A	Area perpendicular to heat flow
Q_{sq}	Total heat absorbed by steam formation in tube - Chu/sec
R_A	Overall heat transfer resistance in dry tube, top of slug to tube - °C,ft,sec/Chu
R_B	Overall heat transfer resistance tube to graphite - °C,ft,sec/Chu
R_{xz}	Resistance - Across slug °C,ft,hr/Chu
R_{zys}	Resistance - Across steam annulus - °C,ft,hr/Chu
R_{xz_s}	Resistance - Across ribs - °C/ft,hr/Chu
θ	Time after water shutoff - seconds
f_x	Fraction of original heat generation
f_v	Fraction of water in annulus converted to steam
h_w	water film coefficient, Chu/hr,ft ² ,°C
h_v	Heat of vaporization - Chu/lb
k_g	Thermal conductivity of pile gas Chu/hr,ft,°C
k_u	Thermal conductivity of uranium, Chu/hr,ft,°C
q_c	Heat generation at center of charge, Chu/sec,ft
q_n	Net heat accumulation in the fuel rod - Chu/sec,ft
q_s	Heat removed by the steam - Chu/sec,ft
r	Radial heat conduction path, ft
t_c	Core temperature at the center of charge - °C
t_g	Graphite bore temperature - °C
t_l	Local water temperature - °C
t_x	Charge surface temperature - °C
t_t	Process tube average temperature - °C
t_{us}	Uranium surface temperature - °C
t_A	temperature drop top of slug to process tube - °C = $t_u - t_t$
t_b	temperature drop across process tube to graphite - °C = $t_t - t_g$
t_w	increase in local water temperature from equilibrium temp to boiling point °C
	average heat capacity of the fuel Chu/ft,°C
	average heat capacity of the process tube Chu/ft,°C
	steam flow - lbs/sec

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Temp °C

Steam

.0031

Fr 8

Br 408

U. #/sec	G' #/sec	Re	$\frac{1}{G'}$	J	Cp	E	$\frac{1}{h}$	$\frac{h}{RTU}$
100	32.2	201	.0050	.45	8.0		1.7	.0203
200	32.2	101	.0022	.45	"		1.7	.0297
300	32.2	101	.0024	.45	"		1.7	.0337
400	32.2	101	.0022	.45	5.5		1.7	.00921
500	32.2	101	.0022	.45	"		1.7	.00458
600	32.2	101	.0022	.45	"		1.7	.00507
700	32.2	2010	.0052	.45	8.35		1.6	.000686
800	32.2	1000	.0055	.45	"		1.6	.00074
900	32.2	1000	.0057	.45	"		1.6	.000803

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$$h = 106 (1.27 + 0.015 t_b) \frac{V^{0.8}}{D_c^{0.2}} (t^{\circ}C)$$

W #/sec	G #/sec	V ft/sec	$V^{0.8}$	$P_c^{0.2}$	h	h'
2.1	3.22	0.54	0.061	1.01	600	.167
2.21	3.22	0.54	0.077	1.01	91	.025
2.32	3.322	0.54	0.082	1.01	15	.0042

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$4.00 - .50$

w lbs/sec	Δp_d psi	$\frac{\Delta p_s}{\lambda}$	$(w/c)_c$ 100°	a ft ² /ft	h_c	β_1	θ_1	θ_2	$\bar{\theta}$	$e^{-\beta_0 \theta}$	f_0	l_e
.01	negl.	6.9×10^{-5}	.40	.377	.025	.0235	2	5	3	3.5	.93	1.0

.0075

Assume

$$\beta_1 = \frac{h_c a}{(L_c - C)_c}$$

$$f(\theta) = \frac{g_0 f_0 + \frac{1}{2} \theta^2}{(w-c)_c}$$

Assume										Assume						Assume	
Re	$q_{(0)A}$ Chairs	$q_{(0)A}$	t_{wi} °C	Saturation Pres. p_s	Temp. t_L	T_{i1}	$h_{e2} T_{i1}$	$F_{(0)}$	$\frac{F_{(0)}}{G}$	$t_{e1} - \frac{F_{(0)}}{G}$	t_{eA2}	T_{eA}	h_e	Δp_e	h_{TPF}		
0	1	5.5	5.5	110°	25	131	120	1.13	16.7	711	-524	283	204	.43		2	
	.5	5.0	5.0					15.5	660	-475	218	202	.31	negl			

$$t_{eA2} = F_{(0)} + e^{-\beta \Delta \theta} (t_{e1} + F_{(0)})$$

$$L = \frac{(WC)_w \Delta t_w}{h \cdot a (T_i - t_{e1})}$$

$$= \frac{h_{TPF} \cdot A}{(W-C)_c}$$

Assume

Δp_e	h_{TPF}	EXIT COND.		R	Δp_f	n_2	Δp_M	$\Delta \frac{1}{T}$	EXIT COND.		h_{TPF}	h_{atm}	g_o	g_s	$F(\phi)$	R_2	$\frac{F_1}{R_1}$
		Pres. psig	Sat Temp.						Pres. psig	Sat Temp.							
2		20	131	250	.03	12	.02	.05	25								
negl.		25							25	131	~.125	6.18	9	9	37.9	.118	32

[illegible]

Assume Vapor Temp

$(w_c) = .45$

q_2	t_{w1}	t_{w2}	t_w	R_1	R_2	R_3	$F(t)$	$F(t)$	t_{c1}	$t_{c1} - \frac{F(t)}{R_3}$	t_{c2}	t_c	t_{w2}
119.2	130	170	150	.005	.283	.00417	.987	48.2	102.2	350	-6.73	359	307
		300	215		.456			48.5	116.2		-8.12	367	270
		230	180					48.4				359	285
		245	193		.36			48.3	115		-5.0	360	285
28.5	285	400	342	.004	.52	.00377	.993	64.5	171.00	480	-16.630	590	425
													412
29.5	412	500	456	.004	.69	.00335	.989	60.3	180.00	470	-17.530	650	569
		530									-17.5	610	530
16	530	560	540	.0035	.71	.00264	.992	33.4	126.50	305	-12.350	400	282
		330	430		.57			33.1	125.50			400	427
9.5	427	380	403	.004	.61	.00336	.989	22.4	66.70				

