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POWER EXCURSION IN A HANFORD REACTOR DUE TO A POSITIVE REACTIVITY RAMP

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POWER EXCURSION IN A HANFORD REACTOR DUE
TO A POSITIVE REACTIVITY RAMP

by

E. D. Jones
Systems Research Operation*
Instrument Research and Development
HANFORD LABORATORIES OPERATION

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September 20, 1961

HANFORD ATOMIC PRODUCTS OPERATION
Richland, Washington

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Purpose

The purpose of this document is to present the results of an analog simulation of the behavior of a Hanford reactor upon the simultaneous loss of primary coolant and introduction of a reactivity ramp during normal shutdown.

Introduction

At time zero the reactor is assumed to be without coolant and subcritical by an amount equal to $70mk + \alpha_m \theta_m$, where $70mk$ is the reactivity worth of the safety rods and $\alpha_m \theta_m = \rho_m$ is the negative reactivity due to the metal temperature, θ_m . Due to fission product decay heat, the reactor has been slowly increasing in temperature, until, at time zero, the whole complex has attained a temperature throughout of 660°C . At this point the reactor suffers a constant, positive rate of change of reactivity, starting at zero; i.e., a reactivity ramp.

Due to the input of the reactivity ramp, the reactor undergoes a power excursion. This power excursion is examined by means of analog simulation to determine the reactivity ramp just sufficient to cause the reactor to go prompt critical without melting of the fuel.

Summary

Curves of reactor power as a function of time for various reactivity ramps are presented in Figures 5 through 12. Average metal temperature is shown as a function of time in Figures 17 through 20. Figures 13 through 16 present the quantity $\frac{\rho - \beta}{\ell^*}$ as a function of time.

The minimum reactivity ramp necessary for the realization of prompt criticality, for fuel temperature coefficients (at 200°C) of $2.5 \times 10^{-5}/^\circ\text{C}$, $1.9 \times 10^{-5}/^\circ\text{C}$, and $1.5 \times 10^{-5}/^\circ\text{C}$, is $9.0 \times 10^{-5}/\text{sec}$.

Discussion

As in the electrical resistance analogy, $R = R_s \frac{\ell}{A}$, the resistance to heat flow through a length L across an area A is $R = \frac{L}{kA}$, where k is thermal conductivity in $\frac{\text{cal}}{\text{cm sec } ^\circ\text{C}}$.

Consider the hollow cylinder of radius r , thickness dr , and length L cm. The resistance to heat flow radially across this element is

$$dR = \frac{dr}{2\pi r L k}$$

Across a cylindrical solid from r_a to r_b , the resistance is thus

$$R = \frac{\ln r_b / r_a}{2\pi L k} \text{ sec } ^\circ\text{C/cal.}$$

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Figure 1 shows the cross section of the reactor lattice cell; regions 0 and 4 are air; 1, 2, and 3 are uranium; and regions 5 and 6 are graphite. Since $q = \frac{\Delta\theta}{R}$, where θ is temperature in $^{\circ}\text{C}$, the heat flow from n_1 to n_2 (see Figure 1) is

$$q_{12} = \frac{2\pi L k_u}{\ln n_2/n_1} (\theta_1 - \theta_2) \text{ cal/sec}$$

where k_u is the thermal conductivity of the uranium metal, and L is the length of the uranium column in a single process tube. Similarly,

$$q_{23} = \frac{2\pi L k_u}{\ln n_3/n_2} (\theta_2 - \theta_3) \text{ cal/sec}$$

$$q_{35} = 2\pi L (\theta_3 - \theta_5) \left(\frac{k_u}{\ln r_3/n_3} + \frac{k_g}{\ln n_5/r_4} \right) \text{ cal/sec}$$

and

$$q_{56} = \frac{2\pi L k_g}{\ln n_6/n_5} (\theta_5 - \theta_6) \text{ cal/sec}$$

where k_g is the thermal conductivity of the graphite. It is assumed that regions 0 and 1 remain at the same temperature, and that region 4 affords perfect thermal contact between regions 3 and 5. The further simplifying assumption is made that the reactor is homogeneous and each fuel column consists solely of uranium fuel elements.

For the i^{th} region, the energy balance is given by

$$\frac{d\theta_i}{dt} = \frac{S_i + q_{hi} - q_{ij}}{M_i C_i}$$

where

- t = time
- S_i = source of heat in region i
- M_i = mass of region i
- C_i = specific heat of region i
- q_{hi} = heat flow from region h to region i
- q_{ij} = heat flow from region i to region j
- $h = i-1, j = i+1$, except where q_{hi} or $q_{ij} = q_{35}$

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The heat source terms in the energy balance equations are $S_i = W_i \frac{N}{ECT}$, where N is reactor power, ECT is 1600, the effective central tubes, and W_i is a weighting factor.

