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EFFECT OF XENON-135 RETENTION UPON HOMOGENEOUS REACTOR BEHAVIOR

Abstract

If aqueous homogeneous reactors are operated with complete recombination of the decomposition gases and no letdown of the high-pressure system, there will be complete retention of the fission fragment and product gases within the reactor system. Under such conditions, partial or total reactor shutdown would lead to an increase in Xe-135 concentration, which may lead to difficulties in maintaining criticality during either the shutdown period or upon returning the reactor to full power. To investigate the effects of xenon concentration transients, calculations were performed for the case of a 4-ft diameter spherical reactor operating at 280°C, containing U-235, heavy water, I-135, and Xe-135, and at initial fluxes of 10^{13} - 10^{15} neutrons/cm²-sec.* The reactor power was reduced to fractions of either 0 or 0.1 of the initial value, and when the xenon concentration had reached a maximum, the reactor power was increased to its original value. The results obtained show that rates of concentration change, temperature rise, and reactivity addition which may be associated with the build-up or burn-out of xenon are low enough to allow sufficient time for corrective measures. However, the total change in temperature or fuel concentration which might be required to maintain criticality may be so large that reliance on either control alone would be impractical. For example, if the flux were initially 10^{14} , a 35% increase in fuel concentration would be needed to keep the reactor critical at the original temperature up to the peak xenon concentration. So large an inventory of extra fuel is clearly undesirable from the standpoints of both economics and safety. Similarly, large temperature changes would

* All fluxes mentioned in this report are average values based on the entire system volume and not on the core alone.

result if the concentration were kept constant. A combination of temperature and concentration control, or removal of xenon by continuous let-down of fuel solution or gas sparging would appear to be necessary; the exact approach to be used would have to be determined in conformance with individual conditions. In using gas sparging some care would be needed to avoid sudden large reactivity additions, although it appears that fairly rapid xenon removal by this means is generally possible with safety.

If decomposition gases were allowed to form, the effects of xenon concentration changes would be reduced to negligible levels.

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ANALYSIS

The questions to be examined are the following:

1. If a homogeneous reactor is shut-down partially or totally how much difficulty in maintaining criticality is presented by the subsequent xenon build-up?
2. If, after such a shut-down, the reactor is made to deliver power at the original rate, does the rapid burn-out of xenon lead to large rates of reactivity addition?
3. What are the consequences of sudden xenon removal by sparging or other means?

These questions were studied by examining a few extreme conditions, as it is not possible to investigate all possible variations which might be experienced.

1. Maintaining Criticality after Partial or Total Shutdown.

An extreme situation examined was the case of no xenon removal either before or after partial shutdown. Here, the reactor is operating at equilibrium at some high-power level, and the power level is suddenly reduced. The xenon concentration will increase to a maximum due to reduced burn-out. How rapidly must the critical concentration be altered to maintain criticality at the same average reactor temperature? Consider a bare thermal reactor of buckling B^2 .

Assume that throughout the xenon transient the reactor is just critical. (Momentary surges due to the reduction in power will be damped out

rapidly and will not have any particular effect upon the xenon level.)
 Since (neglecting resonance capture and changes in τ and D_2 due to changes in fuel concentration)

$$1 = \frac{\eta \Sigma_a(25)}{(1 + \tau B^2) (\Sigma_a(25) + \Sigma + \Sigma(Xe) + D_2 B^2)} \quad (1)$$

then at all times

$$\frac{d \Sigma_a(25)}{dt} = \frac{(1 + \tau B^2)}{\eta - (1 + \tau B^2)} \frac{d \Sigma(Xe)}{dt} \quad (2)$$