Aug Vapor Temp

Δp_r	Δp_r	Δp_r	$F(t)$	$F(t)$	t_{c1}	$t_{c1} - \frac{F(t)}{R_3}$	t_{c2}	t_c	t_{w2}
1.987	48.2	102.2	350	-6.73	359	354	307		
	48.5	116.2		-8.12	367	359	270		
	48.4				359		285		
	48.3	115		-5.0	360		285		
7.993	64.5	171.00	480	-16.630	590	585	425		
							412		
5.989	60.3	180.00	470	-17.530	650	560	569		
				-17.5	610	540	530		
4.992	33.4	126.50	305	-12.350	400	352	282		
	33.1	125.50			400	352	427		
2.989	22.4	66.70							

Aug Vapor Temp

Δp_r Δp_r

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$t_{w1} + t_{w2} = (w_c) t_c$

$(t_1 - \frac{F(t)}{R_3}) t_{c2} = \frac{F(t)}{R_3} + t_c$

$(t_1 - \frac{F(t)}{R_3}) t_{c2} = \frac{F(t)}{R_3} + t_c$

$(t_1 - \frac{F(t)}{R_3}) t_{c2} = \frac{F(t)}{R_3} + t_c$

$$l'(wc)_c \frac{dt_c}{d\theta} = f_0 f_0 l' - h a l' (t_c - t_{cr})$$

$$\frac{dt_c}{d\theta} + \frac{h a}{(wc)_c} t_c = \frac{f_0 f_0}{(wc)_c} + h a t_{cr}$$

$$\frac{dt}{d\theta} + \beta t = F(\theta)$$

$$e^{\beta\theta} \frac{dt}{d\theta} + \beta t e^{\beta\theta} = F(\theta) e^{\beta\theta}$$

$$\frac{d}{d\theta} (t e^{\beta\theta}) = F(\theta) e^{\beta\theta}$$

$$\int_{t_1 e^{\beta\theta_1}}^{t_2 e^{\beta\theta_2}} d(t e^{\beta\theta}) = \bar{F}_\theta \int_{\theta_1}^{\theta_2} e^{\beta\theta} d\theta$$

$$t_2 e^{\beta\theta_2} - t_1 e^{\beta\theta_1} = \frac{\bar{F}_\theta}{\beta} (e^{\beta\theta_2} - e^{\beta\theta_1})$$

$$t_2 = t_1 \frac{e^{\beta\theta_1}}{e^{\beta\theta_2}} + \frac{\bar{F}_\theta}{\beta} - \frac{\bar{F}_\theta}{\beta} \frac{e^{\beta\theta_1}}{e^{\beta\theta_2}}$$

$$t_2 = \frac{\bar{F}_\theta}{\beta} + e^{-\beta\Delta\theta} \left(t_1 - \frac{\bar{F}_\theta}{\beta} \right)$$

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100
TER LOSS - 5 seconds

1000

COSINE CURVE FOR C-PILE

$$f_x = 100 \cos\left(\frac{\pi \cdot x}{2(X+E_1)}\right)$$

Where $X = 11.9'$

$E = 1.53'$ rear *

$E = 1.32'$ front *

46.7

51.3

* G. C. Fuller McDaniel
"C-PILE START-UP TECH. DATA"
HW-29034 Sept 1, 1953

RELATIVE
FLUX

100

90

80

70

60

50

40

30

20

10

0

2

4

6

8

10

12

DISTANCE FROM CENTER OF CHARGE

DECLASSIFIED

50

40

30

20

100

30

25

20

15

10

5

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ROUGH DRAFT

① TEMPERATURES

1. Transient Boilout.

$$\frac{F_o F_z F_p P}{3600} = W_w C_p \left(\frac{110-50}{\Delta\theta_1} \right) + .20 W_w \frac{\Delta H_o}{\Delta\theta_2} \quad (1)$$

Heat Gen.
Chen/sec

Heat Req. to raise
H₂O to boil
Chen/sec

Heat Req. to
boil out H₂O

$$F_o F_z F_p P = W_w \frac{60}{\Delta\theta_1} + \frac{97 W_w}{\Delta\theta_2} \quad (1a)$$

Reactor	F _p	W _w	Δθ	F _z	F _o
B, D, DR, F, H	114	2.54	0-3	1.1	.94
C	112	1.92	3-20		.90
KE, KW	98	2.232	20+		.80

This requires a trial & error calc.

THD

85

200 ft

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(2)

2. To Al. Melting Pt.

a) Fuel

$$(wcp)_s \frac{(t_{s2} - t_{s1})}{\Delta \theta} = \frac{F_u F_r F_p P}{3600} \left(\frac{t_s - t_e}{R_t} - \frac{t_s - t_{sx}}{R_{ev} (3600)} \right)$$

Increase in Fuel Sensible Heat = Avg. Heat Gen. - Heat Flow to tube - Heat Flow to Chg Ends

And solving for t_{s2}

$$t_{s2} = t_{s1} + \frac{\Delta \theta}{(wcp)_s} \left\{ \frac{F_u F_r F_p P}{3600} - \frac{t_{s2} + t_{s1} - t_e - t_{e1}}{7200 R_t} - \frac{t_{s2} + t_{s1} - t_{sx} - t_{sx1}}{7200 R_{ev}} \right\}$$

And finally:

$$t_{s2} = \frac{t_{s1} + \frac{\Delta \theta}{(wcp)_s} \left\{ \frac{F_u F_r F_p P}{3600} - \frac{t_{s1} - t_e - t_{e1}}{7200 R_t} - \frac{t_{s1} - t_{sx} - t_{sx1}}{7200 R_{ev}} \right\}}{1 + \frac{\Delta \theta}{2(wcp)_s} \left(\frac{1}{R_{ev}} + \frac{1}{R_t} \right) \frac{3600}{(3600)^2}}$$

Reactr	$\frac{solid}{(wcp)_s}$	$\frac{Cored}{I \& E}$	R_t	R_{ev}	t_{s1}	t_{e1}	t_{sx1}	θ	F_u	θ
B	.45	.45	.088	76	436	110		0-3	.94	0
C	.45	.45	.088	76	438	110		13-20	.390	
K	.45	.45	.133	76	492	110		20+	.10	

