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ANALYSIS OF 100-K EMERGENCY WATER REQUIREMENTS AFTER CGI-844 PUMP FAILURE

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By Jerri Maley, 4-21-94.
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May 28, 1959

R. F. Corlett

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ANALYSIS OF 100-K EMERGENCY WATER REQUIREMENTS AFTER CGI-844 PUMP FAILURE

This study was made at the request of Reactor Modification Design Unit which is preparing Project CGI-844 for modification of the 100-K main coolant pumps. The purpose was to evaluate how much emergency water would be needed for prevention of excessive water and fuel temperatures when pump failure occurs.

Intersection of this demand curve with the actual pump supply curve indicates when emergency water must be introduced to hold temperatures down. The amount of water needed from the new source is the difference between the curves.

SUMMARY

Figure 2 is a plot of the demand curve determined by this study. Superimposed on the plot is a 5-set, modified pump decay curve furnished by Reactor Modification Design. The plot shows that 20,000 gpm emergency flow would be required within 80 seconds of complete pump power failure. Principal bases for the demand curve are:

1. Constant bulk inlet temperature = 2°C;
2. Constant bulk outlet temperature = 95°C;
3. K-3, I&E fuel elements;
4. Initial reactor flow = 188,000 gpm from which reactor power = 4616 MW at time zero.

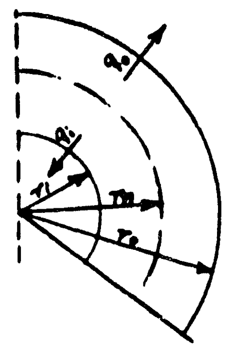
DISCUSSION

The study was begun by deriving a "neutral" radius within the I&E element which could then be treated as an insulated boundary - dividing the fuel element into two concentric "lumps" insulated from each other. To further simplify the problem, water temperatures in the central hole and outer cooling annulus were assumed equal. Characterizing each lump by a single temperature, expressions were then derived for $(T_{lump} - T_{water})$ as a function of time after scram. A similar expression was developed for the moderator - treating it as a single, homogeneous lump. Assuming resistances and water temperatures to remain constant with time and heat generation to be uniform, the transient heat outputs were calculated and added together. Using the heat output totals, the water quantities needed to maintain constant 95°C bulk outlet temperature at different times were calculated which gives the demand curve.