After a reduction in power, the largest value of $\frac{d N_{Xe}}{dt}$ will be less than $\lambda(I) N(I)_0$ where the zero subscript refers to the concentration of iodine at the time of power reduction. The iodine concentration is

$$[N(I)]_0 = \frac{\Sigma_f \bar{\phi} y(I)}{\lambda(I)} \quad (3)$$

(where $\bar{\phi}$ is the average flux over the entire system volume)

so that

$$\frac{1}{\Sigma_a(25)} \frac{d \Sigma_a(25)}{dt} = \frac{1}{N(25)} \frac{d N(25)}{dt} < \frac{(1 + \tau B^2) \sigma(Xe) \Sigma_f(25) \bar{\phi} y_I}{[\eta - (1 + \tau B^2)] \Sigma_a(25)} \quad (4)$$

The fractional rate of fuel concentration increase will be greater for larger fluxes and smaller reactors. However, approximate numbers for B^2 and $\bar{\phi}$ show that this rate is quite small:

$$\tau B^2 \sim 0.5 \text{ (for a spherical reactor around 4 ft-D.)}$$

$$y_I = 0.056$$

$$\frac{\sigma(\text{Xe}) \sigma_f(25)}{\sigma_a(25)} \sim 3 \times 10^{-18} \text{ cm}^2$$

$$\bar{\phi} = 10^{15} \text{ neutrons/cm}^2 \text{ - sec (extremely high)}$$

$$\frac{1}{N_{25}} \frac{dN_{25}}{dt} < 0.056 \frac{1.5}{0.5} \times 3 \times 10^{-18} \times 10^{15} = 5 \times 10^{-4} \text{ sec}^{-1}$$

Thus, it is seen that for a small reactor at an extremely high flux, the maximum rate of concentration change to maintain criticality is less than 0.05% per second. (Note that there is no dependence upon Σ for a given initial flux as long as Σ is constant.) A more realistic example is represented by the curves in Fig. 1. There, a reactor 4 ft in diameter containing only heavy water, U-235, and xenon, operating at 200 Mw is shut down to 20 Mw. The total system volume was taken as 11000 liters, corresponding approximately to a 20 kw per liter external system power density and about 200 kw per liter in the core. The average flux in the system was about 7×10^{13} at full power. As Fig. 1 shows, the necessary rate of fuel increase is quite low, which indicates that reasonable opportunity exists for taking corrective measures. However, it is clear that an undesirable large total fuel addition would be required if concentration control were used, and therefore temperature control or sparging, or both, would be necessary also.

2. Reactivity Additions after Return to Original Power.

Returning to original power may be a far more serious matter than maintaining criticality after a partial shutdown. In this case, the

problem is to prevent the reactor from becoming supercritical due to the rapid burnout of the excess xenon. Suppose that the xenon concentration has risen to the point where $\Sigma(\text{Xe}) = \frac{1}{2} \Sigma_a(25)$. At high fluxes, the rate of change of xenon concentration will be approximately.

$$\frac{d N(\text{Xe})}{dt} = -N(\text{Xe}) \sigma_{\text{Xe}} \bar{\phi} = -\frac{1}{2} \Sigma_a(25) \bar{\phi}$$
 initially for the cases we have chosen. Then by equation (2) the largest fractional concentration change rate is

$$\frac{1}{\Sigma_a(25)} \frac{d \Sigma_a(25)}{dt} \sim \frac{1 + \tau_B^2}{\eta - (1 + \tau_B^2)} \frac{\bar{\phi} \sigma(\text{Xe})}{2}$$

Using the same numbers as before we obtain a maximum fractional concentration change rate of $\sim \frac{1}{2} \%$ per second. A rate of this size might indeed be difficult to manage. However, detailed study of more reasonable cases shows no such rapid rates. Calculations were performed for which the original flux had values of 10^{13} , 10^{14} , and 10^{15} , for a 4-ft diameter spherical reactor at 280°C containing U-235, D_2O , and Xenon. The power was reduced to fractions of 0 and 0.1 of the initial value in each case. The xenon was permitted to reach a maximum, at which point the power was returned to the original value. The following information was obtained at the return-to-power point:

$N_m(\text{Xe})$, the maximum xenon concentration

$N_m(25)$, the maximum fuel concentration

$\frac{d k_{\text{eff}}}{dt}$, the rate of change of the multiplication constant
if the fuel concentration were left unchanged.

