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SUBJECT: Study of Fuel Temperature and Flow Effects of Plugging in SRE Fuel Channels

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I STATEMENT OF PROBLEM

Investigate fuel surface temperature and flow rate effects that might be produced by plugs in SRE fuel channels. Plug geometry and composition is unknown. Assume that the plug material has a low thermal conductivity and that it might deposit anywhere in the fuel channel. Determine what plug geometries are likely to cause severe fuel damage due to overheating and which of these plugs can be detected by observation of variations in outlet fuel channel temperatures.

II SUMMARY OF RESULTS

A. Area Studied

A typical fuel channel was selected for the basis of the study. This channel was assumed to operate at average power in a 37 element Th-U core loading with full power for the core being 20 Mwt. The fuel element studied was the standard SRE 7-rod cluster with a 1/2 inch diameter orifice at the bottom. For the study of fuel temperatures, an outer rod from the cluster was selected and it was assumed that a plug formed at the axial center of the active core. Analysis of the following variables was made:

- 1) Reduction of channel flow as a function of the amount of plugged flow area and the length of the plug.
- 2) Increase in fuel temperature as a function of the power distribution in the fuel rod, the power level of the core, and the amount of fuel rod surface covered by the plug material.

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- 3) Reduction of channel outlet temperature by heat transfer through the moderator to cooler channels.
- 4) Reduction in channel flow area as a function of the amount of fuel rod surface covered by plug material for various hypothetical plug geometries.

B. Results

Conclusions that can be drawn from the study of these variables may be stated as follows:*

- 1) Plugs which locally insulate more than 20 to 30% of the surface of a fuel rod are "dangerous" in that they may cause local fuel surface temperatures to be greater than 1400°F when the reactor operates at full power (20 Mw). (See Fig. 6).
- 2) For the geometries of plugs which seem most likely to form in the fuel region (surface films not included), the amount of fuel rod surface area insulated by the plugs when the insulation is sufficient to be dangerous is correlated with the amount of blocked flow area as shown in Figure 4.
- 3) Heat transfer through the moderator will not significantly affect the outlet thermocouples sensitivity to change in mass flow through a fuel channel, provided the reactor power is above 2 Mw and the channel is not completely or nearly completely plugged. In all cases where the channel Δt is compared to the reactor mixed-mean Δt (or a standard "clean Δt ") for the purpose of detecting plugs, moderator heat transfer will not prevent plug detection if a deviation criterion of the order of 10% is used.
- 4) If a 5% or greater increase in a fuel channel Δt is taken to indicate that a plug exists in that channel, about 80% of all possible plugs will be detected and roughly 95% of all dangerous plugs will be detected by this criterion. A 10%- Δt -deviation criterion will detect about 70% of all possible plugs and roughly 90% of all dangerous plugs. (See Fig. 5 and Table III). (It has been assumed that a standard "clean Δt " can be determined for each fuel channel and set of operating conditions and that the effects on this Δt of core power level, control rod position, etc., are known. Then any increase above this clean Δt is potentially due to flow reduction caused by a plug in the channel. If all fuel channels are orificed to produce a uniform outlet temperature, then the individual channel Δt may be compared to the reactor mixed-mean Δt).

* These conclusions strictly apply only to the "average" channel described above, however, generalization to the core as a whole is fairly safe. A short discussion of the resultant errors is given in Section III-E.

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- 5) At reduced power, plugs must be relatively large to cause excessive overheating of the fuel, therefore fewer plugs that are dangerous at low power would remain undetected than plugs dangerous at full power. When the 5% Δt -deviation criterion is used for detection, 99% of the plugs that are dangerous at 8 Mw or less can be detected.

III METHOD USED, SAMPLE CALCULATIONS

A. Channel Flow Calculations

Figure 1, Geometry Used for Flow Analysis.

The hydraulic model shown in Figure 1 was used to calculate the effect of plugs on flow in the fuel channel. A single, continuous plug adjacent to the fuel can was assumed. The geometry is arbitrary except that A_p , the flow area left open in the plug region, is assumed constant over the length of the plug. The pressure drop in the channel was divided according to its principle sources as follows:

- 1) Δp_1 = pressure drop in the unplugged portion of the channel not including the entrance and exit losses and the orifice drop.
- 2) Δp_2 = pressure drop due to entrance and exit losses at the plug.
- 3) Δp_3 = frictional pressure drop in the plugged region.
- 4) Δp_4 = pressure drop due to the orifice and channel entrance and exit losses.

