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ABSTRACT

The xenon-135 and samarium-149 transients due to rapid power cutbacks and the effects of these transients on reactivity are studied and presented in a general manner, so as to be applicable to both the Converter and PuP Reactors.

I. GENERAL

Xenon and samarium are important and demand design consideration because of their large absorption cross-sections for thermal neutrons. The poison problem is accentuated when the reactor suffers a sudden power cutback to some fraction of operating level or to zero power (scram) since xenon and samarium continue to be formed from fission product decay but are "burned out" at a slower rate. This results in the poison building up to a maximum before it ultimately decays. It is possible for such a poison buildup to make the reactor inoperative for a period of time if the reactivity available is insufficient to override the poison.

Xenon and samarium are formed in the following manner:

$$Te^{135} \xrightarrow{2\ \text{min}} I^{135} \xrightarrow{6.7\ \text{hours}} Xe^{135} \xrightarrow{9.2\ \text{hours}} Cs^{135}$$

$$Nd^{149} \xrightarrow{1.7\ \text{hours}} Pm^{149} \xrightarrow{47\ \text{hours}} Sm^{149}$$

II. XENON BUILDUP

A. Iodine Concentration

Assuming that iodine-135 is produced directly by the fission process in the fractional yield A, then the rate of increase of I^{135} nuclei with time is

$$\frac{dI}{dt} = A\Sigma_f\phi - \lambda_1 I - \phi I\,\sigma_{a_1}$$

where λ_1 is the decay constant for iodine-135 and ϕ is the flux. Since σ_a for I^{135} is approximately equal to 7 barns and the discussion which follows considers fluxes of 10^{15} or less, the term $\phi I\sigma_{a_1}$ may be neglected in comparison with $\lambda_1 I$, ($\lambda_1 = 2.9 \times 10^{-5}$ sec^{-1}). The above equation then becomes

$$\frac{dI}{dt} = A\Sigma_f\phi - \lambda_1 I \qquad (1)$$

In general, ϕ is a function of time, but for purposes of this analysis ϕ is held constant at ϕ_0 until power cutback, at which time ϕ drops to ϕ_1, a fraction of steady operating level, ϕ_0.

B. Xenon Concentration

Xenon is formed by the decay of iodine-135 at a rate $\lambda_1 I$ and is destroyed by neutron capture and radioactive decay, such that the rate of change of Xe with respect to time is

$$\frac{dXe}{dt} = \lambda_1 I - \lambda_2 Xe - \sigma_{a_1}\,Xe\phi_1 \qquad (2)$$

where λ_2 is the decay constant for $Xe^{135} = 2.1 \times 10^{-5}$ sec^{-1} and σ_{a_2} is the thermal neutron absorption cross-section for $Xe^{135} = 2.6 \times 10^{-18}$.

C. Solution of Eqs. (1) and (2)

The assumption is made that the reactor has been running for a long enough time, such that equilibrium iodine and xenon concentrations have been attained. That is:

$$I = \frac{A\Sigma_f\phi_0}{\lambda_1}, \text{ from Eq. (1)}$$

$$X = \frac{\lambda_1 I}{\lambda_2 + \sigma_{a_2}\phi_0} = \frac{A\Sigma_f\,\phi_0}{\lambda_2 + \sigma_{a_2}\,\phi_0}, \text{ from Eq. (2)}$$

These amounts of I and Xe are present at time t = 0 when reactor power is suddenly cut back to P_1, and, for all practical purposes, the flux may be considered to drop to ϕ_1.

