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REACTIVITY ABSORBED BY XENON-135 IN THE SRE

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REACTIVITY ABSORBED BY XENON-135 IN THE SRE

By
R. W. WOODRUFF

ATOMICS INTERNATIONAL
A DIVISION OF NORTH AMERICAN AVIATION, INC.
P.O. BOX 309 CANOGA PARK, CALIFORNIA

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ABSTRACT

The measurement and calculation of the reactivity absorbed by Xe^{135} as functions of time after shutdown for the SRE are described. The measured transient was obtained from critical shim rod configurations. The calculated transient was based on the change in thermal utilization caused by the change in xenon concentration, assuming the the other parameters in k_{eff} remain constant. The xenon concentration was calculated prior to shutdown. The varying reactor power was approximated in 4-hr steps to obtain the concentration present when the power was first reduced to zero. The subsequent concentration was obtained from the radioactive decay law. The measured and calculated transients agreed within 0.14% δk/k. The same calculational technique was applied to various positive and negative step changes in power so that the reactivity absorbed by xenon can be estimated for many reactor conditions. After the reactor scrams from nominal full power, the excess reactivity required for xenon compensation is 2.0% δk/k. A 4-day waiting time after shutdown is required before the reactivity worth of reactor components can be measured with an accuracy of 0.001% δk/k without compensating for xenon.

I. INTRODUCTION

The SRE is a graphite moderated, sodium-cooled, thermal reactor which is used for the evaluation and development of the sodium graphite reactor concept. The fuel elements are 7-rod clusters enriched to 2.78% U^{235}. The lattice is triangular with an 11-in. pitch, and nominal full power is 20 Mwt. A complete description of the SRE has been given by Starr and Dickinson.*

The measurement of the reactivity absorbed by Xe^{135} as a function of time after shutdown was required to determine the excess reactivity necessary for xenon override. It was also required to determine the waiting time after reducing the power to zero before the reactivity worth of reactor components could be measured without correcting for xenon decay.

The transient caused by the shutdown on September 25, 1958 was measured by determining critical shim rod configurations periodically during and after the shutdown. From the shim rod calibration curves,[1] the excess reactivity was obtained as a function of time. The change in this quantity, after correction for temperature effects, yielded the reactivity absorbed by xenon. This curve is compared in Figure 1 to the calculated transient which was obtained from the change in thermal utilization induced by the growth and decay of xenon, assuming that the other parameters which determine k_{eff} were constant. The transients resulting from various step changes in power were obtained by applying the same calculational technique, and these transients are displayed in Figure 2. From the curves, the excess reactivity required for xenon override can be found.

* C. Starr and R. Dickinson, Sodium Graphite Reactors, (Reading, Mass., Addison–Wesley, 1959).