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Tests described in TDR 3298 (Ref. 1) show that, for practical purposes, flow in SRE fuel channels is completely turbulent and therefore that the channel friction factor is a constant over the range of Reynold's numbers of interest. For these calculations, it was assumed that this same constant friction factor also satisfactorily correlates friction pressure drop in the plugged region of the channel. Then the friction pressure drop in any portion of the channel follows the simple relation:

$$\Delta p = C \frac{L}{D} V^2 \quad (1)$$

where

- V = flow velocity (ft/hr)
- L = length of the portion of channel (ft)
- D = equivalent diameter of the portion of channel (ft)
- C = a constant which is determined from tests, theory, or both.

Then

$$\Delta p_1 = C \frac{L_1}{D_c} V_c^2 \quad (2)$$

$$L_1 = L_c - L_p \quad \text{and} \quad V_c = \frac{W}{\rho A_c} \quad (3)$$

with no plug in the channel (the reference condition)

$$\Delta p_{1r} = C \frac{L_c}{D_c} \left[\frac{W_r}{\rho A_c} \right]^2 \quad (4)$$

divide (2) by (4)

$$\frac{\Delta p_1}{\Delta p_{1r}} = \frac{C}{C} \frac{D_c}{D_c} \cdot \frac{L_c - L_p}{L_c} \cdot \left[\frac{W \rho A_c}{W_r \rho A_c} \right]^2 \quad (5)$$

or

$$\Delta p_1 = \Delta p_{1r} \left(1 - \frac{L_p}{L_c} \right) \left(\frac{W}{W_r} \right)^2 \quad (6)$$

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The pressure loss at the entrance to the plug is given by:

$$\Delta P = \frac{\rho}{2g} (V_p - V_c)^2 \quad (7)$$

The pressure loss at the exit from the plug is given by:

$$\Delta P = \frac{\rho}{2g} K V_p^2 \quad (8)$$

where K is an empirical function of A_c/A_p , then

$$\Delta P_2 = \frac{\rho}{2g} [(V_p - V_c)^2 + K V_p^2] \quad (9)$$

$$V_p = \frac{\omega}{\rho A_p}, \quad V_c = \frac{\omega}{\rho A_c} \quad (10)$$

substitute (10) in (9), get:

$$\Delta P_2 = \frac{\rho}{2g} \left(\frac{\omega}{A_c \rho} \right)^2 \left[\left(\frac{A_c}{A_p} - 1 \right)^2 + K \left(\frac{A_c}{A_p} \right)^2 \right] \quad (11)$$

$$\text{let } \frac{\rho}{2g} \left(\frac{\omega_r}{A_c \rho} \right)^2 \triangleq \Delta P_{2r} \quad (12)$$

Then

$$\Delta P_2 = \left(\frac{\omega}{\omega_r} \right)^2 \cdot \Delta P_{2r} \left[\left(\frac{A_c}{A_p} - 1 \right)^2 + K \left(\frac{A_c}{A_p} \right)^2 \right] \quad (13)$$

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In the plugged region,

$$\Delta P_3 = c \frac{L_p}{D_p} V_p^2 = c \frac{L_p}{D_p} \left(\frac{\omega}{\rho A_p} \right)^2 \quad (14)$$

divide by equation (4) and get,

$$\Delta P_3 = \Delta P_{1r} \left(\frac{\omega}{\omega_r} \right)^2 \frac{L_p}{L_c} \left(\frac{A_c}{A_p} \right)^2 \frac{D_c}{D_p} \quad (15)$$

The equivalent diameters (D_c and D_p) are proportional to the ratios of the respective flow areas and wetted perimeters. Since the geometry and sequence of formation of the plugs is not known, D_p is an unknown function of the shape of the plug. To allow completion of the calculation, it was assumed that $D_c/D_p = 1$ (always). (If it is assumed that plugs form randomly as shown in Figure 3 and a new flow area and wetted perimeter are calculated as each new plug forms, it turns out that the ratio D_c/D_p does not vary much from unity).