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$$t_{s2} = \frac{t_{s1} + \frac{\Delta \theta}{.45} \left\{ .0298 P - \frac{t_{s1} - 2t_{e1}}{.176} - \frac{t_{s1} - 2t_{sx1}}{150} \right\}}{1 + \frac{\Delta \theta}{2(.45)} \left(\frac{76 + .09}{.60} \right)}$$

(3)

2. (cont.)

b) Tube

$$(wC_p)_t \frac{(t_{t2} - t_{t1})}{\Delta \theta} = \frac{\bar{t}_s - \bar{t}_t}{3600 R_t} - \frac{(\bar{t}_t - \bar{t}_{tx})}{3600 R_t} - \frac{\bar{t}_t - \bar{t}_g}{3600 R_g}$$

Increase in Tube Sensible Ht. = Heat flow from fuel along tube - Heat flow to Graphite

And Solving for t_{t2} :

$$t_{t2} = t_{t1} + \frac{\Delta \theta}{(wC_p)_t} \left\{ \frac{t_s + t_{s2} - t_{t1} - t_{t2}}{(2) 3600 R_t} - \frac{2t_{t1} + 2t_{t2} - 2t_{tx} - 2t_{tx2}}{(2) 3600 R_t} - \frac{t_{t1} + t_{t2} - t_{g1} - t_{g2}}{(2) 3600 R_g} \right\}$$

And Finally,

$$t_{t2} = \frac{t_{t1} + \frac{\Delta \theta}{(wC_p)_t} \left\{ \frac{t_s + t_{s2} - t_{t1}}{7200 R_t} - \frac{2t_{t1} - 2t_{tx} - 2t_{tx2}}{7200 R_t} - \frac{t_{t1} - t_{g1} - t_{g2}}{7200 R_g} \right\}}{1 + \frac{\Delta \theta}{(wC_p)_t} \left(\frac{1}{R_t} + \frac{2}{R_t} + \frac{1}{R_g} \right) 7200}$$

Reactor	wC_p	R_t	R_{et}	R_g	t_{t1}	t_s	t_{tx}	t_{g1}
B	.101			0.015 0.018				
C	.102			0.015 0.017				
K	.107			0.043 0.05				

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t_g (4)

$$t_{gt1} = (0.30)(t_{gm} - t_{gs}) + t_{gt}$$

$$t_{gt1} = (0.80) \dots$$

GRAPHITE TUBE BLOCK

$$c) (wcp)_{gt} \frac{(t_{gt2} - t_{gt1})}{\Delta\theta} = \frac{F_g F_p P}{3600} + \frac{(t_{gt} - t_{gt})}{R_g} - \frac{(t_{gt} - t_{gt})}{R_g} - 2 \frac{(t_{gt} - t_{gt})}{R_{gt}}$$

Increase in Gr. T.B. Sensible = Heat gain in T.B. + Heat Flow from Tube to F.B. - Heat Flow along chg

And solving for t_{gt2}

$$t_{gt2} = t_{gt1} + \frac{\Delta\theta}{(wcp)_{gt}} \left\{ \frac{F_g F_p P}{3600} + \frac{t_{gt2} + t_{gt1} - t_{gt} - t_{gt}}{7200 R_g} - \frac{t_{gt1} + t_{gt2} - t_{gt} - t_{gt}}{7200 R_g} - \frac{2t_{gt1} + 2t_{gt2} - 2t_{gt} - 2t_{gt}}{R_{gt}} \right\}$$

And finally

$$t_{gt2} = \frac{t_{gt1} + \frac{\Delta\theta}{(wcp)_{gt}} \left\{ \frac{F_g F_p P}{3600} + \frac{t_{gt2} + t_{gt1} - t_{gt} - t_{gt}}{7200 R_g} - \frac{t_{gt1} - t_{gt} - t_{gt}}{7200 R_g} - \frac{2t_{gt1} - 2t_{gt} - 2t_{gt}}{R_{gt}} \right\}}{1 + \frac{\Delta\theta}{(wcp)_{gt}} \left(\frac{1}{R_g} + \frac{1}{R_g} + \frac{2}{R_{gt}} \right)}$$

Reactor	$(wcp)_{gt}$	F_g	F_p	R_g	R_g	R_{gt}	t_{gt1}	t_{gt2}	t_{gt}
B	1.6		114	.248	.015				
C	1.6		112	.217	.015				
K	1.8		98	.25	.043				
θ	0-3	320	20+						
F_{gt}	1.2	2	4						

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NOTE for Pile case
 $R_L = \infty$

d) GRAPHITE FILLER BLOCK

$$(Wc)_F \frac{(t_{GF_2} - t_{GF_1})}{\Delta \theta} = \frac{F_G F_F F_P}{3600} + \frac{(t_{GF_1} - t_{GF_2})}{3600 R_G} - \frac{(t_{GF_1} - t_T)}{R_L} - \frac{2(t_{GF_1} - t_{GF_2})}{R_{LF}}$$

Increase in Graph. F.B. sensible Ht. = Heat gen in F.B. + Heat Flow from T.B. - Heat Flow to Adj. tube - Heat Flow along tube

And Solving for t_{GF_2} :

$$t_{GF_2} = t_{GF_1} + \frac{\Delta \theta}{(Wc)_F} \left\{ \frac{F_G F_F F_P}{3600} + \frac{t_{GF_1} + t_{GF_2} - t_{GF_1} - t_{GF_2}}{7200 R_G} - \frac{t_{GF_1} + t_{GF_2} - t_T}{3600 R_L} - \frac{2t_{GF_1} + 2t_{GF_2} - 2t_{GF_1} - 2t_{GF_2}}{3600 R_{LF}} \right\}$$

graphite filler block

And Finally:

$$t_{GF_2} = \frac{t_{GF_1} + \frac{\Delta \theta}{(Wc)_F} \left\{ \frac{F_G F_F F_P}{3600} + \frac{t_{GF_1} + t_{GF_2} - t_{GF_1} - t_{GF_2}}{7200 R_G} - \frac{t_{GF_1} - t_T}{3600 R_L} - \frac{2t_{GF_1} - 2t_{GF_2} - 2t_{GF_2}}{3600 R_{LF}} \right\}}{1 + \frac{\Delta \theta}{7200 (Wc)_F} \left(\frac{1}{R_G} + \frac{1}{R_L} + \frac{2}{R_{LF}} \right)}$$