$\frac{1}{N(25)} \frac{dN(25)}{dt}$, the necessary fractional rate of fuel concentration change to maintain criticality.

$\frac{dk_{eff}}{dT}$, the temperature coefficient of the multiplication constant

ΔT_{max} , an estimate of the maximum temperature rise which might occur if the fuel concentration were kept constant and the xenon were burned out.

Δk_{eff} , the excess reactivity present if the xenon were suddenly decreased to the minimum level which would be reached after returning to power.

$\frac{dT}{dt}$, the time rate of change of temperature to maintain criticality at constant fuel concentration.

t_{min} , an estimate of the time required to reach a minimum xenon concentration at constant temperature and power following return to power.

The following analysis was performed to determine the desired quantities:

To determine xenon concentrations, the differential equations

$$\frac{dN(I)}{dt} = y(I) \frac{KP}{V_s} - \lambda(I)N(I) \quad (5)$$

$$\frac{dN(Xe)}{dt} = \lambda(I)N(I) + y(Xe) \frac{KP}{V_s} - (\lambda(Xe) + \sigma(Xe) \bar{\phi}) N(Xe) \quad (6)$$

were solved subject to the boundary conditions

$$N(I)_0 = \frac{y(I)KP(0)}{V_s \lambda(I)} \quad (7)$$

$$\text{and } N(Xe)_0 = \frac{y(I) + y(Xe)}{\lambda(Xe) + \sigma(Xe) \bar{\phi}(0)} \frac{KP(0)}{V_s} \quad (8)$$

where the subscript 0 indicates an initial concentration. Where a purely analytical solution was employed, constant power and constant flux were assumed. If $\sigma(Xe) \bar{\phi}$ is less than $\lambda(Xe)$, the constant flux assumption is quite accurate. In those cases where $\sigma(Xe) \bar{\phi}$ was greater than $\lambda(Xe)$, the solution was broken up into time intervals of one hour during which the flux was taken constant at the value at the start of that interval. Since such a procedure is rather lengthy, and high accuracy was not essential for the purposes of this report, finite interval calculations were used only where necessary to avoid a large error.

The solutions to (5) and (6) assuming constant flux are

$$\begin{aligned} N(Xe) = & e^{-\lambda(I)t} \left[\frac{N(I)_0 \lambda(I)}{k - \lambda(I)} + \frac{KPy(I)}{V_s (\lambda(I) - k)} \right] \\ & + e^{-kt} \left[\frac{\lambda(I) N(I)_0}{\lambda(I) - k} + \frac{\lambda(I) KPy(I)}{V_s k [k - \lambda(I)]} + N(Xe)_0 - \frac{y(Xe) KP}{V_s k} \right] \\ & + \frac{KP}{V_s k} [y(I) + y(Xe)] \end{aligned} \quad (9)$$

where $k = \lambda(Xe) + \sigma(Xe) \bar{\phi}$

$$N(I) = \left[N(I)_0 - \frac{KP y(I)}{V_s \lambda(I)} \right] e^{-\lambda(I)t} + \frac{KP y(I)}{V_s \lambda(I)} \quad (10)$$

Note that the iodine concentration expression is correct for constant power and is independent of flux variations. The maximum xenon concentration was found either by differentiating (9) and equating the derivative to zero, or numerically where the finite difference method was used.

The concentration of fuel required was found from the two-group critical equation for a bare reactor:

$$N(25) = \frac{(1 + \tau B^2) (\Sigma + \Sigma(Xe) + D_2 B^2)}{\sigma_a(25) (\eta - (1 + \tau B^2))} \quad (11)$$

The necessary rate of change of fuel concentration to achieve criticality is

$$\frac{dN(25)}{dt} = \frac{\sigma(Xe) (1 + \tau B^2) \frac{dN(Xe)}{dt}}{\sigma_a(25) [\eta - (1 + \tau B^2)]} \quad (12)$$

The derivative, $dN(Xe)/dt$, is obtained by differentiating equation (9), and the fractional rate of change of concentration is calculated by dividing (12) by $N(25)$.