1. Derivation of Neutral Radius (r_n)

   a. First expression for Q ratio

      Let ϵ = heat generation intensity = $\frac{\text{Btu}}{\text{hr-ft}^3}$



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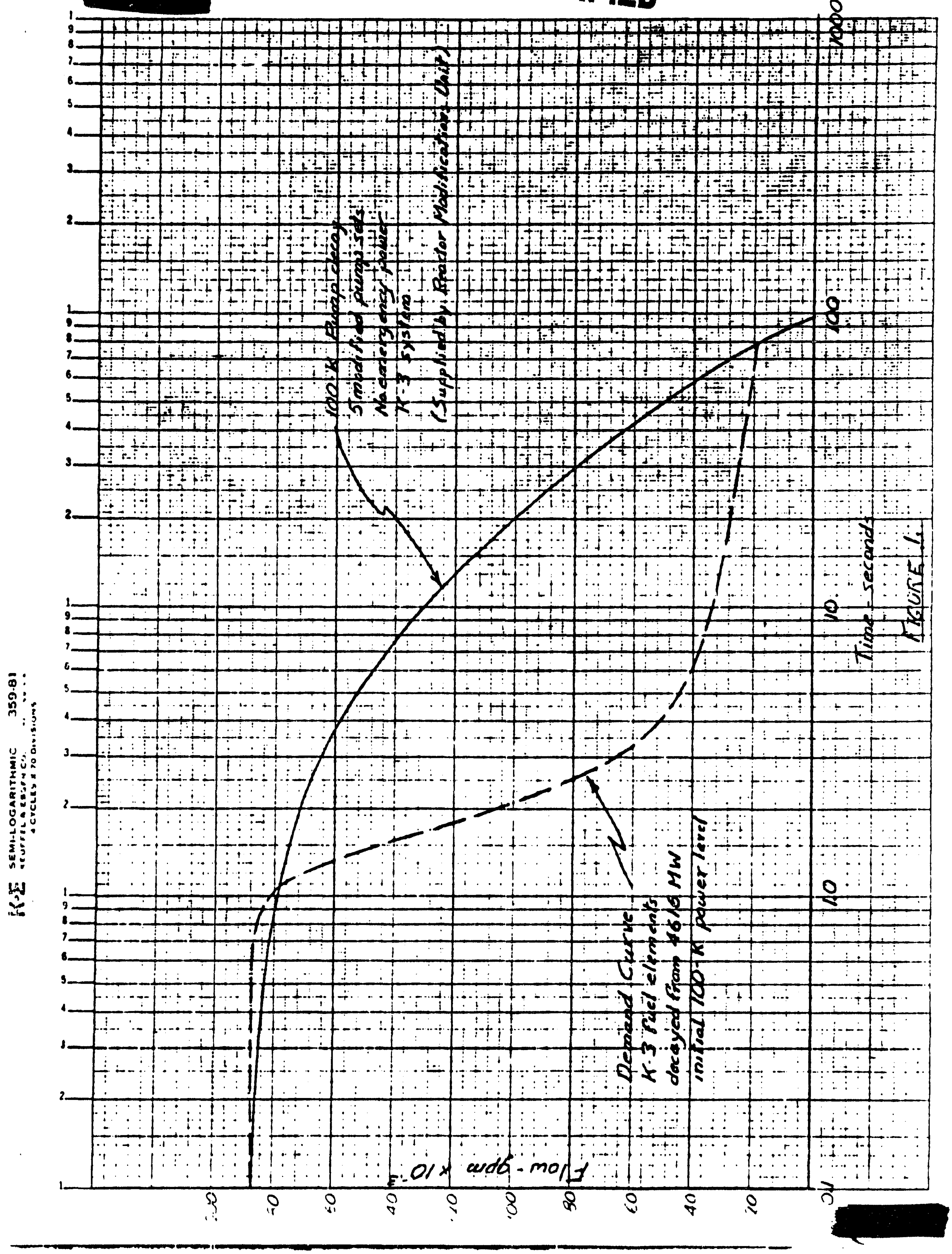

FIGURE 1.

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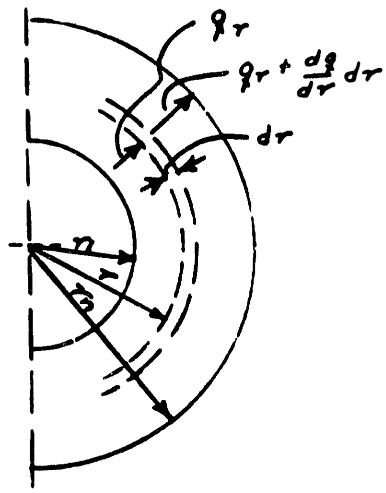
Taking an energy balance,

$$q_r + \frac{dq}{dr}\, dr = q_r + (2\pi r)\, dr\, L$$

$$\frac{dq}{dr}\, dr = \epsilon\,(2\pi r)\, dr\, L \qquad \text{----------} \quad (1)$$

Taking the rate equation,



$$q = -k\,(2\pi r)\, L\, \frac{dt}{dr}$$

$$\frac{dq}{dr} = -k\,(2\pi L)\left[r\,\frac{d^2t}{dr^2} + \frac{dt}{dr}\right] \quad \text{---} \quad (2)$$

Substituting (2) into (1), rearranging and integrating

$$t = -\frac{\epsilon}{K}\,\frac{r^2}{4} + C_1 \ln r + C_2 \quad \text{----} \quad (3)$$

when $r = r_1$, $t = t_1$

$r = r_n$, $\frac{dt}{dr} = 0$ (insulated boundary condition)

It follows that,

$$k\,(T - T_1) = \frac{\epsilon\, rn^2}{2}\,\ln\frac{r}{r_1} - \frac{\epsilon}{4}\,(r^2 - r_1^2)$$