The orifice and fuel channel entrance and exit geometries are fixed. Therefore, pressure drop in these regions can be represented directly by:

$$\Delta P_4 = \Delta P_{4r} \left(\frac{\omega}{\omega_r} \right)^2 \quad (16)$$

Combining equations (6), (13), (15), and (16), get;

$$\Delta P_{Tr} = \Delta P_1 + \Delta P_2 + \Delta P_3 + \Delta P_4 =$$

$$\left(\frac{\omega}{\omega_r} \right)^2 \left\{ \Delta P_{1r} \left[1 - \frac{L_p}{L_c} + \frac{L_p}{L_c} \left(\frac{A_c}{A_p} \right)^2 \right] + \Delta P_{4r} + \Delta P_{2r} \left[\left(\frac{A_c}{A_p} - 1 \right)^2 + K \left(\frac{A_c}{A_p} \right)^2 \right] \right\} \quad (17)$$

ΔP_{Tr} , the lower-plenum-to-upper-plenum dynamic pressure drop, is a constant. Then the ratio of plugged flow to the reference flow is given by:

$$\frac{\omega}{\omega_r} = \left\{ \frac{\Delta P_{1r} \left[1 - \frac{L_p}{L_c} + \frac{L_p}{L_c} \left(\frac{A_c}{A_p} \right)^2 \right] + \Delta P_{4r} + \Delta P_{2r} \left[\left(\frac{A_c}{A_p} - 1 \right)^2 + K \left(\frac{A_c}{A_p} \right)^2 \right]}{\Delta P_{Tr}} \right\}^{-\frac{1}{2}} \quad (18)$$

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The dimensionless constants in equation (18) were evaluated from various sources of experimental and analytical information on SRE. (See Ref. 1, 2, and 3). Representative values for full flow past a standard 7-rod cluster located in the central region of the core were used. A .500 inch diameter orifice was assumed.

Table 1

Reference Qualities Used
for Calculation of (w/wr)

w_r	4.3 #/sec
ΔP_{tr}	1.5 psi
ΔP_{1r}	0.83 psi
ΔP_{4r}	0.67 psi
$\Delta P_{2r} = \frac{w_r^2}{2g A_c^2 \rho}$	0.10 psi
L_o	7.68 ft

Figure 5 is a plot of equation (18) over the full range of possible L_p/L_C 's and A_p/A_C 's. All combinations of L_p/L_C and A_p/A_C which yield w/w_r greater than 0.91 (or 0.95) describe plug geometries which are not detectable according to the criteria previously stated. It was assumed that the probability of a plug forming with any given combination of L_p/L_C and A_p/A_C is equal to the probability of a plug forming with any other combination of L_p/L_C and A_p/A_C .

B. Fuel Temperature Calculations

The IBM 709 code "Tiger II" was used to calculate the temperature distribution in partially insulated fuel rods. Figure 2 shows the grid used for these calculations and the relative heat generation used at each node point. The flux distribution used to determine the heat generation was obtained from SRE exponential experiments described in NAA-SR-3096 (Ref. 4).* The rod was assumed to be insulated over some fraction of its surface in the region of highest heat generation. The calculation was 2-dimensional and thus assumed that the insulated region was long relative to the diameter of the rod.

* Detailed flux distributions for Th-U fuel are not available. The distributions used here were obtained with 2.78% enriched uranium metal fuel. Self-shielding is slightly more severe with Th-U fuel than with the 2.78% uranium fuel therefore, these calculations slightly underestimate the worst maximum fuel temperature.

FIG. 2

FINITE-DIFFERENCE MODEL USED FOR FUEL TEMP. CALCULATION

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The average local heat generation rate at the plug was determined as follows:

From NAA-SR 3096 (Ref. 4)

$$\frac{P_o}{P_i} = 1.83$$

$$P_T = 6 P_o + P_i = P_o \left(6 + \frac{1}{1.83} \right)$$

$$\text{Then } P_o = \frac{P_T}{6 + \frac{1}{1.83}} = 0.1528 P_T$$

where

P_o = average heat gen. in outer rod

P_i = average heat gen. in inner rod

P_T = average heat gen. in seven rods

For the average fuel element in a 37 element loading at 20 Mw:

$$\overline{P_T} = \frac{20 (3.412 \times 10^6)}{37} = 1.843 \times 10^6 \text{ Btu/hr}$$

The axial peak/average = 1.20 (TDR 2101, Ref 3)

$$\left(\frac{P_o}{L} \right)_{\max} = \frac{1.843 \times 10^6 (1.20)(.1528)}{6 (12)} = 4.69 \times 10^3 \text{ Btu/hr-in}$$

Then

$$\overline{q}''' = \frac{4.69 \times 10^3}{\frac{\pi}{4} (0.75)^2} = 10.62 \times 10^3 \text{ Btu/hr-in}^3$$

and the local heat generation is given by:

$$q_i''' = \frac{10.62 \times 10^3}{2.11} \times (\text{local relative flux})$$

where 2.11 is the average relative neutron flux.