Eq. (1) may be written

$$\frac{dI}{dt} + \lambda_1 I = A\Sigma_f \phi_1$$

subject to the condition that at

$$t = 0,\ I = \frac{A\Sigma_f \phi_0}{\lambda_1}$$

The solution is

$$I = \frac{A\Sigma_f}{\lambda_1}\left[(\phi_0 - \phi_1)e^{-\lambda_1 t} + \phi_1\right]$$

Eq. (2) may be written

$$\frac{dXe}{dt} + (\lambda_2 + \sigma_{a_2}\ \phi_1)\ Xe = \lambda_1 I = A\Sigma_f\left[(\phi_0 - \phi_1)e^{-\lambda_1 t} + \phi_1\right]$$

The solution is

$$Xe = A\Sigma_f \left\{ \frac{(\phi_0 - \phi_1)}{[(\lambda_2 + \sigma_{a_2}\ \phi_1) - \lambda_1]} (e^{-\lambda_1 t} - e^{-(\lambda_2 + \sigma_{a_2}\phi_1)t}) + \left(\frac{\phi_0}{\lambda_2 + \sigma_{a_2}\phi_0} - \frac{\phi_1}{\lambda_2 + \sigma_{a_2}\phi_1}\right) e^{-(\lambda_2 + \sigma_{a_2}\phi_1)t} + \frac{\phi_1}{(\lambda_2 + \sigma_{a_2}\ \phi_1)} \right\} \quad (3)$$

As will be seen later, it is convenient to write Eq. (3) in the form

$$\frac{\Sigma_a(Xe)}{\Sigma_a U}$$

$$\frac{\Sigma_a\ (Xe)}{\Sigma_a U} = 0.84\sigma_{a_2} A \left\{ \frac{(\phi_0 - \phi_1)}{[(\lambda_2 + \sigma_{a_2}\ \phi_1) - \lambda_1]} (e^{-\lambda_1 t} - e^{-(\lambda_2 + \sigma_{a_2}\phi_1)t}) + \left(\frac{\phi_0}{\lambda_a + \sigma_{a_2}\phi_1} - \frac{\phi_1}{\lambda_2 + \sigma_{a_2}\phi_1}\right) e^{-(\lambda_2 + \sigma_{a_2}\phi_1)t} + \frac{\phi_1}{\lambda_2 + \sigma_{a_2}\phi_1} \right\}$$

where $\Sigma_f U$ has been replaced by $0.84\ \Sigma_a U$.

III. SAMARIUM BUILDUP

A. Promethium Concentration

Since neodymium has a 1.7 hour half-life, the assumption is made that 47 hour promethium is formed directly as a fission product.

$$\frac{dPm}{dt} = B\Sigma_f\phi - \lambda_3 Pm - \phi\ Pm\ \sigma_{a_3} \quad \text{with } B = 0.014$$

As in the discussion of iodine buildup, the absorption cross-section of Pm is small, and hence $\phi Pm\sigma_a$ may be neglected in comparison with $\lambda_3 Pm$

$$\frac{dPm}{dt} = B\Sigma_f\phi - \lambda_3 Pm \tag{4}$$

B. Samarium Concentration

Samarium is formed by the decay of promethium-149 at a rate $\lambda_3 Pm$ and is destroyed by neutron capture, such that the rate of change of Sm with respect to time is

$$\frac{dSm}{dt} = \lambda_3 Pm - \sigma_{a_3}\, Sm\phi \tag{5}$$

where

$\lambda_3 = 4.1 \times 10^{-6}\ \text{sec}^{-1}$

$\sigma_{a_3} = 5.3 \times 10^{-20}\ \text{cm}^2$

C. Solution of Eqs. (4) and (5)

When the same conditions are applied to Eqs. (4) and (5) as were applied to Eqs. (1) and (2), the following results.

$$\text{Equilibrium Pm} = \frac{B\Sigma_f\phi_0}{\lambda_3}$$

$$\text{Equilibrium Sm} = \frac{\lambda_3\ Pm}{\sigma_{a_3}\phi_0} = \frac{B\Sigma_f}{\sigma_{a_3}}$$

The solution of Eq. (4) is

$$Pm = \frac{B\Sigma_f}{\lambda_3}\left[(\phi_0 - \phi_1)\ e^{-3t} + \phi_1\right]$$

The solution of Eq. (5) is

$$Sm = \frac{B\Sigma_f}{\sigma_{a_3}}\left\{\frac{(\phi_0 - \phi_1)\sigma_{a_3}}{(\sigma_{a_3}\phi_1 - \lambda_3)}\left[e^{-\lambda_3 t} - e^{-\sigma_{a_3}\phi_1 t}\right] + 1\right\} \tag{6}$$