Reactor	$(Wc)_F$	F_G	R_G	R_L^*	R_{LF}	t_{GF_1}	t_{GF_2}	t_{GF_3}
B	9.4		.248	.252				
C	9.4		.217	.224				
K	9.2		.25	.27				
θ	0-3	3-20	20+					
F_{GF}	4.8	8	16					

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* $R_L = R_c - R_{3/2}$

(6)

e) TIME Effects

Time After Event. θ	Time Inter- val Δθ	All Reactors				Reactor		
		F ₀	F ₂	F ₆	F ₇	B F _P	C F _P	K F _P
3	3	.94	1	21.6	4.8	114	112	98
10	7	.90		2	8			
20	10	.80		4	16			
30	10							
50	20							
100	50							
150	50							
200	50							
500	300							
1000	500							

SUMMARIZED EQUATIONS

I Time to Start Boil $\Delta\theta_1 = \frac{B}{F_2 P / P} = \frac{C}{F_2 P} = \frac{K}{F_2 P}$

II Time to Boil Dry $\Delta\theta_2 = \frac{F_2 P}{F_2 P} = \frac{F_2 P}{F_2 P} = \frac{F_2 P}{F_2 P}$

III Fuel Temp (Assuming No change in tube and end fuel temps.)
 $t_{s2} = \frac{\Delta\theta}{1 + \frac{\Delta\theta}{F_2 P}}$

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(7)

f) LONGITUDINAL COEFFICIENTS

$$R_{L_u} = \frac{12L_u}{12k_u A_u} + \frac{12L_c}{12k_s A_u} = \frac{99}{(17)\frac{\pi}{4}\left(\frac{1.4}{12}\right)^2} + \frac{.005}{.018(.016)}$$

$$R_{L_u} = 49.5 + 26 = \underline{\underline{75.5}}$$

$$R_{L_t} = \frac{1.2L_t}{12k_{AI} A_t} = \frac{96}{(12)(120)(.00225)} = \underline{\underline{30}}$$

$$R_{G_t} = \frac{2L_G}{12k_{G_t} A_{G_t}} + \frac{2L_c}{12k_g A_{G_t}}$$

$$R_{G_t} = \frac{48}{6(\quad)(4.19^2)} + \frac{.005}{6(\quad)(\quad)}$$

$$R_{G_t} = \quad + \quad = \underline{\underline{\quad}}$$

$$R_{G_F} = \frac{24(L_G)}{12k_{G_F} A_{G_F}} + \frac{24L_c}{12k_g A_{G_F}}$$

$$R_{G_F} = \frac{2(4.19)}{(\quad)(3 \times 6)} + \frac{2(.005)}{(\quad)(18)}$$

$$R_{G_F} = \quad + \quad = \underline{\underline{\quad}}$$

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Summary of Center of tube

	B	C	D	DR	F	H	KE	KW
2. t_L =	55.9	48.8	55.4	56.9	54.3	53.1	53.2	57.6
3. t_{re} =		180 172.178	17.9				190	202
4. t_{ave} =		438 435	436 ^{OK}				485	492
5. t_c =		670 664	66.9				748 740	
6. t_{smax} =		484	580				626	
7. t_{smin} =		150	156				387	
Power level		1000	980				1320	
inlet temp		6.8°C	7.4°C				6.2	

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C REACTOR P12

SLUG	Θ	$\Delta \Theta$	INITIAL TEMP t_{s1}	Q	t_{L1}	t_{L2}	t_{s1}
	2	>	Boil. Out				
	3	1	433	105,000	110	144	+100
	5	2	502	105,050	144	160	+100
	10	5	625	105,500	198	245	+100
	15	5	730	105,000	284	380	+100

TAIL FAILURE CHARGE TEMPERATURES

SLUG	AG	(Q-EE)	1 + 0.003546	TS	CASE 2 - No REACTOR SCRAM
-t ₁	162	0			
	64.2		1.004	50	
	128		1.007	625	
	321		1.0175	935	
	320		1.0175	1230	

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GRAPHITE TUBE BLOCK	θ	$\Delta\theta$	INITIAL TEMP t_{0,t_1}	$F_{0,t}$	F_T	F_P	t_{t_1}	t_{t_2}	$\frac{t_{t_2} - t_{t_1}}{0.0}$
(	2	}	251	1790			110	144	10
	3								
	5	}	251	1790			144	160 188	17
	10								
		}	251	1790			188	210	59

TUBE BLOCK

t_{G1}	t_{G2}	$t_{G1} - t_{G2}$	$\frac{A \theta}{5700} (Q + \epsilon t_{G1} - \epsilon t_{G2})$	$1 + 0.006 \Delta \theta$	t_{G2}
0		0.43			
41.9	1.9	-1370	0.56	1.006	251
41.9	1.9	-1370	1.73	1.012	251
41.9	1.9	-1370	7.95	1.03	251

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TUBE	ϕ	NO	INITIAL TEMP	t_{s1}	t_{s2}	$t_{s1} + t_{s2} - t_{t1}$	t_{t1}	t_{t2}	T
						0.176			
(	2	1	110	501	4700		251	253	
	3								
	5	2	144	502	625	5580	251	251	
	10								
	15	5	289	930	1230		251	251	
	20								

$$\frac{t_{t1} - t_{t0} - t_{t2}}{0.030} = \frac{\Delta \theta (\sum T_1 - \sum T_2)}{364} \cdot \frac{1 + 0.107 \Delta \theta}{t_{t2}}$$