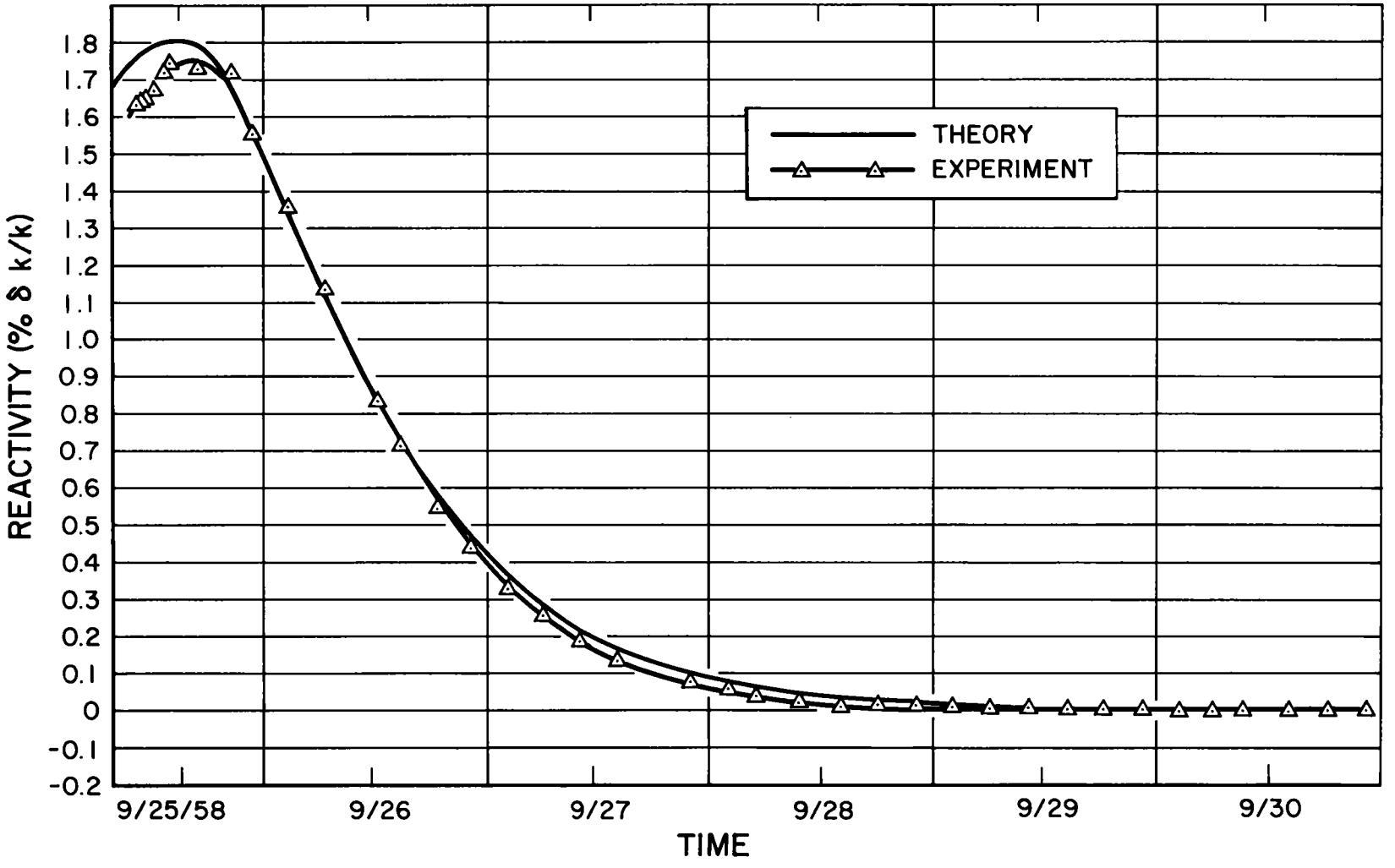

Figure 1. Reactivity Absorbed by Xe^{135} after Shutdown on September 25, 1958

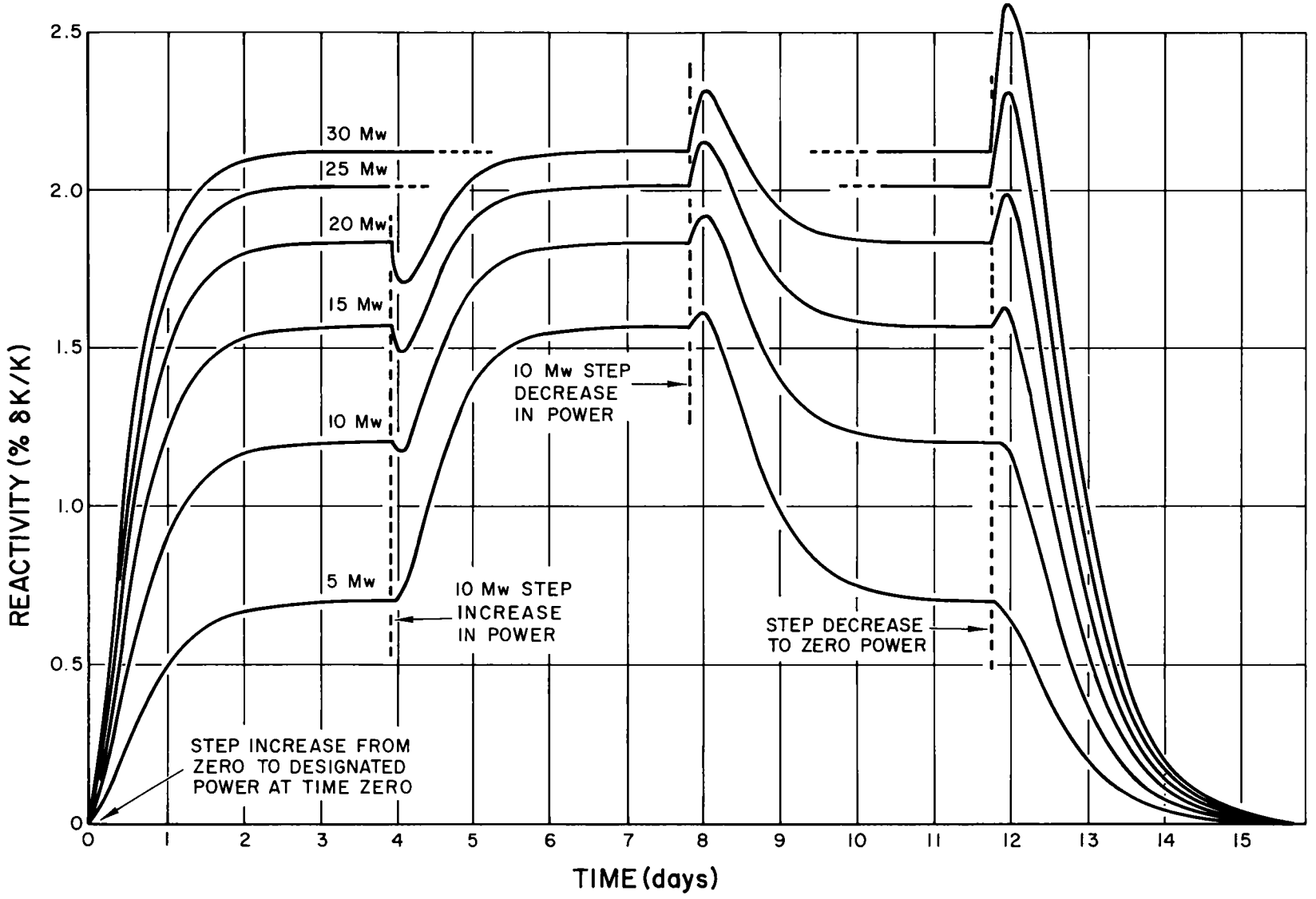

Figure 2. Reactivity Absorbed by Xe^{135} for Various Power Histories

II. MEASURED TRANSIENT

The excess reactivity of the core as a function of time is given by

$$\rho_e(\tau) = C + \int_{T=T'}^{T''(\tau)} \left(\frac{d\rho}{dT}\right) dT + \int_{P=0}^{P'(\tau)} \left(\frac{d\rho}{dP}\right) dP - \rho_x(\tau) \quad . \qquad \ldots(1)$$

The symbols are defined in Section VI. Equation 1 is applicable for a time interval short enough for long-term reactivity effects to be neglibible. Reactivities $\rho_e(\tau)$ were obtained from shim rod configurations at criticality and their calibration curves.[1] Temperature T' is arbitrary; the value selected (337°F) was the average coolant temperature near the conclusion of the measurements. Because the reactor power and the xenon concentration were then zero, the value of the constant C was obtained directly from the corresponding shim rod configuration. The measured isothermal temperature coefficient[1] was fitted with

$$\frac{d\rho}{dT} = \left[-7.26 \cdot 10^{-5} \left(\frac{T}{°F}\right)^2 + 4.88 \cdot 10^{-2} \left(\frac{T}{°F}\right) + 5.71\right] \frac{10^{-4}\%}{°F} \quad . \qquad \ldots(2)$$

For the power coefficient, the following expression was derived from the isothermal temperature coefficient and the fuel temperature coefficient:

$$\frac{d\rho}{dP} = \left(9.4 \pm 24 - \frac{3.88\,P}{Mw}\right) \frac{10^{-4}\%}{Mw} \quad . \qquad \ldots(3)$$

Since $\rho_e(\tau)$, C, $T''(\tau)$ and $P'(\tau)$ were measured, Equation 1 could be solved for $\rho_x(\tau)$ by applying Equations 2 and 3.

Prior to the measurement, the reactor was operated at 20 Mwt for a time interval sufficiently long to establish xenon equilibrium. The power was then lowered to approximately 10 Mwt, and was subsequently varied between 10 and 20 Mwt for a reactor oscillator experiment. After this experiment, the reactor was shut down according to the normal operating procedure. Critical shim rod configurations were recorded periodically during and following the shutdown.