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This expression was used to determine the local heat generation for the Tiger II calculation. Th-U fuel was assumed and a fuel thermal conductivity of 23.5 Btu/hr ft-°F was used. (Ref. 5).

The effective heat transfer coefficient, h' , per foot of the surface of the fuel was determined as follows:

$$\pi D_1 h' = \frac{1}{R} =$$

$$\frac{1}{R_{NA} + R_{SS} + R_{NaK}}$$

$$R_{Na} = \frac{1}{h_{Na} \pi D_3}$$

h_{Na} was calculated from

$$h_{Na} = .625 (Re \cdot Pr)^{0.4}$$

or

$$\begin{aligned} h_{Na} &= .625 \frac{k_{Na}}{D_3} \left[\frac{\omega D_3}{A_F \mu} \cdot Pr \right]^{0.4} \\ &= \frac{.625 (41)}{.0352} \left[\frac{1.3 \times 10^4 (.0352)}{.0191 (.71)} (.0051) \right]^{0.4} \\ &= 5700 \text{ Btu/hr-ft}^2\text{-°F} \end{aligned}$$

$$R_{SS} = \frac{x}{k_{SS} \pi D_2}$$

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$$R_{NaK} = \frac{\kappa}{k_{NaK} \pi \bar{D}_i}$$

Then

$$R = \frac{12}{5700 \pi (.790)} + \frac{.010}{15.6 \pi (.760)} + \frac{.010}{11.5 (\pi) (.780)}$$

$$= 1.462 \times 10^{-3} \text{ } ^\circ\text{F/Btu/hr-ft}$$

$$h' = \frac{1}{\pi \bar{D}_i R}$$

$$= \frac{12}{\pi (.750) 1.462 \times 10^{-3}} = 3480 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$$

This value for effective heat transfer coefficient was used for all calculations. The sodium heat transfer coefficient, h_{Na} , was assumed to be independent of flow rate because of the low full-flow Nusselt Number, ($Nu \approx 5$).

In order to check the Tiger-II calculations, the exact temperature distribution in a round rod with a uniformly distributed heat source and uniform temperature at the surface was calculated. This temperature distribution is given by:

$$t_s - t_r = \frac{q''' b^2}{4 k} \left[1 - \left(\frac{r}{b} \right)^2 \right]$$

The calculated temperatures are plotted in Fig. 7 where they are compared to the Tiger II calculation at the same power (20 Mw) with a non-uniform, distributed heat source and no insulation on the rod.

In order to determine the relative effect of the non-uniform flux distribution in the rod on the temperature patterns, several additional calculations with Tiger-II were made using a uniform distribution of heat generation in the fuel rod. The results of these calculations are summarized in Fig. 6 (Curve A). Fig. 8 shows a comparison of the two calculation methods at 20 Mw where 25% of the rod surface area was assumed to be insulated on the side where maximum heat generation occurs. The assumption of uniform heat generation reduces the calculated hot spot temperature by about 130°F for this case. Should the insulated region be on the inside of the rod rather than the outside, the hot spot temperature would actually be less than that indicated by the calculation which assumes uniform heat generation. Referring again to Fig. 6, curve A would then roughly represent the "average" hot spot temperature for the 6 outer fuel rods if a large number of plugs formed and they

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were distributed randomly around the circumference of the rod. Curve B shows the maximum possible hot spot temperature for the same situation.

Plotted in Fig. 9 through 12 are the calculated temperature distributions for the four cases indicated on the figures. The nonuniform heat generation distribution (Fig. 2) was used in each of these calculations. Plotted in Fig. 13 and 14 are the calculated temperature distributions for two cases where a uniform heat generation in the rod was assumed.

C. Determination of the Dangerous Plug Detection Efficiency of the Outlet Thermocouple

The most difficult and elusive problem raised by this study was problem of determining a reasonable method for relating the variations of outlet temperature produced by plugs (used for detecting the plug) to the possible increases in fuel temperature that might be produced by the plugs. It was shown that the fuel temperature increases of interest were those produced by the partial insulation of the surface of a fuel rod while outlet temperature variations were due to reductions in mass flow caused by the plug's restriction of the coolant flow volume in the fuel channel. These results are summarized in Figs. 5 and 6. The problem, then was to investigate the many variations of plug geometries that suggested themselves and to determine the probability that a dangerous geometry exists whenever a particular flow variation exists. More specifically, the problem was to determine the fraction of "all possible" dangerous geometries that would not reduce flow more than a specified amount; 10% for instance. The following procedure was followed in order to obtain an approximate solution to this problem.