Eq. 6 may be rewritten

$$\frac{\Sigma_a(Sm)}{\Sigma_a U} = 0.84B\left\{\frac{(\phi_0-\phi_1)\sigma_{a_3}}{(\sigma_{a_3}\phi_1-\lambda_3)}\left[e^{-\lambda_3 t}-e^{-\sigma_{a_3}\phi_1 t}\right]+1\right\} \quad (7)$$

IV. EFFECT OF POISONS ON MULTIPLICATION

The effective multiplication factor for a bare reactor is given by

$$k_{eff} = k_\infty \frac{e^{-\mathcal{B}^2\tau}}{1+L^2\mathcal{B}^2} = \eta\epsilon\, pf\, \frac{e^{-\mathcal{B}^2\tau}}{1+L^2\mathcal{B}^2}$$

Since there is negligible change in neutron scattering due to the presence of Xe and Sm, the fast neutron leakage will remain constant. The thermal migration area will decrease somewhat, but the thermal non-leakage probability, $1/1+L^2\mathcal{B}^2$, is not very sensitive to changes in L^2 and, for purposes of this analysis, can be considered invariant. Therefore, k_{eff} may be taken proportional to the thermal utilization, f.

If f_1 is the thermal utilization at t = 0, that is with steady state Xe and Sm poisons, and f_2 is the thermal utilization at time t, then

$$\frac{k_{eff_2}-k_{eff_1}}{k_{eff_2}} = \frac{f_2-f_1}{f_2} \equiv \text{reactivity, } \rho, \text{ if at t = 0, the reactor is critical; i.e., } k_{eff_1} = 1$$

$$\rho = \frac{f_2-f_1}{f_2} = 1-\frac{f_1}{f_2} = 1-\frac{\Sigma_a U/(\Sigma_a U+\Sigma_a R+\Sigma_a P_0)}{\Sigma_a U/(\Sigma_a U+\Sigma_a R+\Sigma_a P)} = 1-\frac{\Sigma_a U+\Sigma_a R+\Sigma_a P}{\Sigma_a U+\Sigma_a R+\Sigma_a P_0}$$

$$\rho = 1-\frac{1+\dfrac{\Sigma_a R}{\Sigma_a U}+\dfrac{\Sigma_a P}{\Sigma_a U}}{\dfrac{\Sigma_a R}{\Sigma_a U}+\dfrac{\Sigma_a P_0}{\Sigma_a U}}$$