The positions of the shim rods were measured with Veeder Root revolution counters which are attached to the drive mechanisms and have a least count equivalent to 1/160 in. of shim rod movement. Three of the four shim rods were always returned to the same positions, which were within 3 in. of each other, when obtaining a critical configuration. Since the core is 73 in. high and the shim rods are parallel to its axis, these three rods were essentially ganged. Shim rod three, which was positioned for criticality, had been calibrated after the first 100 Mwd of operation[1] with the remaining rods ganged. Since this experiment was conducted after 1100 Mwd, a second calibration, following the experiment, was necessary and was in agreement with the first one. The quantity $C - \rho_e(\tau)$, was determined as a function of time from the calibration curve for shim rod three. The integrated coefficients were calculated, using Equations 2 and 3, from the power and temperature histories shown in Figures 3 and 4. The terms in Equation 1 were determined and these are displayed in Figure 5.

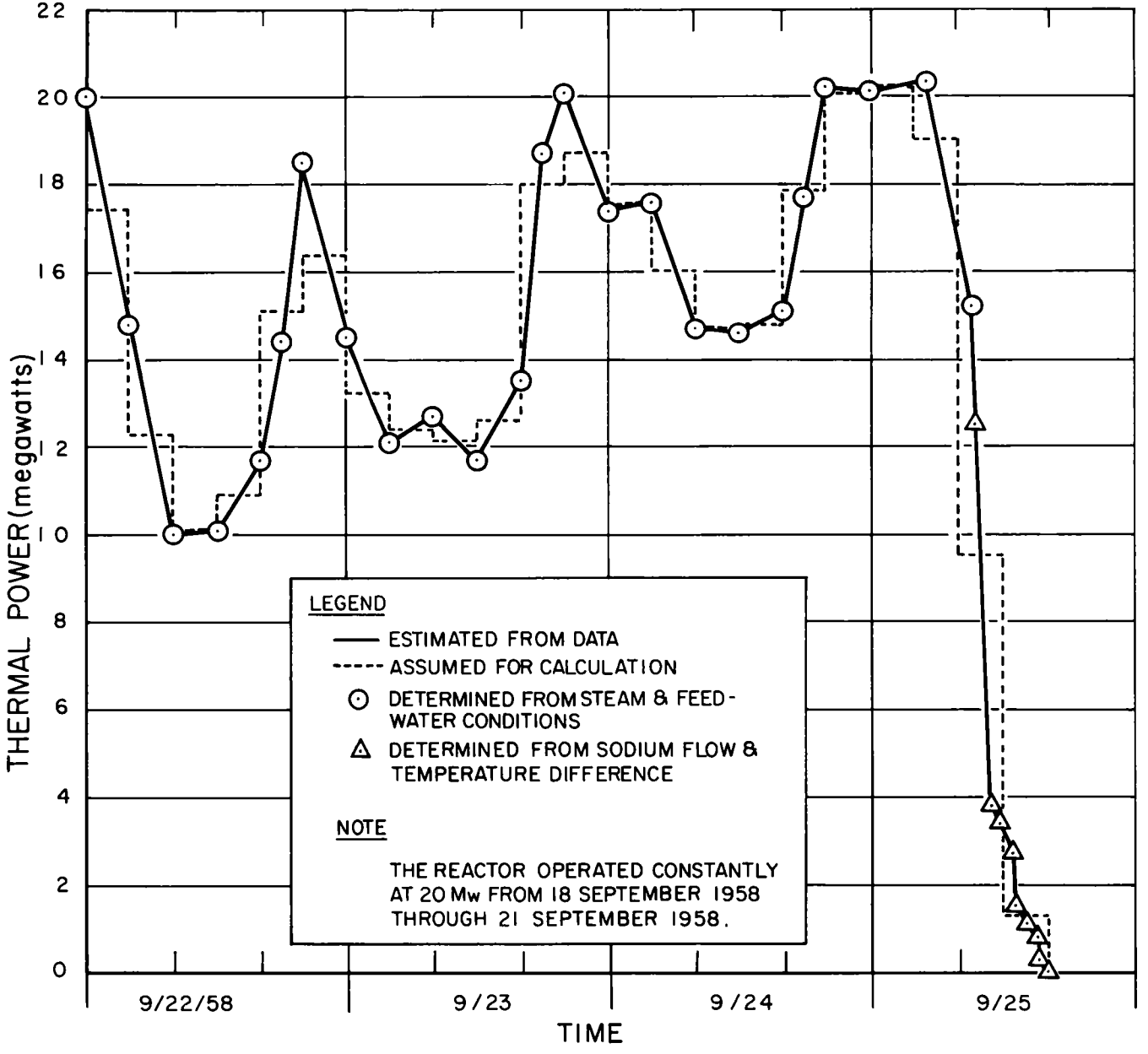

Figure 3. Power History Prior to Shutdown on September 25, 1958

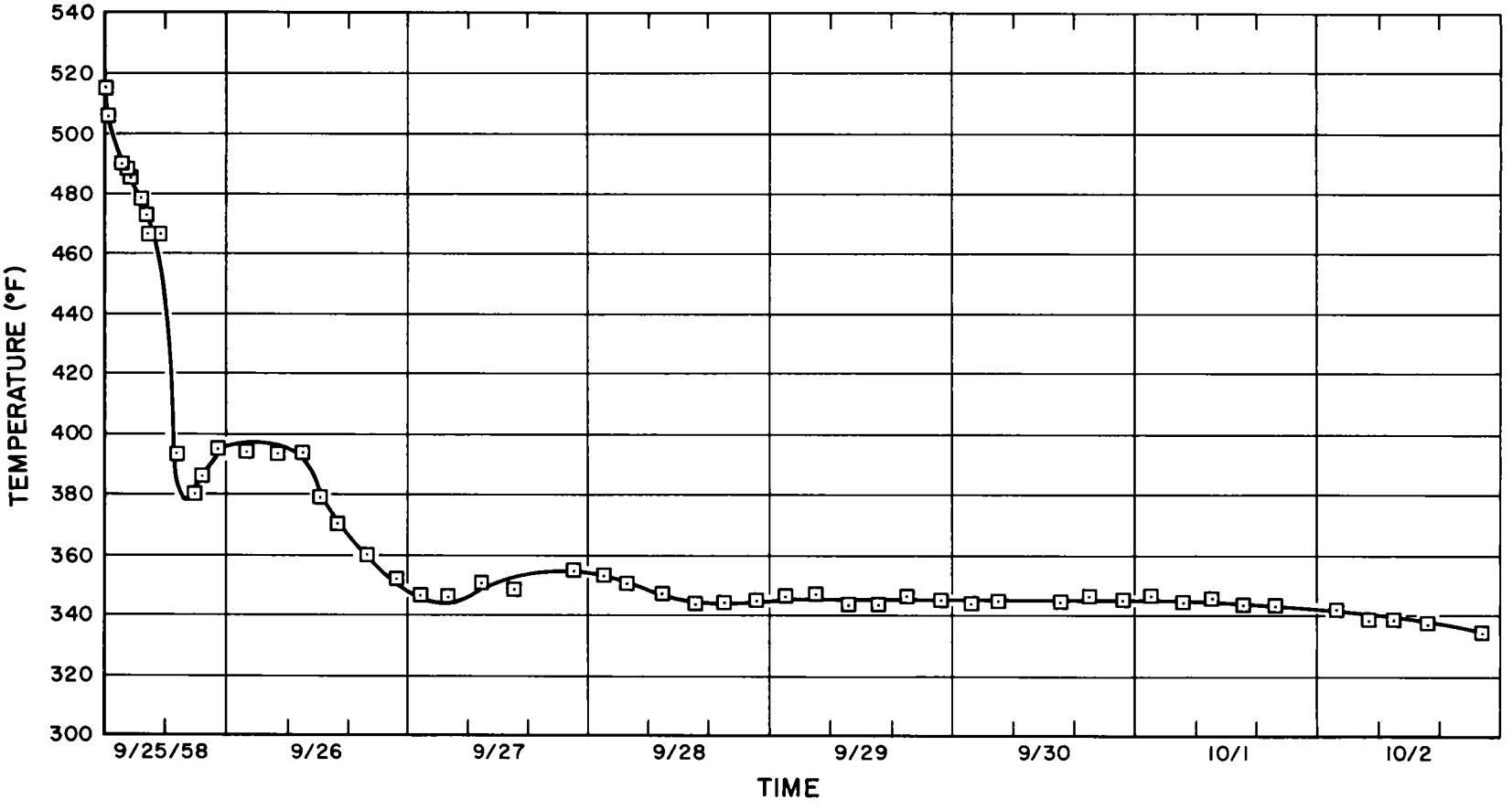

Figure 4. Temperature History Following the Shutdown on September 25, 1958

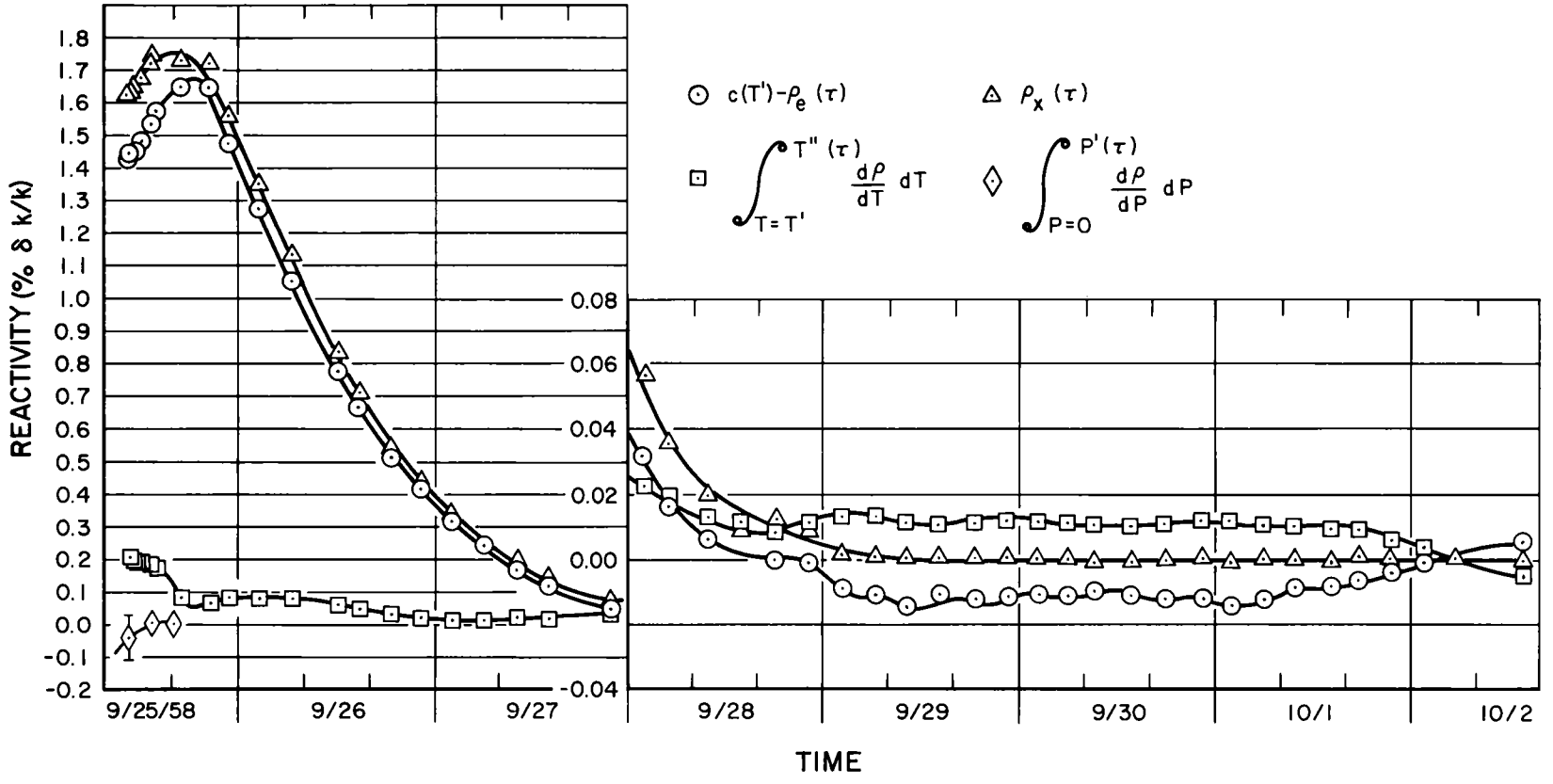

Figure 5. Combined Reactivity Effects of Xe^{135} and the Power and Isothermal Temperature Coefficients Commencing on September 25, 1958