-13,200

49

1.107

144

-12,000

97

1.214

198

-10500

245

1.535

289

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C REACTOR

Location	θ	$\Delta\theta$	Initial Temp t_{s1}	$F_u F_r$	Q	t_{s2}
<u>Feed</u>						
	2		Boil out			
	3	1	438	.94	105,000	200
	5	2	502	.18	20,100	144
	10	5	523	.095	10,700	180
	20	10	545	.07	7,850	250
	30	10	573	.057	6,370	266
	40	10	592	.051	5,710	310
	100	60	606	.031	3,480	317
	200	100	610	.026	2,920	330
	400	200	626	.024	2,700	415
	800	400	681	.019	2,130	499
	1200	400	777	.017	1,910	650
						645
						754
						745

$$t_{s2} = t_{s1} + \frac{\Delta\theta}{1620} (112500 F_u F_r - 1 + .0035 \Delta\theta)$$

R PIGTAIL FAILURE CHARGE TEMPERATURES

t_{t_1}	$t_{s_1} - t_{t_1} - t_{t_2}$	$\frac{\Delta t}{1620} (Q - \Sigma t)$	14.003508	t_{s_2}	t_{t_2}
	7.176				
110	730	64.5	1.009	505	144
	1010	64.2		502 ✓	
144	1010	23.5	1.007	523	196
196	+438	31.9	1.017	545	266
	-346	32.2		545	
266	-176	47.8	1.035	573	-
310	-300	47.0	1.035	592	
306 308	-136	36.0	1.035	606	
312	-233	134	1.21	610	
354	-905	236	1.35	626	
415	-1610	532	1.7	681	
500	-2670	1185	2.4	778	
	-2650	1180		777	
646	-3590	1360	2.4	870	
	-3480	1330		880	

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LOCATION
TUBE

Θ $\Delta\Theta$

INITIAL
TEMP t_{e1}

t_{s2}

$\frac{t_{s1} + t_{s2} - t_{e1}}{.176}$

t_{ge1} t_{ge2}

2

110

438

3

1

110

500

4700

251 251

5

2

144

523

5000

251 251

10

5

196

545

4950

252 256

20

10

266

570

4920

251 251

573

4990

30

10

310

595

4870

257 251

592

265

40

10

306

606

5060

259 261

308

265 272

100

60

317

610

5110

272 308

315

200

100

354

620

4970

313 381

626

5000

377

400

200

415

655

4920

377 495

681

5060

474

800

400

501

800

5560

476 638

777

5100

617

1200

400

646

870

5690

617 744

880

5750

729

$$t_{t2} = \frac{t_{t1} + \frac{\Delta\Theta}{364}}{1 + 0.107 \Delta\Theta} \left(\frac{t_{s1} + t_{s2}}{.176} \right)$$

$\frac{t_{e_1} - t_{e_1} - t_{e_2}}{.030}$	$\frac{\Delta\theta}{364} (\Sigma T_s - \Sigma T_e)$	$1 + .107 \Delta\theta$	t_{e_2}	t_{s_2}
-13,200	49	1.107	144	
-12,100	94	1.214	196	
-10,400	211	1.535	266	
-8,750	375	2.07	310	
	374		310	
-6,870	323	2.07	306	
-4,060	328		308	
-7,140	336	2.07	310	
7,650	350		317	
-8,770	2290	7.42	352	
8,950	2310		354	
-11,340	4500	11.7	415	
-11,200	4500		415	
-15,200	11,000	22.4	486	
-14,000	10,800		501	
-20,400	28,500	43.8	650	
-19,800	27,800		646	
-23,800	32,400	43.8	754	
-23,400	32,000		745	
			744	

$t_{s_2} - t_{e_1}$

$\frac{t_{e_1} - t_{e_1} - t_{e_2}}{.030}$

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LOCATION
GRAPHITE TUBE
BLOCK

Θ ΔΘ

INITIAL
TEMP.
 t_{G,t_1}

$(F_{G,t} F_r)$

$(F_{G,t} F_r F_P)$

t_{t_1}

t_t

2						
3	1	251	.016	1796	110	14
20	12	251	.0021	235	144	350
40	240	257	.0020	224	310	316 312
100	60.0	272	.0016	179	317	336 35
200	100	313	.0014	157	354	42 41
400	200	377	.0011	123	415	53 48
800	400	476	.0009	100	501	67 64
1200	400	617	.0008	90	646	77 75

$t_{t_1} =$

$$t_{t_1} + \frac{\Delta\theta}{5750} \left(F_{G,t} \right)$$

$t_{L_1} + t_{L_2} - t_{L_1}$.030	$t_{G_{F_1}}$	$t_{G_{F_2}}$	$t_{G_{F_1}} - t_{G_{F_1}} - t_{G_{F_2}}$.43 .4	$\frac{\Delta\theta}{5700} (Q + 2t_L - \Sigma t_L)$ 1.1006 $\Delta\theta$	$t_{G_{F_2}}$
+100	419	420	-1370	1.56	251
9100	419	419	-1370	3.2	257
12100	419	420	-1350	4.7	272
12,500 13,100	419	420	-1310	14.8 153	308 313
15,500	419	419	-1230	296	381
15,200				291	377
19,100	419	420	-1070	712	495
17400				668	476
23200	419	419	-844	1690	658
22300				1620	617
26600	419	419	-515	1910	744
25900				1860	729
					727

F₂ F_P P +

$$\frac{t_{L_1} + t_{L_2} - t_{L_1}}{.030} - \frac{t_{G_{F_1}} - t_{G_{F_1}} - t_{G_{F_2}}}{0.43}$$

1.063 $\Delta\theta$

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LOCATION
GRAPHITE
FILLER BLOCK

$\ominus$	$\otimes$	t_{GF}	$(F_G F_T)$	$F_G F_T F_P P$	t_s
2					
3	1	419	.048	5370..	25.
20	17	419	1007	785	25?
40	200	419	10067	750	25
200	160	419	.0054	606	25.
800	600	419	.0030	337	272
					377

$$t_{GF_2} = \frac{t_{GF_1} +}{}$$

t_{G_1}	$t_{G_1} + t_{G_2} - t_{G_1}$	$\frac{\Delta \theta}{33800} (Q + \Sigma t)$	$1 + .0007 \Delta \theta$	t_{G_2}
	.43			
251	193	.17	1	419
255	204	.497	1.01	419
259	256	.59	1.012	419
272	590	5.64	1.112	419 387
400 377	1250	28	1.22	419 312

$$\frac{\Delta \theta}{33800} \left(F_{G_1} F_{G_2} F_{P P} + \frac{t_{G_1} + t_{G_2} - t_{G_1}}{.43} \right)$$

$$1.0007 \Delta \theta$$

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[REDACTED]

(1)

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C-PILE

I- Reverse Flow-

a) general

When there is a sudden front
pigtail failure there is a
sudden flashing to steam
with steam flow from the
center of charge in both
directions. This is followed
by a period of two-phase
or 100% steam flow from
near the front. Then two-phase
reverse flow and finally
liquid flow with adequate
cooling.