The weighting factors W_i are found as follows*: Figure 2 shows (relative) flux as a function of radius for the fuel slug. For a given point on the curve, the ordinate and abscissa are multiplied together and the product is the ordinate of the point on the curve in Figure 3 whose abscissa is the same as that of the given point of Figure 2. The curve of Figure 3 is divided into three parts, corresponding to the three uranium regions shown in Figure 1. Since the heat generated in region i of the uranium is proportional to the flux in that region, it is proportional to the area of region i under the curve of Figure 3 divided by the total area under that curve. It is assumed that the amount of heat generated in the graphite is the same throughout the graphite, so that the heat generated in region i of the graphite is proportional to the cross sectional area of region i divided by the total cross sectional area of the graphite, in the lattice cell of Figure 1. Of total prompt power, 94.38% is generated in the uranium and 5.62% in the graphite. Since S_i is that fraction of the total heat generated in a single tube which is generated in region i, we have,

$$W_1 = .9438 B \frac{a_1}{a_1 + a_2 + a_3}$$

$$W_2 = .9438 B \frac{a_2}{a_1 + a_2 + a_3}$$

$$W_3 = .9438 B \frac{a_3}{a_1 + a_2 + a_3}$$

$$W_5 = .0562 B \frac{A_5}{A_5 + A_6}$$

and

$$W_6 = .0562 B \frac{A_6}{A_5 + A_6}$$

where

$$B = \frac{1}{4.186} \frac{\text{cal/sec}}{\text{watt}}, \text{ which converts watts to cal/sec}$$

a_i = that part of the area under the curve of Figure 3 belonging to the i^{th} region

A_5 and A_6 are the cross sectional areas of regions 5 and 6 (Figure 1).

* The method used here was suggested by R. E. Tiller

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From Figure 3, the weighting factors W_i are

$$W_1 = .04235 \frac{\text{cal/sec}}{\text{watt}}$$

$$W_2 = .06936 \frac{\text{cal/sec}}{\text{watt}}$$

$$W_3 = .1138 \frac{\text{cal/sec}}{\text{watt}}$$

$$W_5 = .004261 \frac{\text{cal/sec}}{\text{watt}}$$

and

$$W_6 = .009169 \frac{\text{cal/sec}}{\text{watt}}$$

In terms of the preceding material, the energy balance equations for the five regions can be written

$$\frac{d\theta_1}{dt} = 3.327N \times 10^{-8} - 1.364(\theta_1 - \theta_2)$$

$$\frac{d\theta_2}{dt} = 3.637N \times 10^{-8} + .9102\theta_1 - 2.220\theta_2 + 1.310\theta_3$$

$$\frac{d\theta_3}{dt} = 4.282N \times 10^{-8} + .9398\theta_2 - 3.398\theta_3 + 2.458\theta_5$$

$$\frac{d\theta_5}{dt} = 6.336N \times 10^{-11} + .09714\theta_3 - .1041\theta_5 + .006957\theta_6$$

$$\frac{d\theta_6}{dt} = 6.341N \times 10^{-11} + .003235(\theta_5 - \theta_6)$$

From these equations are found the temperatures of the three uranium regions; then the (space) average uranium temperature is

$$\theta_m = \frac{\sum_i A_i \theta_i}{\sum_i A_i}$$

where

A_i = cross sectional area of region i .

θ_i = temperature of region i .

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This average fuel temperature is multiplied by the temperature-dependent metal temperature coefficient, α_m , to yield ρ_m , the negative reactivity due to metal temperature:

$$\alpha_m \theta_m = \rho_m.$$

The metal temperature coefficient is given by

$$\alpha_m = -\frac{C}{T^2}$$

so that

$$\rho_m = -\alpha_m C T^{-2}$$

where T is Kelvin temperature and C is a constant. Three functions of α_m have been used: those for which, at 20°C, α_m is $2.5 \times 10^{-5}/^\circ\text{C}$, $1.9 \times 10^{-5}/^\circ\text{C}$, and $1.5 \times 10^{-5}/^\circ\text{C}$. For these values, C is 4.279×10^{-4} , 3.252×10^{-4} , and 2.568×10^{-4} , respectively. There is also a graphite coefficient of reactivity, but its effects are neglected.