We also know that $q_1 = \epsilon\pi(r^2 - r_1^2)\, L$

where $r = r_n$ and path length is divided by 2 due to average generation assumption. Whence,

$$k\,(T_1 - T_n) = \frac{q_1}{2\pi L}\left(1/2 - \frac{r_n^2}{r_n^2 - r_1^2}\,\ln\frac{r_n}{r_1}\right) \quad \text{----} \quad (4)$$

Similarly for outer part,

$$k\,(T_n - T_o) = \frac{q_o}{2\pi L}\left(1/2 - \frac{r_n^2}{r_o^2 - r_1^2}\,\ln\frac{r_n}{r_o}\right) \quad \text{-----} \quad (5)$$

[redacted]

Adding (4) and (5), and rearranging,

$$\frac{q_i}{q_o} = - \frac{\left(1/2 - \frac{r_n^2}{r_o^2 - r_n^2} \ln \frac{r_o}{r_n}\right)}{\left(1/2 - \frac{r_n^2}{r_n^2 - r_i^2} \ln \frac{r_n}{r_i}\right)} \quad \text{--- (6)}$$

b. <u>Second Expression for Q Ratio</u>

$$\frac{dt}{dr_i} = - \frac{\epsilon r_i}{2K} + \frac{C_1}{r_i}$$ ---- from one step in derivation of (3)

Substituting $\frac{dt}{dr}$ into the rate equation ($q = - k (2\pi r) L \frac{dt}{dr}$ gives,

$$q_i = - k\, 2\pi\, r_i\, L \left[\frac{\epsilon r_n^2}{2K} \frac{1}{r_i} - \frac{r_i}{2K}\right] \quad \text{----(7)}$$

Similarly for outer part,

$$q_o = - k\, 2\pi\, r_o\, L \left[\frac{\epsilon}{2K} r_n^2 \frac{1}{r_o} - \frac{\epsilon r_o}{2K}\right] \quad \text{--------(8)}$$

Solving for $\frac{q_i}{q_o}$ from (7) and (8),

$$\frac{q_i}{q_o} = \frac{- K\, 2\pi\, r_i\, L \left[\frac{\epsilon r_n^2}{2K} \frac{1}{r_i} - \frac{\epsilon r_i}{2K}\right]}{- K\, 2\pi\, r_o\, L \left[\frac{\epsilon r_n^2}{2K} \frac{1}{r_o} - \frac{\epsilon r_o}{2K}\right]}$$

Simplifying

$$\frac{q_i}{q_o} = \frac{r_n^2 - r_i^2}{r_n^2 - r_o^2} \quad \text{--------------------------------(9)}$$

We now have two expressions for $\frac{q_i}{q_o}$ which we can equate ((9) and (6)). Simplifying leads to a solvable expression for r_n:

$$r_n = \sqrt{\frac{r_o^2 - r_i^2}{2 \ln \frac{r_o}{r_i}}}$$

From the K-3 fuel element dimensions

r_o = .685 inches

r_i = .2455 inches,

r_o was found to be = .4464 inches.

Nomenclature above is as usually defined for heat transfer work;

r = radius

k = thermal conductivity, etc. (= assumed constant through fuel element)

2. <u>Derivation of Transient Temperature Expressions for the Fuel Element and Graphite</u>

<u>Energy Balance</u>

E = uniformly generated energy in Btu/hr-ft.

C = heat capacity in Btu/°F/ft.

q = heat going to sink in Btu/hr-ft.