In a recent report it was
found that steam removal
at the center of charge is
essentially complete after
~~about~~ 2 seconds. (1)

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[REDACTED]

b) Cold water Flow

The flow pressure-drop characteristics for a C-Pile tube are shown in Figure 1,

c) Critical flow

① Present

The most restrictive flow cross-section will be at the "inlet" venturi which has a free cross-section of .00185 ft². This is because the C-reactor flow monitors are connected directly to the inlet nozzle rather than to the inlet cross-heads.

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With two-phase flow it is important to determine the critical flow characteristics of this fitting since ~~the~~ the critical pressure at this point.

may be a significant, or even controlling, portion of the overall pressure drop. The calculation of the critical flow conditions for 160°C inlet water and various flow rates is shown in Table II. And the critical geometry conditions are shown below:

TABLE-I GEOMETRIC PROP.

Condition	Position	Minimum Diameter in D_e	Free Area Location f^2	Actual Root Hose Press PSI ²
Pigtail Throat Area, or Flow Instr. throat if on Nozzle	B	.412	.0036	15-30
	C	.385	.00186	20-35
	K	.75	.00306	70-85
Annulus around Solid Charge	B	.150*	.0025	
	C	.124*	.0031	
	K	.220*	.0037	

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* Equivalent dia. of annulus
= $d_o - d_i$

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TABLE - II REVERSE CRITICAL FLOW
IN C-REACTOR, AT PRESENT COND.
($S = .00188$, $t_i = 110^\circ\text{C}$)

Flow gpm	Time			Heat		Inlet		Critical	
	lbs sec	lbs ft ² sec	lbs hr	After Decay	Fast Heat Gen.	Enthalpy	Temp	pc	Q
G	$\bar{v} = .017$			Loss	F_r	F_u	Orig. Curr. P K _u (750)		
	W	S _u	W						psig
10	1.3	710		10	.115	.85	1000	93	110
5	.65	355					186	384	17
2	.26	142					465	623	5
1	.13	71					930	1128	3
0.5	.065	36						1686	0
40	5.2								
20	2.6								
10	1.3	710		0-4	1	.94	1000	890	110
5	.65	355					1720	2000	~120
2	.26	142							~80
1	.13	71							~40
0.5	.065	36							~30
10	1.3	710		5-10	.13	.90	1000	97	110
5		355					194	198	295
2		142					485	392	12
1		71					970	683	16
								1168	4
10	1.3	710		11-20	.09	.86	1000	74	110
5		355					148	198	272
2		142					370	346	7
1		71					740	568	2
								938	0
0.5	.065								
0.1	.013								

$$w = \frac{G}{448 \bar{v}}$$

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C (Cont.)

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5. New Inlet Nozzles

These

would be installed with the flow monitors mounted on the cross header. Under these conditions the nozzle outlet cross-section would be $\sim .0037 \text{ ft}^2$, or similar to the new B, P, F assemblies.

Thus the limiting cross-section would now be the front end of the active charge with an annular face cross-section of $.1031 \text{ ft}^2$.

Critical flow conditions for this case are shown in Table III.

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⑦

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TABLE III REVERSE CRITICAL FLOW
IN C-REACTOR WITH NEW NOZZLE
($S = .0031$, $t_c = 110^\circ\text{C}$)

gpm	Flow		$\frac{\text{lbs}}{\text{hr}}$	Time After H ₂ O Loss	Decay Factor F_d	Heat Decay Orig. Point P_o Kw	Decay Point P_i $\frac{\text{Btu}}{\text{lb}}$ (950)	Inlet Enthalpy		E_T	p_c psig	η
	$\frac{\text{lbs}}{\text{sec}}$	$\frac{\text{ft}^2}{\text{sec}}$						t_i $^{\circ}\text{C}$	t_i			
10	1.3	422	0-4	1	.94	1000	890	110	198	1088	85	8
5	.65	211					1780			2000	60	10
2	.26	84									~40	
1	.13	42					8900			9100	~20	
0.5	.065	21										
10	1.3	422	5-10	.13	.90	1000	97	110	198	295	7	10
5	.65	211					194			392	1	2
2	.26	84					485			683	0	5
1	.13	42					970			1188	0	9
.5	.065	21								2000	0	10
10	1.3	422	10-20	.09	.86	1000	74	110	198	272	4	7
5	.65	211								346	0	18
2	.26	84								568	0	41
1	.13	42					740			938	0	7
.5	.065	21					1480			1668	0	10

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d. Two Phase Flow

A rough value of this is obtained from the following ~~approximate~~ approximate equation:

$$\Delta P_{TBF} = R \Delta p_f$$

Where Δp_f is the pressure-drop for all liquid flow at the given flow rate and R is a TPF correction factor given by Martinelli and depends upon the exit quality (obtained from the Critical flow tables) and the average pressure. This requires a trial and error solution to obtain a reasonable check between the assumed

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average pressure and that given by the relationship:

$$\bar{p} = p_c + \frac{R \Delta p_f}{2} \quad (2)$$

c - Steam Flow (100 quality)

This was determined in the following approximate manner. There are two main flow restrictions:

- (1) The fuel column
- (2) The venturi on the inlet nozzle.