The following assumptions were made:⁽¹⁾ plugs form randomly throughout the fuel tube region. Their cross-sectional geometry is approximately that shown in Fig. 3. The existence of a plug at A, for instance, does not increase or decrease the probability of a plug at B, C or D, etc.*

* There are conflicting physical arguments which can be advanced to show that the existence of one plug (like A) may influence the probability that other plugs (like B or E) will exist in the channel at the same axial location. The first argument refers to the velocity effect; a plug at A will increase the local velocity and thus tend to reduce the likelihood that more deposits (plugs) will accumulate at the same section. It can also be argued, that plugs may tend to grow radially from a certain location by the gradual accumulation of materials. Thus a plug at A may tend to promote a plug at B. Since these arguments tend to cancel each other in net effect, the assumption of independent probability seems reasonable.

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FIG 3

GEOMETRY AND DISTRIBUTION OF
RANDOMLY FORMED PLUGS

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All plugs (A, B, C, D, etc) have the same axial length and the same axial location, however, the length is arbitrary and all lengths are equally probable.

Two plugs adjacent to each other (like A-B) continuously insulate $\frac{1}{3}$ of the surface of a rod. Referring to Figure 6, the average hot spot temperature resulting from such a combination of plugs would be 1400°F (curve A) and the worst possible hot spot temperature would be 1550°F (curve B). These temperatures are probably high enough to cause severe fuel damage in a matter of hours due to fuel-clad eutectic formation (Ref. 6). At worst, a single plug (like C) will produce hot spot temperatures no greater than 1200°F . Combinations of two or three non-continuous plugs on a single rod (like D-E-F) produce hot spot temperatures only slightly higher than the single plug hot spot temperature (see Fig. 15). Therefore, two adjacent plugs (like A-B) are necessary for a dangerous situation to exist.

The probability that two adjacent plugs (like A-B) exist in the channel cross-section is an increasing function of the total number of plugs existing in the cross section at any time. There are 24 assumed possible positions in which plugs may exist and examination of these positions relative to each other and the fuel rods reveals that no more than 12 positions can be filled without at least one continuous combination like A-B being formed. Therefore, if more than 12 positions are filled (more than 50% of the flow area occupied by plugs), the probability that a dangerous situation exists is 1.0. If less than 12 positions are filled, the probability that a dangerous combination exists is a complicated function of the blocked area having the form shown as a dashed line in Figure 4. This probability function was approximated by a straight line as shown in Figure 4. Having determined a correlation function relating blocked flow area to insulated surface area (Fig. 4), at the danger point for the particular discrete distribution of plugs described above, (Figure 3), it was then assumed that this function adequately approximates the desired general function relating blocked flow area and insulated surface area for all unspecified plug geometries.

It is shown that (Section III-D below), heat transfer through the moderator would not significantly reduce the outlet temperature of a partially plugged channel. Therefore, any flow reduction due to a plug produces a corresponding increase in the channel delta t. Figure 5 shows the relation between plug size (length and area) and the resulting flow reduction and (for the reason stated above) also shows the relation between plug size and the resulting increase in channel delta t. If a standard clean-channel delta t can be established and an allowable deviation from this standard is established, then the fraction of dangerous plugs that will not be detected can be estimated.

FIG 4
PROBABILITY DISTRIBUTION
ASSUMED FOR THE DETERMINATION
OF THE DANGEROUS PLUG DETECTION
EFFICIENCY OF THE SEE OUTLET THERMOCOUPLE

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Since it was assumed that all lengths and areas of plugs were equally probable, then, if all possible plugs were classified according to length and area (as in Table II), each class will contain the same total number of plugs. For convenience in the calculation, it was assumed that during the life of reactor, 10 plugs of each class form.

Table II

Distribution of Plugs According to Length and Area

Plug Length (L_p/L_c)	Plug Area (α)			
	0 - .1	.1 - .2	.2 - .3	etc.
0 - .1	10	10	10	etc.
.1 - .2	10	10	10	
.2 - .3	10	10	10	
etc	etc.			

Figures 4, 5, and 6 were used to determine the number of each class that were dangerous and the number that were detectable by the particular delta t deviation rule selected. Delta t deviation rules of 5% and 10% were examined.