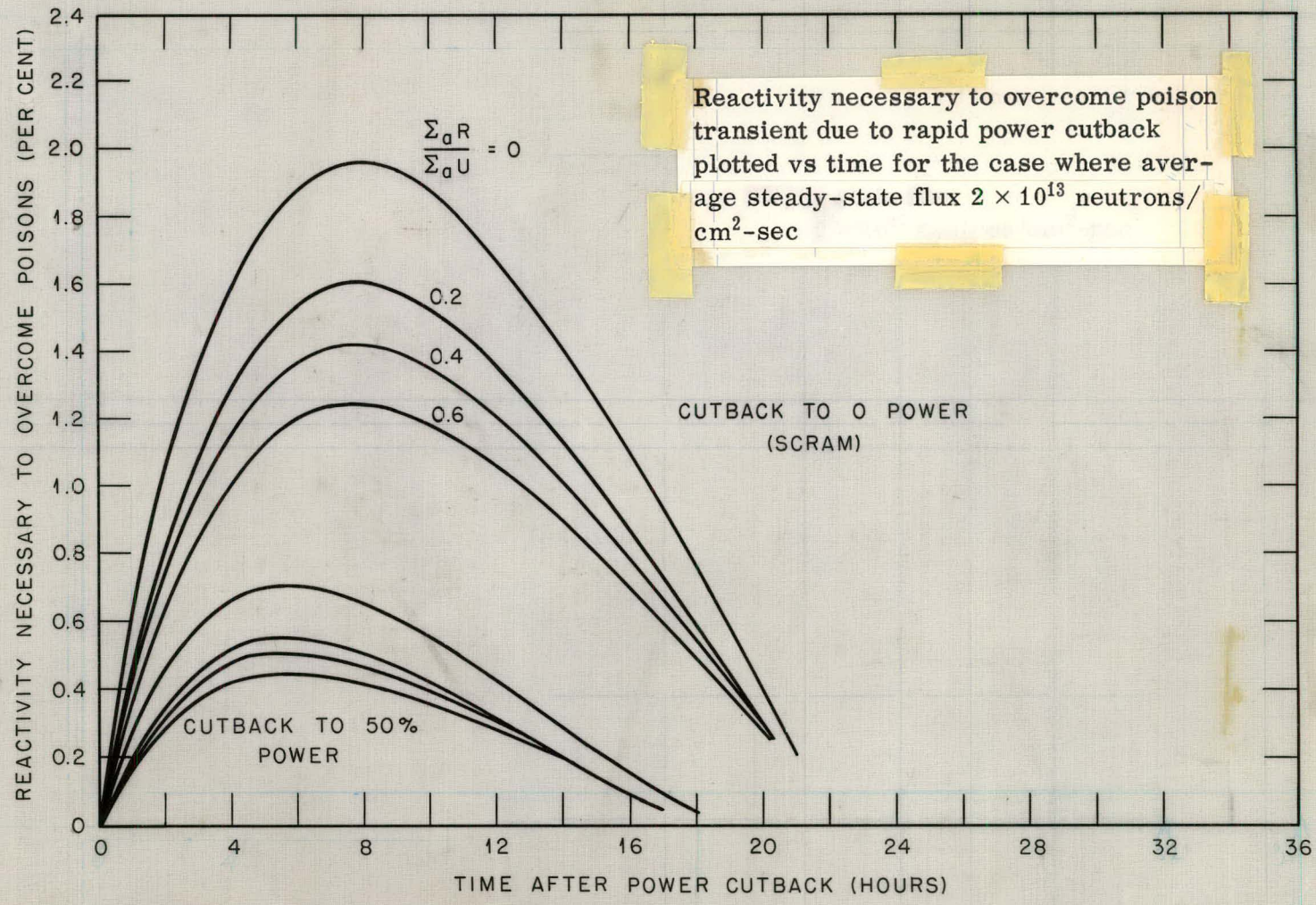
where $\Sigma_a U$ = absorption cross section of the fuel