The pressure-drop for steam flow past the charge is obtained in the following manner. From Table I the Annulus equiv. dia is 0.184" and from Fig 1 this system has a pressure-drop of 14 psig at 10 gpm

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Then from Cameron () Page 86
 The pressure drop of a 0.184" dia
 system with 10 gpm flow is given
 as 27.3 psig for 100 equiv feet of
 pipe. Consequently the equivalent
 length of the charge is given
 by

$$\Delta l_e = \frac{14}{27.3} (100) = \underline{\underline{51 \text{ ft}}}$$

Let F_s be the fraction of charge
 with all steam flow then
 the ~~total~~ ^{charge} pressure drop is:

$$\Delta p_{f_{1/2}} = \Delta p_f (1 - F_s) R + \Delta p_s F_s \frac{51}{100}$$

Where Δp_s is the steam flow pressure drop per
 100 ft of pipe obtained from Crane's Tech paper 410 pg-3-21

In addition to this line effect

we must determine the pressure
 drop through the venturi. This
 is obtained from Crane's Bulletin

X
 critical
 flow
 pg =

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DP-Psi

LOGARITHMIC 358-110
KEUFFEL & ESSER CO. MADE IN U.S.A.
2 X 2 CYCLES

gpm

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C Tube
32 slug/charge

FNB → FNB Pressure Loss at 110°C

① Solid slugs

② Old I&B slugs

③ "New" I&B slugs

TABLE-V CRITICAL STEAM FLOW THRU VENTURI
(S=.00186) (No Quality)

Assumed Steam Conditions				VENTURI					Crit.			
Temp OF	Line Pres. Psia Psig	k	d ₀	$\frac{d_0}{d_i}$	Critical Pres Ratio $\frac{p_2}{p_1}$	$\frac{p_2}{p_1}$ psia	$\frac{\Delta p}{p_1}$	Y	$\bar{u}_2$	Δp	Flow w- lbs/sec	
Present Pigtail	300 20 5	1.32	.385	0.47	.55	11	.45	.69	41	.9	.025	
	40 25	1.32			.55	22	.45	.69	20	18	.05	
	60 45	1.31			.55	33	.45	.69	13	27	.08	
500	20 5	1.30		0.47	.55				52	9	.025	
	40 25	all above the same as above →							26	18	.04	
	60 45								17	27	.07	
New Pigtail	300 20 5	1.32	.82	.50	.55	11	.45	.69	41	9	.10	
	16 2	1.32			.55	9	.45	.69	50	7	.08	
Critical Flow at inlet fitting												
S=.0021												

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TABLE IV TWO-PHASE FLOW
REVERSE DIRECTION THRU K

FLOW		TIME AFTER H ₂ O LOSS to acc	Critical Cond.		Ass. Avg. Pres R	Frict	
Liq. gpm	Vap lb ₃ /sec		p _c psia	y		Δp Liq	Frac of Boil Liq

Present Normal + Flow Monitor

1	.13	5-10	4	~100	25	300	.23	110
.077	.01		4	~100	25	300	.0024	110
	.02							

.02

20 90

IN
CHARGE ($S = .0031 \text{ ft}^2$)

In DP		Inertia DP				
ΔP_V	EXIT PRES	V_2	G_I	ΔP_I	ΔP_{TRF}	
7	10	38	42	2010	2017	X
10	25	17	3.2	5		
			6.4	22		
	20	17	6.4	22		

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TABLE - I REVERSE FLOW - 100% STEAM

($L_c = 5$)

STEAM COND.										Pres. Drop. Assum		Steam Flow	
Pres psia	Temp °F	Temp °F	Pres psia	Temp °F	Temp °F	Frac. of Steam Cool. L _g L _s	ΔP lb	ΔP 100	f			1000 lbs hr	lbs sec
35	260	11.9	300	30	14.8	13.3	.90	46	5	11	.025	0.15	.042
			500	30	18.9	15.3						0.13	.036
35	260	11.9	300	32.5	13.6	12.7			20	39	.025	0.011	.0031
			500	32.5	17.4	14						0.01	.003
			700	32.5	21	16.5						0.01	.003
176	308	5.7	500	40	14.1	10.3			36	70			
			700	40	17.2	12							

STEAM

($L_e = 51'$, $D_{eq} = .18''$)

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op. Assum
f

Steam Flow
 $\frac{1000 \text{ lbs}}{\text{hr}} \quad \frac{\text{lbs}}{\text{sec}}$

.025

0.15 .042

0.13 .036

.025

0.011 .0031

0.10 .003

0.01 .003

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TABLE-VI TOTAL PRESSURE-DROP EFF.
FOR REVERSE FLOW

Flow gpm. $\frac{\text{lbs}}{\text{sec}}$	Exit Temp.	Venturi		100% Steam Seet.			TPF Seet.		P_R
		Pres. psig.	crit Line Pres. psig.	$\frac{\Delta p}{100}$	f_s	Δp	Δp_I		
.02	500	-4	5	2.2	.5	1.1	22		28

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TABLE II - SLUG TEMPS AFTER BOIL

(24.5)

TIME	POWER DECAY FACT.	HEAT GEN. Ch. sec. ft. 130.5	q_s KW	q_{fact}	t_h	t_L	R_1	w_g	$t_h t_L$	$\frac{t_h t_L}{R_1}$	R_2	w_c	$t_h t_L$	$\frac{t_h t_L}{R_2}$
3.5	.16	9.4*	770	0	4.4	490	130	.46	360	.27	90	.10	70	.78
4.5	.14	3.8*	720		3.8	499	140	.	359	.27			60	.67
6.5	.13	3.2	680		3.2	517	158		359	.26			42	.47
10.5	.12	2.9	430		2.9	542	186		356	.26			14	.16
14	.08	2.0	350		2.0	562	200		362	.27			0	.0
24	.06	1.47	260		1.47	602	227		373	.28			-27	.30
34	.053	1.30	170		1.30	626	227	.54	399	.30		.10	-27	.30
54	.045	1.10	150		1.10	645	227		418	.31		.10	-27	.30
75	.042	1.03	130		1.05	672	248		424	.32			-48	.53
100	.034	.83	100											
200	.03	.74	86											
300	.10													

NOTE q_s is assumed effective as soon as are reached. Actually there would be ad.

t_c	t_c	$\frac{dt_c}{d\theta}$	$\frac{dt_c}{d\theta}$	t_c	t_c	θ
t_c	R_2					
70	.78	9	10.5*	499	140	4.5
60	.67	8	9*	517	158	6.5
42	.47	6.3	7	542	186	10.5
14	.16	5.7	4.1	562	200	14
0	.0	2.5	2.7	600	227	24
27	.30	2.6	0	626	227	34
27	.30	1.85	0	645	227	54
27	.30	1.3	1	672	248	75
48	.53	1.3	0	705	248	100
48	.53	.02	0	<u>707</u>	248	200

soon as tube powers below boiling disease requirements
be additional steam cooling at earlier times.