Referring to Figure 4, an average of 10% of the plugs with in the range 0 - .1 are potentially dangerous in that 1/3 or more of a fuel tube may be insulated. Of these, some are detectable and some are not, depending on the plug length and resulting flow reduction. Axial location of short plugs is also important since the upper 1.67 feet (22%) of the fuel tube contains no fuel. The relative number of dangerous plugs of $\alpha = 0 - .1$ and length $L_p/L_c = 0 - .1$ is therefore about $0.8 \times 0.1 \times 10$, while for a plug of $\alpha = 0 - .1$ and length $L_p/L_c = .1 - .2$, the relative number of dangerous plugs is about $0.9 \times 0.1 \times 10$. For all $L_p/L_c > 0.2$ the number is $1 \times 0.1 \times 10$.

The figures of column 3, Table III were determined in this manner.

Summary of Calculation of Dangerous Plug Detectability

Table III

1 Plug Length L_p/L_c	2 Total No. Plugs*	3 No. Dangerous Plugs**	4 Total No. Plugs not Detected		5 No. Dangerous Plugs not Detected	
			$\frac{\Delta T}{\Delta T_c} < 1.05$	$\frac{\Delta T}{\Delta T_c} < 1.10$	$\frac{\Delta T}{\Delta T_c} < 1.05$	$\frac{\Delta T}{\Delta T_c} < 1.10$
0 - .1	100	60	40	50	12.8	17.2
.1 - .2	100	68	29	40	6.7	14.8
.2 - .3	100	75	23	33	6.0	11.1
.3 - .4	100	75	19	29	3.1	8.5
.4 - .5	100	75	15	26	3.5	6.5
.5 - .6	100	75	13	22	1.9	5.0
.6 - .7	100	75	13	20	1.6	4.0
.7 - .8	100	75	11	18	1.3	3.7
.8 - .9	100	75	9	16	1.0	3.1
.9 - .10	100	75	8	15	1.0	2.5
Total	1000	728	180	269	37.9	76.4

* All ranges of α

** At least one third of a fuel rod insulated.

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The totals in columns 4 and 5 were calculated from Figure 5. For example, in the range $L_p/L_0 = 0 - 0.1$, the plug area, α must average greater than about 40% to produce enough flow resistance for $\Delta t/\Delta t_r$ to be greater 1.05. Again, since all flow areas are equally probable, 40 out of 100 plugs in the range $L_p/L_0 = 0 - 0.1$ will be undetectable by the 5% deviation rule.

Columns 6 and 7 were calculated by examining each area-length classification individually, determining the number of undetectable dangerous plugs in the class, and summing the results. For example, in the class $L_p/L_0 = 0.1 - 0.2$, $\alpha = 0.1 - 0.2$, there are $10 \times .3 \times .9 = 2.7$ dangerous plugs, all of which are not detected by either the 5% or 10% rule. The class $L_p/L_0 = 0.2 - 0.3$, $\alpha = .3 - .4$ occupies the hatched region shown in Figure 5. For this class the number of dangerous plugs is given by $10 \times .7 \times 1 = 7$. About 40% of the hatched region in Figure 5 is above the line $\Delta T/\Delta T_r = 1.10$, therefore, the number of dangerous plugs undetectable by the 10% rule is $7 \times .4 = 2.8$.

The overall dangerous plug detection efficiency of the 10% rule is then $728-76/728 = .895$ and the efficiency of the 5% rule is $728-38-728 = 0.950$.

D. Heat Transfer to the Moderator

If, while the reactor is operating at constant power, a plug produces a reduction in the mass flow rate through a fuel channel, there will be a proportional increase in the indicated channel delta t unless heat transfer to the moderator causes sufficient cooling of the existing sodium to give a "false" reading on the exit temperature thermocouple. Heat transfer through the moderator was estimated by assuming that the moderator coolant temperature maintains its normal value while the fuel coolant in a single channel increases to an abnormally high value. Then heat would flow by conduction through the graphite to the moderator coolant. A circular geometry was assumed as shown in the following sketch.

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Heat transfer in the graphite is given by:

$$\frac{q}{L} = \frac{2\pi k_G (t_1 - t_2)}{\ln(D_2/D_1)}$$

or

$$t_1 - t_2 = \frac{q/L \ln(D_2/D_1)}{2\pi k_G} \quad (D-1)$$

In the helium gap,

$$\frac{q}{L} = \frac{2\pi D_1 k_{He} (t_0 - t_1)}{\delta}$$

or

$$t_0 - t_1 = \frac{q/L \delta}{2\pi D_1 k_{He}} \quad (D-2)$$

The minimum helium gap, δ , is .007 in. and the irradiated graphite thermal conductivity, k_g , is 20 Btu/hr-ft-°F (Ref. 7).