The reactor kinetic equations are solved for power, N, as a function of time. The constantly changing value of ρ , total reactivity, fed into the appropriate kinetic equation is

$$\rho = \rho_r + \rho_m$$

where ρ_r is the reactivity ramp input. Since, at low power, $\frac{d\rho_m}{dN}$ is negligible, it is assumed to be zero until the power level reaches .1 megawatt*. Initial power level is $N = 10^{-3}$ watt, with the reactor subcritical by 70 milli-k, due to the safety rods, plus an amount $\rho_m = \alpha_m \theta_m$ due to the initial metal temperature. At time zero, the temperature of the lattice cell is assumed to be 660°C throughout the cell. The reactor kinetic equations yielding power are

$$\frac{dN(t)}{dt} = \frac{\rho - \beta}{\ell^*} N(t) + \rho e^{-B^2 \tau} \sum_{i=1}^6 \lambda_i C_i(t)$$

and

$$\frac{dC_i(t)}{dt} = \frac{\beta_i N(t)}{\ell^* \rho e^{-B^2 \tau}} - \lambda_i C_i(t)$$

* During computer runs for which $N < .1$ MW, switch #10 (Figure 4) was open.

where

- N = neutron population, proportional to power
- ρ = reactivity, k_{ex}/k_{eff}
- β_i = that fraction of all neutrons which is in the i^{th} delayed group
- β = total delayed neutron fraction
- ℓ^* = mean thermal neutron lifetime in the finite reactor
- p = resonance escape probability
- e^{-TB^2} = fast neutron nonleakage probability
- λ_i = decay constant of the i^{th} delayed neutron group precursor
- C_i = i^{th} delayed group precursor concentration.

These seven equations were programmed for the Beckman EASE analog computer to yield N , which is scaled so that it may be regarded as reactor power. When N reached a value corresponding to 10^5 watts, the program was altered to include the five-region energy balance equations. The analog circuit used is shown in Figure 4. Four cases, shown in Table I, were examined.

An XY-recorder* was used to record reactor power as a function of time; the results are shown in Figures 5 through 12. For convenience and ease in reading, each computer run is shown with its own time scale, starting at zero. The time of a single power excursion is equal to the sum of the times of its constituent computer runs. Since the maximum output of each amplifier on the computer is limited to 100 volts, each of the curves of Figures 5 through 8 represents two decades of power (except for the final runs for Cases 1, 2, and 4). For each case, the reactor power curves have been transformed into a single curve on semilogarithmic paper; these curves are presented in Figure 9 through 12.

Figures 13 through 16 show, for each of the four cases, the quantity $\frac{\rho - \beta}{\ell^*}$ as a function of time. Total reactivity, ρ , may be found from this quantity, since β and ℓ^* are constants (see Table III). This quantity is presented instead of reactivity because it was conveniently available, and because the reactor is prompt critical if, and only if, the quantity $\rho - \beta$ vanishes.

Temperatures for the five regions of Figure 1 and average metal temperature, θ_m , are shown for various times during the computer runs in Table II. Figures 17 through 20 present average metal temperature as a function of time for the four cases considered.

Within the accuracy of computer specifications, the following conditions are reflected in Figures 5 through 20:

- Case 1 - The quantity $\frac{\rho - \beta}{\ell^*}$ went to $-.01$, where it turned around and went more negative again. The reactor was closest to prompt critical at 1017.5 seconds after time zero. With the circuit of Figure 4, the next higher reactivity ramp would be $10^{-4}/\text{sec}$, which would send the reactor prompt critical. Region 1 of the fuel (Figure 1) reached melting temperature at 1022.9 seconds after time zero.

* PACE Variplotter

Case 2 - According to the digital voltmeter, the reactor came within a negligible amount of prompt critical at 992.9 seconds after time zero. An increase in $\frac{d\rho}{dt}$ of less than $1 \times 10^{-5}/\text{sec}$ would send the reactor prompt critical. With the accuracies involved, it is not possible to state with absolute assurance that the reactor was less than prompt critical when $\frac{\rho - \beta}{\rho^*}$ reached its peak and turned around, although the digital voltmeter indicated that this was the case in more than one trial with excellent reproducibility. The fuel melted in 997.1 seconds.

Case 3 - The reactor attained prompt criticality at 1014.7 seconds after time zero, at which time $\frac{\rho - \beta}{\rho^*}$ reached a peak of zero and began to decrease. Due to potentiometer drift, the reactivity ramp, $\frac{d\rho}{dt}$, was very slightly less than $9.0 \times 10^{-5}/\text{sec}$. The next higher ramp would be more than enough to cause the reactor to go prompt and not turn around before the fuel melted.