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prob. - 653

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Steam Cooling of Charge

1. Boiling Zone: (at 230°F)

$$w \Delta H_v = \frac{h A_B}{3600} (\bar{t}_s - 230) + \frac{h A_B}{3600} (\bar{t}_t - 230)$$

Heat of
Evaporation

Heat Removed
from Charge

Heat Removed
from Tube

Whence

$$\frac{h A_B}{3600} (\bar{t}_s - 230) = (F_x F_k F_f F_p P) l - (w c_p)_s \left(\frac{t_{s2} - t_{s1}}{\Delta \theta} \right)$$

And

$$\frac{h A_B}{3600} (\bar{t}_t - 230) = \frac{(\bar{t}_t - t_t)}{R_g} - (w c_p)_t \left(\frac{t_{t2} - t_{t1}}{\Delta \theta} \right)$$

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STEAM COOLING OF CHARS

INITIAL CONDITIONS = 5 seconds after
H₂O Loss

Segment	t_w	t_t	$\bar{T}_s$	$\bar{T}_{ot}$	$\bar{T}_{cf}$	Q cal/sec	A_s	R	h_B	$(w/c)_s$	$(w/c)_t$	R_g	A_c
A	110	160	250	190	230	4.81	1.51	4	10	1.8	.48	54	1.1
B	102	150	435	240	360	15.7	1.89	5		2.25	.60		2.1
C	60	144	500	250	420	19.4	1.89	5		2.25	.60		2.1
D	44	108	395	200	320	15.7	1.89	5		2.25	.60		2.1
E	18	45	130	90	120	4.9	1.51	4	1	1.8	.48	7	1.7

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Summarized Equations for

$$\underline{w_T = .02 \text{ lbs/sec}}$$

$$\begin{aligned} \underline{A} \quad 950 w_{wA} &= \frac{10(1.51)}{3600} \left(\frac{t_{s1} + t_{s2}}{2} - 110 \right) \\ &+ \frac{(10)(1.51)}{3600} \left(\frac{t_{t1} + t_{t2}}{2} - 110 \right) \end{aligned}$$

$$w_{wA} \approx \frac{.0042}{950} (400 + 220) = .0027 \text{ lbs/sec}$$

$$\underline{B} \quad w_{wB} \approx \frac{.0053}{950} (770 + 200) = .0054 \text{ lbs/sec}$$

$$\underline{C} \quad w_{wC} \approx \frac{.0053}{950} (900 + 180) = .0060 \text{ lbs/sec}$$

$$\underline{D} \quad w_{wD} \approx \frac{.0053}{950} (700 + 20) = .0040 \text{ lbs/sec}$$

$$\underline{E} \quad w_{wE} \approx \frac{.0042}{950} (160 - 50) = .0005 \text{ lbs/sec}$$

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Total

.0126

Exit Anal = 93%

STEAM COOLING THE FUEL

FUEL

(112,000) lbs

TIME AFTER H ₂ O LOSS sec Δθ	F ₂ F _u	$\frac{F_2 F_u}{3600}$	h	A _C	t ₂	$\frac{h A_B}{3600} \left(\frac{t_{s1} - 230}{2} \right)$	$\frac{h A_B}{7200}$	$\frac{w C_p}{\Delta \theta} \left(\frac{t_{s1} - 230}{2} \right)$	$\frac{h A_B}{7200}$	$\frac{w C_p}{\Delta \theta}$	$Q + \frac{w C_p}{\Delta \theta} t_{s1} - \frac{h A_B}{7200} \left(\frac{t_{s1} - 230}{2} \right)$	t _{s2}	Δw _{av}	% Eff
5														
10 > 5	.095	14.7	20	1.89	523	.01055	.00525	.09	.00525	.09	57.7	603	.0154	
20 > 10	.07	10.9			603							631	.0115	
40 > 20	.054	8.4			631							626	.0089	
100 > 60	.051	7.9			626							618	.0083	
200 > 100	.031	4.8												
400 > 200	.026	4.1												
800 > 400	.024	3.7												

$$t_{s2} = \frac{Q + \frac{w C_p}{\Delta \theta} t_{s1} - \frac{h A_B}{3600} \left(\frac{t_{s1} - 230}{2} \right)}{\frac{h A_B}{7200} + \frac{w C_p}{\Delta \theta}}$$

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TABLE STEAM FLOW PAST CHARGE
($d_c = 0.124"$)

STEAM FLOW			AVE. CONDITIONS					Re	f	$\frac{\Delta p}{100}$	Δp	p_1	$\bar{p}$
$\frac{\text{lbs}}{\text{sec}}$	$\frac{\text{lbs}}{\text{sq ft}^2}$	$\frac{1000 \text{ lbs}}{\text{hr}}$	Temp.		Assum. Press.	Sp. Viscosity							
w	W	w'	$^{\circ}\text{C}$	$^{\circ}\text{F}$	psia	Vol. $\bar{\nu}$	cp μ'						
.0035	.90	.010	110	230	10	16	.0135	1.53×10^3	.05	130	31	10	21
			150	302		17.7	.0155	1.34					
			200	392		20	.017	1.22					
			110	230	25	10.5			.05	95	23	10	21
			150										
		200											
.0020	.64	.0072	110		25	10.5			.05	42	10	10	15
					15	13							
.0035	1.13	.0126	110		20	12			.05	175	42	10	36
					30	15				220	52		36
										220	46	10	36

$$W = \frac{u}{S} = 322 W$$

$$Re = \frac{DW}{\mu'} = \frac{.124 W}{(12)(.000672) \mu'} = 22.8 \frac{W}{\mu'}$$

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gases

Gases in straight tubes

$$h = \frac{16.6 c_p (C')^{0.8}}{(D_i')^{0.2}}$$

c - Sp. Ht. - Btu/lb, °F c_p - cal/lb, °C

C' - Mass velocity lb/sec, ft²

D_i' - Inside dia. - in

Perry 2nd Ed

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