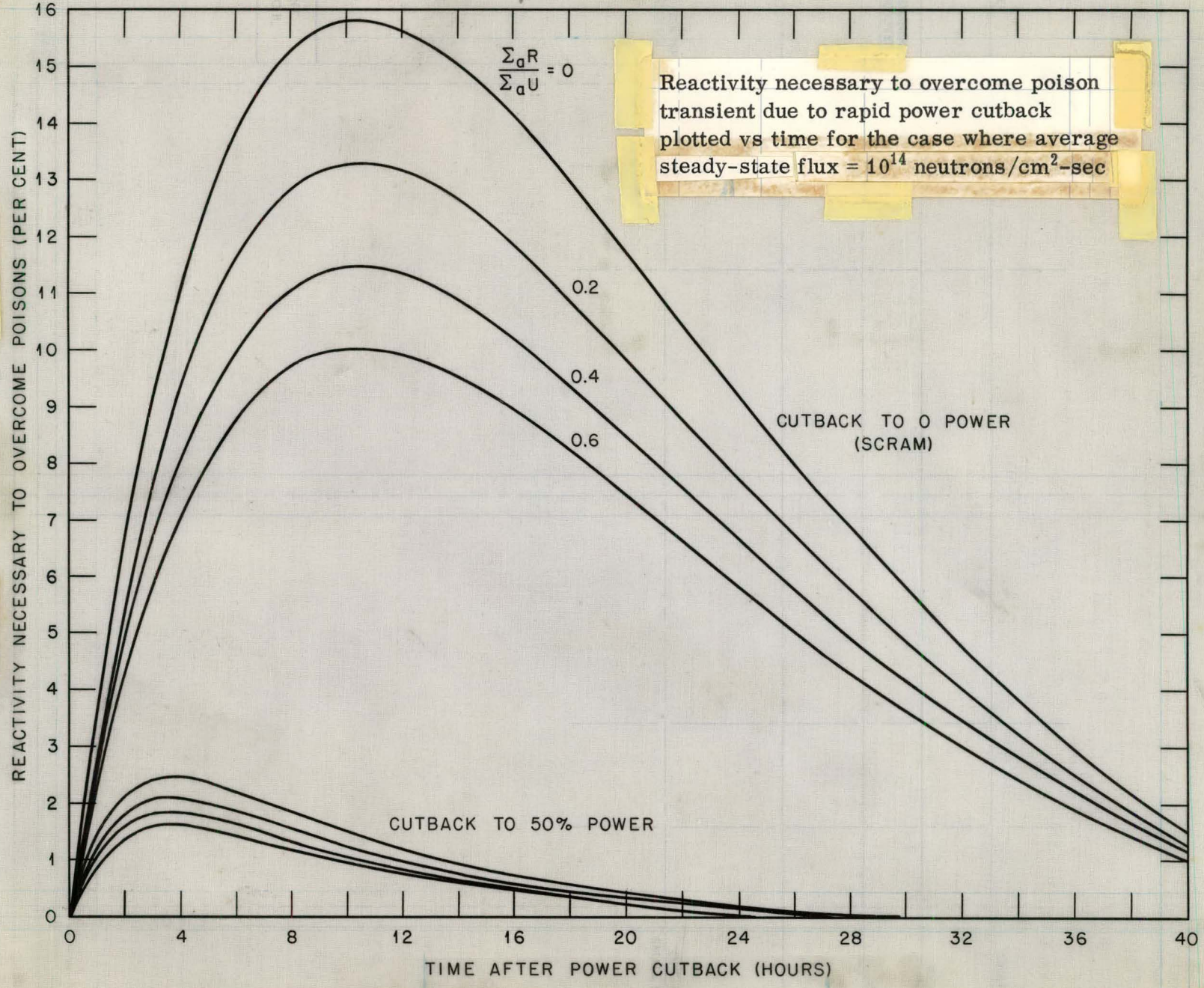
$\Sigma_a R$ = absorption cross section of the moderator and structure