Case 4 - The quantity $\frac{\rho - \beta}{\rho^*}$ reached a peak of approximately -.18 and turned around and went more negative again. The fuel melted at 1095.2 seconds after time zero.

The constants and parameters used in this problem were supplied by R. E. Tiller. They are presented in Table III.

With the conditions of this problem, the reactor will go prompt critical under a reactivity ramp of $\frac{d\rho}{dt} = 9.0 \times 10^{-5}/\text{sec}$ for each of the three metal temperature coefficients considered.

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TABLE I

	Case 1	Case 2	Case 3	Case 4
α_m	$2.5 \times 10^{-5}/^{\circ}\text{C}$	$1.9 \times 10^{-5}/^{\circ}\text{C}$	$1.5 \times 10^{-5}/^{\circ}\text{C}$	$1.5 \times 10^{-5}/^{\circ}\text{C}$
ρ_r	$9.0 \times 10^{-5}/\text{sec}$	$9.0 \times 10^{-5}/\text{sec}$	$9.0 \times 10^{-5}/\text{sec}$	$8.0 \times 10^{-5}/\text{sec}$

TABLE II

Case 1

Seconds After Time Zero	Reactor Power (Watts)	Temperature - $^{\circ}\text{C}$					
		θ_1	θ_2	θ_3	θ_5	θ_6	θ_m
0 - 1007.1	10^5	660.0	660.0	660.0	660.0	660.0	660.0
1013.1	10^7	660.4	660.4	660.4	660.2	660.0	660.4
1018.3	10^9	686.6	684.1	675.5	661.6	660.1	680.7
1022.9	10^{11}	1133.6	1060.8	883.3	693.8	661.5	995.8

Case 2

Seconds After Time Zero	Reactor Power (Watts)	Temperature - $^{\circ}\text{C}$					
		θ_1	θ_2	θ_3	θ_5	θ_6	θ_m
0 - 981.7	10^5	660.0	660.0	660.0	660.0	660.0	660.0
987.9	10^7	660.4	660.4	660.4	660.2	660.0	660.4
992.9	10^9	686.4	683.9	675.4	661.6	660.1	680.5
997.1	10^{11}	1133.8	1069.6	896.6	690.0	661.4	1004.7

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TABLE II (cont.)

Case 3

Seconds After Time Zero	Reactor Power (Watts)	Temperature - °C					
		θ_1	θ_2	θ_3	θ_5	θ_6	θ_m
0 - 1003.3	10^5	660.0	660.0	660.0	660.0	660.0	660.0
1009.7	10^7	660.4	660.4	660.4	660.2	660.2	660.4
1014.7	10^9	686.2	683.8	675.3	661.6	660.4	680.4

Case 4

Seconds After Time Zero	Reactor Power (Watts)	Temperature - °C					
		θ_1	θ_2	θ_3	θ_5	θ_6	θ_m
0 - 1078.8	10^5	660.0	660.0	660.0	660.0	660.0	660.0
1085.6	10^7	660.5	660.5	660.5	660.2	660.0	660.5
1091	10^9	688.4	685.5	676.2	661.9	660.2	681.9
1095.2	10^{11}	1133.9	1071.3	899.8	690	661.4	1006.8

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TABLE III

$\lambda_1 = 3.033$	$\beta_1 = 30.23 \times 10^{-5}$
$\lambda_2 = 1.1462$	$\beta_2 = 84.37 \times 10^{-5}$
$\lambda_3 = .3048$	$\beta_3 = 260.9 \times 10^{-5}$
$\lambda_4 = .1171$	$\beta_4 = 127.8 \times 10^{-5}$
$\lambda_5 = .03056$	$\beta_5 = 140 \times 10^{-5}$
$\lambda_6 = .01249$	$\beta_6 = 20.37 \times 10^{-5}$
	<hr/>
	$\beta = 663.67 \times 10^{-5}$

$$l^* = 1.1347 \times 10^{-3} \text{ sec}$$

Density of uranium: 18.9 gm/cm^3

Density of graphite: 1.588 gm/cm^3

Specific heat of uranium: $.0336 \text{ cal/gm}^\circ\text{C}$

Specific heat of graphite: $.28 \text{ cal/gm}^\circ\text{C}$

Thermal conductivity of uranium: $.11 \frac{\text{cal}}{\text{cm sec } ^\circ\text{C}}$

Thermal conductivity of graphite: $.0496 \frac{\text{cal}}{\text{cm sec } ^\circ\text{C}}$

Length of uranium column: 680.97 cm

Fuel enrichment: $.947\%$ by weight

Total worth of vertical safety rod system: 70 mk

Effective central tubes (ECT): 1600

α_m (at 20°C): $2.5 \times 10^{-5}/^\circ\text{C}$, $1.9 \times 10^{-5}/^\circ\text{C}$, and $1.5 \times 10^{-5}/^\circ\text{C}$.