Then

$$\frac{\ln D_2/D_1}{2\pi k_G} = \frac{\ln 11/2.8}{2\pi (20)} = 2.84 \times 10^{-3}$$

and

$$\frac{\delta}{2\pi D_1 k_{He}} = \frac{.007}{2\pi (2.80)(914)} = 1.09 \times 10^{-2}$$

The average power in a fuel channel at 20 Mw is,

$$\frac{q}{L} = \frac{20 (3.43 \times 10^6)}{37 (6)} = 3.07 \times 10^5 \text{ Btu/hr/ft}$$

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The temperature differences calculated from equations D-1 and D-2 as a function of q/L are shown below.

q/L (BTU/Hr-ft)	$t_1 - t_2$ (°F)	$t_o - t_1$ (°F)	$t_o - t_2$ (°F)
10^3	10.9	2.84	13.7
10^4	109	28.4	137
10^5	1090	284	1370

The criterion for detecting plugs of interest in this investigation allows exit temperature deviations of the order of 50°F or less. This would result in moderator heat transfer rates of about $.4 \times 10^4$ Btu/hr/ft which is only 1.3% of the full power fuel heat transfer rates in the channel. Therefore, no significant error in the exit temperature reading should result from moderator heat transfer at 20 Mw. At 2 Mw the moderator heat transfer rate would be of the order of 13% of the fuel heat transfer rate and therefore might introduce an error as much as 7°F (out of 50°F) in the indicated channel delta t. This much error is on the verge of being significant, however, it is not felt that the plug detection efficiency of the outlet thermocouple is seriously impaired. At power levels below 2 Mw serious errors could result from this effect.

E. Estimate of Errors Resulting from Generalizations of Conclusions Based on Average Channel Calculations to Core as a Whole

Two important effects which act in opposite directions must be examined to determine the radial variation in the core of the sensitivity of the outlet thermocouple to dangerous plugs. These are:

1. The probability that a given sized plug will be dangerous is lower in the outer region of the core because of the lower power level there.
2. The sodium flow rate through channels in the outer region of the core is less sensitive to the presence of plugs in the fuel region because of the relatively higher pressure drop through the orifice in these channels.

From Ref. 3, the sodium flow rate in the outermost channel for the 37-element Th-U loading is 3.1 #/sec. An orifice size that will produce this flow rate at a core delta p of 1.5 psi can be

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obtained from Ref. 1. A .296" diameter orifice will do the job and the resulting pressure drops will be split to 0.5 psi through the element and 1.0 psi through the orifice. If these reference conditions are plugged into equation 19, the following flows and delta t's are calculated:

Plugged Area $\propto$	Plug Length L_p/L_o	Flow Reduction w/w_r	Delta t Increase $\Delta T / \Delta T_r$	
			Outer Channel	Avg. Channel
0.2	0.1	0.987	1.01	1.02
0.4		0.942	1.06	1.08
0.6		0.833	1.20	1.25
0.2	0.3	0.972	1.03	1.05
0.4		0.900	1.11	1.17
0.6		0.747	1.34	1.45
0.2	0.5	0.955	1.03	1.08
0.4		0.856	1.17	1.25
0.6		0.684	1.46	1.65
0.2	1.0	0.915	1.09	1.15
0.4		0.781	1.28	1.43
0.6		0.578	1.73	2.02

When these results are plotted on Figure 5 (dashed lines) and compared to the previous results it is seen that these lines cross the $\Delta t / \Delta T_r = 1.10$ line at an average of about 7% higher $\propto$ than the corresponding lines for the average fuel elements. Then, on the average for detection by the 10% rule, the flow area of outer fuel channels must be blocked about 7% more than the flow area of the average channels.

The power in the outer fuel channels is 87% of the power in the average fuel channel (Ref. 3). Referring to Figure 6, the average fuel surface area insulation required to produce a hot spot temperature of 1400°F is increased from 32% to 39% when power is reduced to 87%. This results in an increase in the average size of the dangerous plugs which roughly corresponds to the plug size increase required to make plugs in this region of the core as detectable as those in average channels. Thus, effects 1 and 2 cancel and conclusions reached regarding the average channel can be safely generalized to the core as a whole.