III. CALCULATED TRANSIENT

Glasstone and Edlund[2] give the following differential equations for the time rate of change of I^{135} and Xe^{135}:

$$\frac{dI}{d\tau} = -\lambda_i I + \gamma_i \Sigma_{fu} \phi \qquad \ldots(4)$$

and

$$\frac{dX}{d\tau} = \lambda_i I + \gamma_x \Sigma_{fu} \phi - \lambda_x X - \sigma_x \phi X \ , \qquad \ldots(5)$$

where the symbols are those defined in Section VI. The solutions to these equations, after a step change in flux at τ equal to zero, are:

$$I(\tau) = I(0)\, e^{-\lambda_i \tau} + \frac{\gamma_i \Sigma_{fu} \phi}{\lambda_i} \left(1 - e^{-\lambda_i \tau} \right) \qquad \ldots(6)$$

and

$$X(\tau) = \frac{(\gamma_i + \gamma_x) \Sigma_{fu} \phi}{\lambda_x + \sigma_x \phi} + \frac{\lambda_i I(0) - \gamma_i \Sigma_{fu} \phi}{\lambda_x - \lambda_i + \sigma_x \phi} \, e^{-\lambda_i \tau}$$

$$+ \left[X(0) - \frac{(\gamma_i + \gamma_x) \Sigma_{fu} \phi}{\lambda_x + \sigma_x \phi} - \frac{\lambda_i I(0) - \gamma_i \Sigma_{fu} \phi}{\lambda_x - \lambda_i + \sigma_x \phi} \right] e^{-(\lambda_x + \sigma_x \phi)\tau} \ . \qquad \ldots(7)$$

After obtaining values for the parameters, the average xenon concentration in fuel and the reactivity which it absorbed were determined as functions of time by approximating the power history with a series of steps.

The values of the yields and disintegration constants given by Glasstone and Edlund were used, viz

$$\gamma_i = 0.056 \qquad \lambda_i = 2.9 \cdot 10^{-5} \, sec^{-1}$$

$$\gamma_x = 0.003 \qquad \lambda_x = 2.1 \cdot 10^{-5} \, sec^{-1} \ .$$

Average values of the cross sections Σ_{fu} and σ_x for Maxwellian energy distributions were calculated as functions of the moderator temperature using the data presented by Hughes and Harvey.[3] Fillmore[4] uses 190°C at zero power and 425°C at full power for the average moderator temperature under normal operating conditions. Assuming a linear relationship between power and temperature, the cross sections were expressed as functions of power; thus,

$$\Sigma_{fu} = \left(0.5150 - 0.00505 \frac{P}{Mw}\right) cm^{-1}$$

and

$$\sigma_x = \left(250.5 - 2.325 \frac{P}{Mw}\right) 10^{-20}\ cm^2 .$$

From the sensible energy of fission and Σ_{fu}, the average flux in the fuel can be expressed as

$$\phi = \left(0.0575 \frac{P}{Mw} + 3.925\right) \frac{10^{11} P}{Mw \cdot cm \cdot sec} ,$$

where the fast effect has been neglected.

The iodine and xenon concentrations were calculated for equilibrium at 20 Mw by setting Equations 4 and 5 equal to zero. These were the concentrations at midnight of September 25, 1958. Using them for $I(0)$ and $X(0)$ in Equations 6 and 7, the concentrations were calculated at the end of the first 4-hr power step in Figure 3. The values obtained were substituted in Equations 6 and 7 as $I(0)$ and $X(0)$ in order to obtain the concentrations at the end of the next step. This procedure was continued until the xenon concentration was known at the end of each 4-hr interval from three days before until seven days after shutdown.