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TABLE IV

Pot Settings For Circuit of Figure 4

<u>Pot</u>	<u>Setting</u>	<u>Pot</u>	<u>Setting</u>	<u>Pot</u>	<u>Setting</u>
0	.3232	22	.5610*	59	.3000
1	.3033	24	.9398	60	.0247*
2	.0180*	25	.5610*	61	.0306
3	.0224	32	.2180	66	.5610*
4	.1278	33	.1041	67	.9102
5	.1146	37	.0070	68	.5610*
6	.0101*	40	.4553	69	.1364
7	.3083	48	.8813	70	.0971
8	.1500	50	.0107*	72	.0032
9	.1171	51	.2500	75	.3398
10	.1319	52	.0125	81	.0100
11	.0754	53	.1000	84	.0032
12	.1000	54	.0112*	85	.2458
13	.3333	55	.6667	87	.7527*
17	.1364	56	.3048	91	.0585
19	.2220	57	.6813	98	.3266
20	.1310	58	.0113*	84	.0008
21	.5610*				or
					.0009

(reactivity
ramp)

	<u>Pot</u>						
<u>Run</u>	<u>16</u>	<u>18</u>	<u>30</u>	<u>74</u>	<u>77</u>	<u>α_m</u>	<u>Setting on Pot 82</u>
5	.0003	.0003	zero	.0004	zero	$2.5 \times 10^{-5}/^{\circ}\text{C}$	.4436
6	.0283	.0309	.0001	.0364	.0001	$1.9 \times 10^{-5}/^{\circ}\text{C}$	.3372
7	.2828	.3091	.0054	.3640	.0054	$1.5 \times 10^{-5}/^{\circ}\text{C}$	.2662

For the first run, the input to pot 87 is -100 volts; for succeeding runs, the input is +100 volts.

* These are initial condition pots and must be reset at the beginning of each run.

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FIGURE 1

Cross Section of Lattice Cell

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FIGURE 2
Relative Flux vs. Radius for Uranium Fuel Slug

FIGURE 3

Relative Flux Times Radius vs. Radius for Uranium Fuel Slug

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FIGURE 4
Analog Circuit

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FIGURE 5a
Reactor Power vs. Time
Case 1

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FIGURE 5b

Reactor Power vs. Time

Case 1

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FIGURE 6a
Reactor Power vs. Time
Case 2

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FIGURE 6b

Reactor Power vs. Time
Case 2

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FIGURE 7a
Reactor Power vs. Time
Case 3

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FIGURE 7b
Reactor Power vs. Time
Case 3

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FIGURE 8a

Reactor Power vs. Time
Case 4

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FIGURE 8b
Reactor Power vs. Time
Case 4

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FIGURE 8c
 Reactor Power vs. Time
 Case 4

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FIGURE 9a

Reactor Power vs. Time
Case 1

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FIGURE 9b

Reactor Power vs. Time
Case 1

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FIGURE 9c
Reactor Power vs. Time
Case 1

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FIGURE 10a

Reactor Power vs. Time
Case 2

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FIGURE 10b

Reactor Power vs. Time
Case 2

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FIGURE 10c

Reactor Power vs. Time
Case 2

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FIGURE 11a

Reactor Power vs. Time
Case 3

FIGURE 11b

Reactor Power vs. Time
Case 3

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FIGURE 11c

Reactor Power vs. Time
Case 3

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FIGURE 12a

Reactor Power vs. Time
Case 4

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FIGURE 12b

Reactor Power vs. Time
Case 4

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FIGURE 12c

Reactor Power vs. Time

Case 4

FIGURE 13
 $\frac{\rho - \beta}{l^*}$ vs. Time
 Case 1

FIGURE 14

$\frac{\rho - \beta}{l^*}$ vs. Time

Case 2

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FIGURE 15

$\frac{\rho-\beta}{l^*}$ vs. Time

Case 3

FIGURE 16

$\frac{\rho-\beta}{l^*}$ vs. Time
 Case 4

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FIGURE 17
Average Fuel Temperature vs. Time
Case 1

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FIGURE 18

Average Fuel Temperature vs. Time
Case 2

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