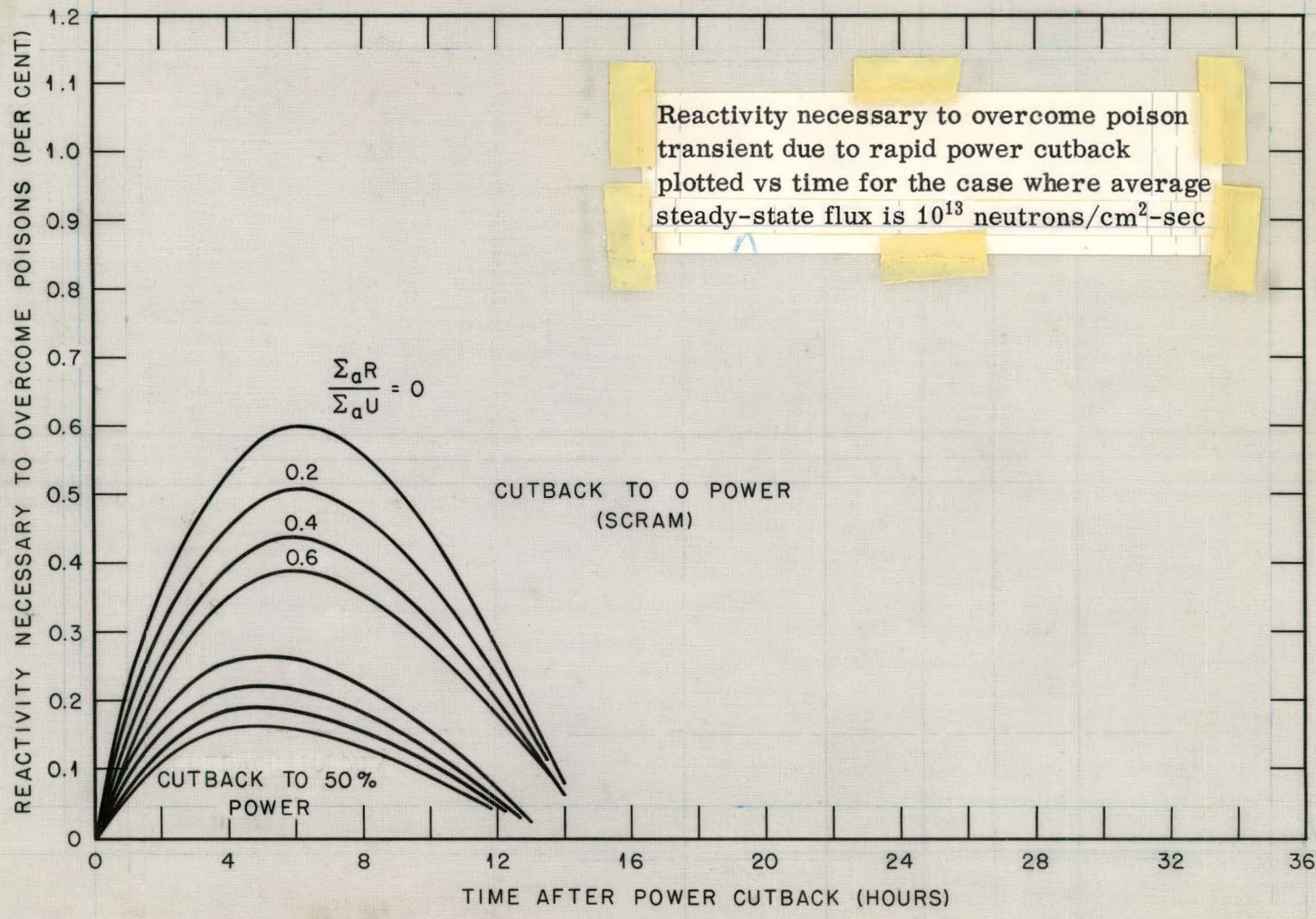
$\Sigma_a P_0$ = absorption cross section of the equilibrium poison