To find $d k_{eff}/dt$ for constant $N(25)$, equation (1) is differentiated, noting that the reactor is just critical at the point where the derivative is taken:

$$\begin{aligned} \frac{d k_{eff}}{dt} &= - \frac{\eta \Sigma_a(25) \frac{d \Sigma(Xe)}{dt}}{(1 + \tau B^2) (\Sigma_a(25) + \Sigma + \Sigma(Xe) + D_2 B^2)^2} \\ &= - \frac{1}{\Sigma_a(25) + \Sigma + \Sigma(Xe) + D_2 B^2} \frac{d \Sigma(Xe)}{dt} \\ \frac{d k_{eff}}{dt} &= - \frac{(1 + \tau B^2) \sigma(Xe)}{\eta \Sigma_a(25)} \frac{dN(Xe)}{dt} \quad (13) \end{aligned}$$

The temperature coefficient at the point of maximum xenon concentration was determined by calculating k_{eff} at 285°C under the assumption that the ratio of fuel and xenon concentrations to water concentration was constant, so that

$$\frac{dk_{eff}}{dT} = \frac{k_{eff}(285^{\circ}) - 1}{5} \text{ } ^{\circ}\text{C}^{-1} \quad (14)$$

The temperature rise which might occur if the reactor were allowed to burn out the xenon without changing uranium concentration was also estimated. After returning the reactor to full power the xenon concentration will decline to a minimum value and then increase asymptotically to the original equilibrium value. This minimum xenon concentration was estimated by differentiation of equation (9), and the increase in k_{eff} using this xenon concentration and the maximum fuel concentration was computed. (For high fluxes, the xenon concentration so calculated is too high; in such cases the xenon was neglected with little error because even the overestimated value is still too small to seriously affect Δk_{eff} .) Dividing Δk_{eff} by the temperature coefficient of reactivity obtained by equation (14) gave a rough estimate of the size of the temperature rise which might be experienced.

To obtain the maximum rate of temperature increase, dk_{eff}/dt was divided by the temperature coefficient:

$$\frac{dT}{dt} = - \frac{dk_{eff}/dt}{dk_{eff}/dT} \quad (15)$$

Table I summarizes the results which have been obtained. Note that for a given reactor size, the maximum xenon concentration achieved after shutdown is larger for larger initial fluxes. Usually, the value

TABLE I

Effects of Xenon Concentration Variation on Reactor Characteristics Following
Return to Power from a Partial or Total Shutdown. Xenon Concentration
at Maximum Upon Return to Power