Glasstone and Edlund conclude that the effect of xenon on the parameters which determine k_{eff} is negligible except for the thermal utilization, hence

the reactivity absorbed by xenon is proportional only to the thermal utilization. Therefore,

$$\rho_x = \frac{f - f'}{f'} \quad , \qquad \ldots(8)$$

where the unprimed symbol is for the clean reactor. For a homogeneous reactor, they demonstrate that

$$\rho_x = \frac{f \sigma_x X}{\Sigma_{au}} . \qquad \ldots(9)$$

This is also applicable to a heterogeneous reactor. By definition,

$$f = \frac{\int_u \Sigma_{au} \phi \, dV}{\int_u \Sigma_{au} \phi \, dV + \int_g \Sigma_{ag} \phi \, dV}$$

and

$$f' = \frac{\int_u \Sigma_{au} \phi \, dV}{\int_u (\Sigma_{au} + \sigma_x X) \phi \, dV + \int_g \Sigma_{ag} \phi \, dV} \quad ;$$

these are applicable to either reactor. Substituting these expressions in Equation 8 also yields Equation 9.

The parameters in Equation 9 must be obtained. The same procedure as for Σ_{au} and σ_x gives

$$\Sigma_{au} = \left[0.0850 \left(\frac{P}{Mw} \right)^2 - 8.65 \left(\frac{P}{Mw} \right) + 695.0 \right] 10^{-3} \ cm^{-1} \ .$$

Fillmore[4] calculated the thermal utilization at zero and full power, using a two-region, two-group model. From a linear interpolation of his results, the expression for the thermal utilization is

$$f = 0.8140 + 0.001315\ P/Mw\ .$$

After the power had been reduced to zero, the coolant and moderator temperatures were allowed to drift below 190°C. For this condition, the following values of the parameters were applied in Equation 9:

$$\sigma_x = \left(3.008 - 0.00132\ \frac{T}{^\circ F}\right) 10^{-18}\ cm^2$$

$$\Sigma_{au} = \left(0.8591 - 0.000442\ \frac{T}{^\circ F}\right) cm^{-1}$$

$$f = 0.814\ .$$

Equation 9 is plotted in Figure 1 as a function of time for comparison with the measured transient.

IV. OTHER TRANSIENTS

Because of the agreement between the measured and calculated transients as demonstrated in Figure 1, transients resulting from various step changes in power were calculated and are displayed in Figure 2. These curves permit the estimation of the effect of xenon in the SRE for relatively constant power operation after a change in power. For a variable power history, the calculation can be performed, as in Section III and to the exactness required, by making the steps in power as narrow as necessary.

V. CONCLUSIONS

The reactivity absorbed by xenon in a heterogeneous reactor can be calculated from

$$\rho_x = \frac{f\Sigma_x}{\Sigma_{af}} .$$

For the SRE, the agreement between theory and experiment is within 0.14% δk/k for a transient with a 1.81%δk/k peak. The excess reactivity required for xenon override, after scram from nominal full power, is 2.0%δk/k. Figure 5 shows that the minimum waiting time after shutdown, before measuring the reactivity worth of reactor components to an accuracy better than 0.001%δk/k, is four days.

VI. NOMENCLATURE

Variables and constants:

C = Excess reactivity of the core when $P = O$, $T = T'$ and $\rho_x = O$

f = Thermal utilization

I = I^{135} concentration

P = Power

T = Inlet coolant temperature at power or average coolant temperature at zero power

V = Volume

X = Xe^{135} concentration

γ = Fission yield

λ = Disintegration constant

$\rho_e(\tau)$ = Excess reactivity of the core at τ

$\rho_x(\tau)$ = Reactivity absorbed by xenon at τ

σ = Microscopic cross section

Σ = Macrosopic cross section

τ = Time

ϕ = Thermal flux

Coefficients:

$\frac{d\rho}{dP}$ = Power coefficient of reactivity

$\frac{d\rho}{dT}$ = Isothermal temperature coefficient of reactivity for the reactor core

Subscripts:

au = Absorption in fuel

e = Excess

u = Fuel

fu = Fission in fuel

i = I^{135}

g = Moderator

x = Xe^{135}

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1. R. W. Campbell, "Low Power Physics Experiments on the Sodium Reactor Experiment" NAA-SR-3341 (1959)

2. S. Glasstone and M. C. Edlund, The Elements of Nuclear Reactor Theory, (New York: D. Van Nostrand Company, Inc., 1952)

3. D. J. Hughes and J. A. Harvey, Neutron Cross Sections, BNL-325 (1955)

4. F. L. Fillmore, "Two-Group Calculations of the Critical Core Size of the SRE Reactor" NAA-SR-1517 (Rev) (1959)


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