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IV. REFERENCES AND APPENDICES

1. TDR 3298 (rev. 1), J. A. Hagel, "Pressure Drop - Flow Tests of Two Types of SRE Fuel Element".
2. TDR 52, T. T. Shimazaki, "Pressure Drop and Orificing the SRE 7-rod and Hollow Ruel Elements".
3. TDR 2101, T. T. Shimazaki, "Calculated Thermal Performance of the SRE with Thorium-Uranium Fuel Loading."
4. NAA-SR-3096, W. W. Brown, F. L. Fillmore, B. L. Scott, "Exponential Experiments with Graphite Lattices Containing Multirod Slightly Enriched Uranium Fuel Clusters."
5. Dr. G. Bentle, Atomics International, unpublished.
6. NAA-SR-4448, A. A. Jarrett, "SRE Fuel Element Damage."
7. IOL, C. W. Griffin to W. S. DeBear, dated Sept. 15, 1959, Subject: "The Determination of Feasible Fuel Cladding Temperatures."

Nomenclature

- A = various areas as defined in text (ft^2)
L = various lengths as defined in text (ft)
w = flow rate (#/hr)
q = heat flow (Btu/hr)
 Δp = pressure drop due to dynamic effects such as friction (psi)
V = velocity (ft/hr)
D = various diameters as defined in text (ft)
k = thermal conductivity (Btu/hr-ft- $^{\circ}\text{F}$)
 ρ = density (#/ft ^{3})
r = a subscript indicating a reference condition at which pressure drops and flows are known.
P = heat generation rate (Btu/hr)
 q''' = specific heat generation rate (Btu/hr-in ^{3})
h = heat transfer coefficient (Btu/hr- $^{\circ}\text{F}$ -ft ^{2}).
R = heat transfer resistance ($^{\circ}\text{F}$ /Btu-hr-ft)
t = temperature ($^{\circ}\text{F}$)
 α = fraction of channel flow area occupied by plug (dimensionless).

FIG. 5

MASS FLOW REDUCTION IN SRC
FUEL CHANNEL DUE TO FORMATION
OF PLUGS IN FUEL TUBE REGION

$\frac{W}{W_0}$ = $\frac{\text{MASS FLOW PLUGGED CHANNEL}}{\text{MASS FLOW OPEN CHANNEL}}$

$\frac{L_P}{L_0}$ = $\frac{\text{LENGTH OF PLUG}}{\text{LENGTH OF AVECTURE}}$

$\frac{A_P}{A_0}$ = $\frac{\text{FLOW AREA OF PLUGGED CHANNEL}}{\text{FLOW AREA OF OPEN CHANNEL}}$

ORIFICE DIA = $\frac{1}{2}$ " , CORE DP = 1.5 PSI

$\Delta = 1 - \frac{A_P}{A_0} = \frac{\text{FLOW AREA OCCUPIED BY PLUG}}{\text{TOTAL FLOW AREA}}$

RECALCULATED 4/5/59

FIG 6
VARIATION OF HOT SPOT TEMP.
WITH FRACTION OF SURFACE INSULATED
FOR SRG TH-U FUEL ROD IN
PARTIALLY PLUGGED CHANNEL

PC Hayes
1/11/60

FIG 7

TEMPERATURE DISTRIBUTION IN SRE FUEL ROD AT 20MW
(TH-H FUEL)

FIG 8
TEMP DISTRIBUTION IN OUTER ROD
FROM 7 ROD SRE FUEL CLUSTER
(TH-M FUEL)
POWER = 20 MW

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FIG 10
TEMPERATURE DISTRIBUTION IN SRE FUEL ROD AT 2 MW
(Th-U FUEL)

FIG 11

TEMPERATURE DISTRIBUTION IN SRE FUEL ROD AT 2 MW
(T_H - H FUEL)

FIG 12
TEMPERATURE DISTRIBUTION IN SRS FUEL ROD AT 2 MW
(TH-H FUEL)

r/b

FIG 13
TEMPERATURE DISTRIBUTION IN SRG FUEL ROD AT 20 MW
(TA-U FUEL, UNIFORM HEAT GENERATION)

r/b

FIG. 14
TEMPERATURE DISTRIBUTION IN SRE FUEL ROD AT 20 MW
(THICK FUEL; UNIFORM HEAT GENERATION)

FIG 15

TEMPERATURE DISTRIBUTION ON THE SURFACE OF
SRE FUEL ROD AT 20 MW.
TH-U FUEL - UNIFORM HEAT GENERATION

- 1 NO INSULATION
- 2 15% INSULATION AT ONE SPOT
- 3 15% INSULATION AT THREE SPOTS