R = over-all heat transfer resistance in hr-°F-ft./Btu

θ = time in hours

T = characteristic lump temperature in °F

T_w = water temperature in °F

heat in = heat out + accumulation

$$E_1 = q_1 + C \frac{dt_1}{d\theta} \quad \text{-------------------(10)}$$

<u>Rate Equation</u>

$$q_1 = \frac{1}{R_1} \quad (T_1 - T_w) \quad \text{---------------(11)}$$

Combining (10) and (11), and rearranging,

$$\frac{dt_1}{d\theta} + \left(\frac{1}{R_1 C_1}\right) T_1 = \frac{E_1}{C_1} + \frac{T_w}{R_1 C_1}$$

This is a linear, first order differential which solves to

$$T_i - T_o = C_1 e^{-\frac{\theta}{RC}} + \left[\int \frac{E}{C} e^{\frac{\theta}{RC}} d\theta \right] e^{-\frac{\theta}{RC}}$$

evaluating C_1 when time = θ and $T_i = (T_i)_\theta$

$$\text{gives } C_1 = \left[(T_i)_\theta - T_w \right] e^{\frac{\theta}{RC}} - \left[\int \frac{E}{C} e^{\frac{\theta}{RC}} d\theta \right]_\theta$$

for any time $\theta + \Delta\theta$ (after simplifying) therefore;

$$(T_i - T_w)_{\theta+\Delta\theta} = (T_i - T_w)_\theta e^{\frac{\Delta\theta}{RC}} + e^{-\frac{\theta+\Delta\theta}{RC}} \int_\theta^{\theta+\Delta\theta} \frac{E}{C} e^{\frac{\theta}{RC}} d\theta$$

Now choosing small enough time increments so that average E values may be used,

$$(T_i - T_w)_{\theta+\Delta\theta} = \left[(T_i - T_w)_\theta - R_i \bar{E}_i \right] e^{-\frac{\Delta\theta}{R_i C_i}} + R_i \bar{E}_i \quad \text{------(12)}$$

An identical expression can be written for the outer part,

$$(T_o - T_w)_{\theta+\Delta\theta} = \left[(T_o - T_w)_\theta - R_o \bar{E}_o \right] e^{-\frac{\Delta\theta}{R_o C_o}} + R_o \bar{E}_o \quad \text{-------(13)}$$

So also for the graphite lump,

$$(T_g - T_w)_{\theta+\Delta\theta} = \left[(T_g - T_w)_\theta - R_g \bar{E}_g \right] e^{-\frac{\Delta\theta}{R_g C_g}} + R_g \bar{E}_g \quad \text{---------(14)}$$

Resistance values for each fuel element lump and the graphite were determined from estimates of their operating temperatures at the power level chosen for this study and the steady state heat generations. Heat capacity values were estimated from data in Bonilla, "Nuclear Engineering". Using these numbers together with heat generation data explained below, and appropriate time increments, the equations were evaluated over the time period shown on Figure 1.

Since the lump resistances were assumed to be constants over the time interval, dividing the resistances into the Δ T values determined above gave the total

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heat going to sink for each lump, i.e.:

$$q = k A \frac{\Delta T}{\Delta X} = \frac{(T)_\theta - T_w}{R}$$

assuming then that $C_p = 1.0$ for water and using the previously stated criterion that bulk outlet temperature minus bulk inlet temperature will be arbitrarily held constant (95°C - 2°C = 93°C), the water required at various times was evaluated. This gave the demand curve shown on Figure 1.

3. Heat Generation Data

The decay of flux following reactor scram was obtained from estimates by D. L Condotta for K-reactor. Transient fission product decay heat was obtained from HW-33870, "Heat Generation and Total Heat Output from the Pile After Shutdown", by S. S. Jones. The flux decay data included the estimated delay time for rods to enter the active zone upon initiation of the scram signal. A delay time of 0.3 seconds for signals to reach the scram circuit was also added in.

The split of fission and fission product decay heat was estimated and used as follows:

Fission Heat (94%)

fuel	tubes	graphite
94%	0%	6%

Fission Product Decay Heat (6%)

fuel	graphite
90%	10%

Note

A transient temperature computer solution for an I&E element is apparently not available. Such a program is desirable and if time permits, it is recommended that a code be developed and applied to this problem since the solution herein is admittedly simplified.

Acknowledgement

Numerical solution of the integrals and curve plotting was accomplished by W. T. Morgan whose assistance was appreciated.

Richard F. Corlett
Reactor Design Analysis Unit
Process Design Sub-Section
NPR PROJECT SECTION

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8/18/94

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