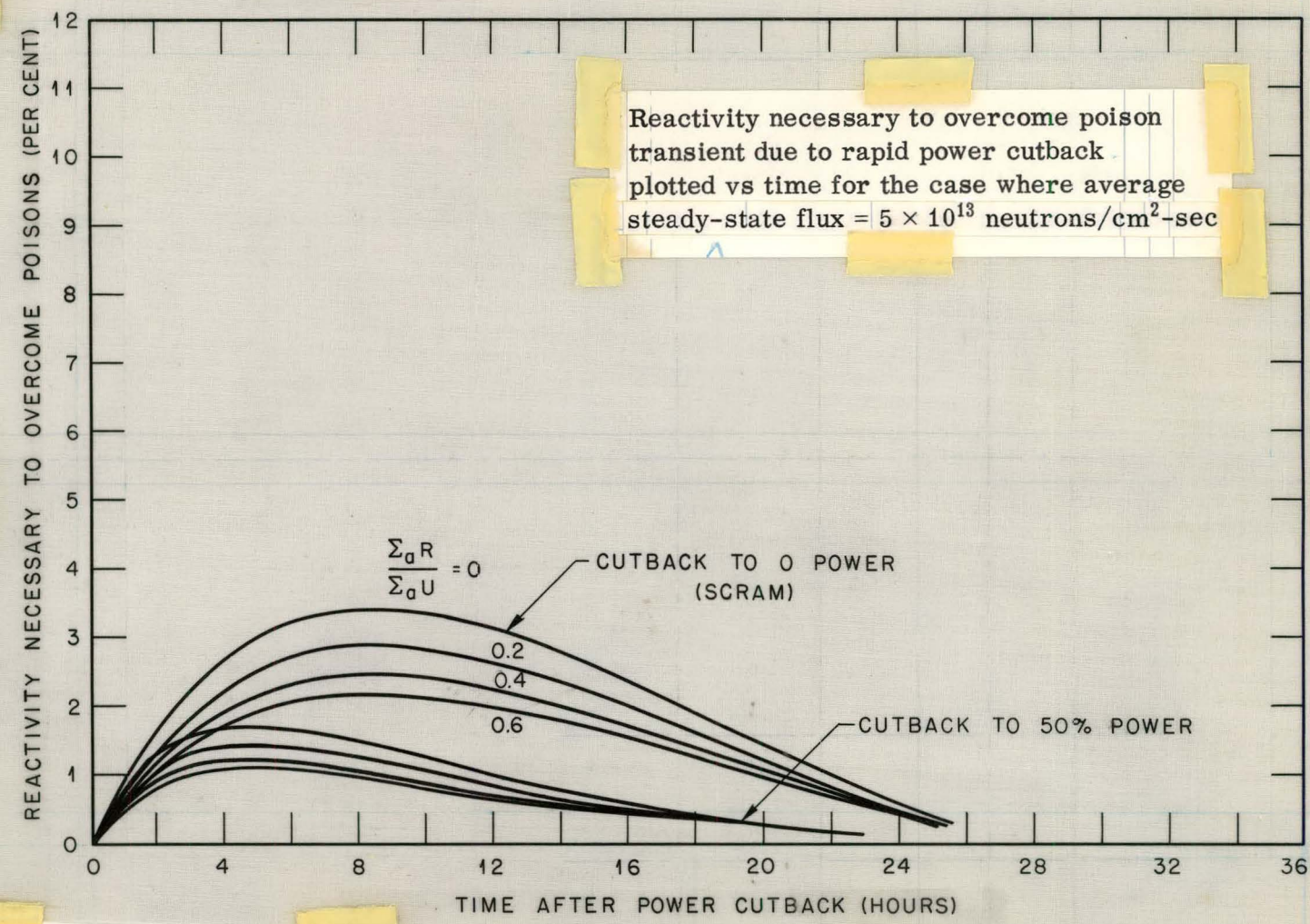
$\Sigma_a P$ = absorption cross section of the poison at time t

In the plotting of ρ vs t, the parameters ϕ_0 and $\Sigma_a R/\Sigma_a U$ are varied over the range of interest in the Converter and PuP Reactors. $\Sigma_a R/\Sigma_a U$ is allowed to take on the values, 0, 0.2, 0.4 and 0.6, and ϕ_1/ϕ_0 is permitted to assume the values 0 and 0.5.


Reactivity necessary to overcome poison transient due to rapid power cutback plotted vs time for the case where average steady-state flux 2 × 10^13 neutrons/cm^2-sec
REACTIVITY NECESSARY TO OVERCOME POISONS (PER CENT)
TIME AFTER POWER CUTBACK (HOURS)
ΣaR/ΣaU = 0
0.2
0.4
0.6
CUTBACK TO 0 POWER (SCRAM)
CUTBACK TO 50% POWER
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
0
4
8
12
16
20
24
28
32
36




Reactivity necessary to overcome poison transient due to rapid power cutback plotted vs time for the case where average steady-state flux is 10^{13} neutrons/cm^2-sec
REACTIVITY NECESSARY TO OVERCOME POISONS (PER CENT)
TIME AFTER POWER CUTBACK (HOURS)
$\frac{\Sigma_a R}{\Sigma_a U} = 0$
0.2
0.4
0.6
CUTBACK TO 0 POWER (SCRAM)
CUTBACK TO 50% POWER
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
0
4
8
12
16
20
24
28
32
36


Reactivity necessary to overcome poison transient due to rapid power cutback plotted vs time for the case where average steady-state flux = 5 × 10^13 neutrons/cm^2-sec
REACTIVITY NECESSARY TO OVERCOME POISONS (PER CENT)
TIME AFTER POWER CUTBACK (HOURS)
ΣaR/ΣaU = 0
CUTBACK TO 0 POWER (SCRAM)
0.2
0.4
0.6
CUTBACK TO 50% POWER
0
1
2
3
4
5
6
7
8
9
10
11
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0
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