Reactor Diameter ft.	ϕ_0	$\frac{P}{P_0}$	N_{Xe} Atoms per cubic cm	$N_{\text{Xe}}(25)$ Atoms per barn-cm	$\frac{dk_{\text{eff}}}{dt}$ sec. ⁻¹	$\frac{-1}{N_{\text{Xe}}(25)} \frac{dN_{\text{Xe}}(25)}{dt}$ sec. ⁻¹	$\frac{-dk_{\text{eff}}}{dT}$ °C. ⁻¹	ΔT_{max} °C. (Approx.)	Δk_{eff} °C.	$\frac{dT}{dt}$ °C/sec	t_{min} hrs. (Approx.)
4	10^{13}	0.1	1.34×10^{14}	2.72×10^{-5}	6.48×10^{-7}	2.66×10^{-6}	3.69×10^{-3}	2	7.5×10^{-3}	1.75×10^{-4}	10
4	10^{13}	0	1.38×10^{14}	2.73×10^{-5}	7.38×10^{-7}	3.03×10^{-6}	3.69×10^{-3}	2	8.6×10^{-3}	2.00×10^{-4}	10
4	10^{14}	0.1	6.15×10^{14}	3.77×10^{-5}	1.66×10^{-5}	6.84×10^{-5}	3.36×10^{-3}	20	6.6×10^{-2}	4.95×10^{-3}	5
4	10^{14}	0	9.28×10^{14}	4.46×10^{-5}	2.08×10^{-5}	8.54×10^{-5}	3.22×10^{-3}	30	1.0×10^{-1}	6.46×10^{-3}	5
4	10^{15}	0.1	1.46×10^{15}	5.63×10^{-5}	1.68×10^{-4}	6.87×10^{-4}	3.07×10^{-3}	40	1.2×10^{-1}	5.46×10^{-2}	1
4	10^{15}	0	8.63×10^{15}	2.14×10^{-4}	8.61×10^{-5}	3.53×10^{-4}	2.64×10^{-3}	> 50	2.7×10^{-1}	3.27×10^{-2}	3
∞	10^{15}	0	3.06×10^{13}	2.98×10^{-7}	3.57×10^{-4}	6.88×10^{-4}	1.08×10^{-3}	> 50	5.1×10^{-1}	3.31×10^{-1}	2

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of dk_{eff}/dt when power is restored will also increase with increasing flux. However, since it is the initial power which was restored and not the initial flux, the flux at the point of restoration of power may be depressed enough to show a smaller value of dk_{eff}/dt . Indication of this is given in the 10^{15} flux case for a 4-ft reactor, where the reduction to 0.1 of the original power shows a higher dk_{eff}/dt than for reduction to zero power.

For a given flux, larger reactors will have a smaller maximum concentration of xenon after shutdown than smaller reactors, since this concentration depends upon the original power density (i.e., the original equilibrium iodine concentration). Since, for high fluxes, at the return to power point:

$$\frac{dN(Xe)}{dt} \sim -\Sigma(Xe) \phi \quad (16)$$

it follows from equation (13) that

$$\frac{dk_{eff}}{dt} = + \frac{(1 + \gamma_B^2) \sigma(Xe)}{\eta \Sigma_a(25)} \Sigma(Xe) \phi \quad (17)$$

If we make the further approximation that $\Sigma(Xe)$ is proportional to the original power; i.e., to $[\Sigma_a(25)]_0 \phi_0$ then we have

$$\frac{dk_{eff}}{dt} \sim \frac{(1 + \gamma_B^2) [\Sigma_a(25)]_0^2 \phi_0^2}{[\Sigma_a(25)]^2} \quad (18)$$

For a given ϕ_0 , it would appear that dk_{eff}/dt is proportional to the square of the ratio of the initial and final fuel concentrations. Generally speaking, the smaller the reactor, the smaller this ratio will

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be, so that dk_{eff}/dt increases with increasing size. Formula (18) also suggests that for a given B^2 and ϕ_0 , $\frac{dk_{\text{eff}}}{dt}$ should not be strongly temperature dependent except where the fast leakage is high.

Combination of equations (12) and (13) leads to the following proportionality between the time rate of change of multiplication constant and fractional concentration change rate necessary to maintain criticality:

$$\frac{1}{N_{25}} \frac{dN_{25}}{dt} = - \frac{dk_{\text{eff}}}{dt} \left[\frac{\eta}{\eta - (1 + \tau B^2)} \right] \quad (19)$$

For large reactors (low fast leakage) the required concentration change rate would increase in absolute value with size at a given flux. For very small reactors, however, the situation might be reversed since dk_{eff}/dt is not as sensitive to size as $\eta - (1 + \tau B^2)$.

Although the estimates of ΔT_{max} , the temperature to which the reactor might rise if left at the maximum concentration, are large at the higher fluxes, the rates at which reactivity or temperature might rise are rather slow even for the most extreme cases. It must also be remembered that these results refer to reactor systems in which xenon is removed only by neutron absorption and decay. Were a reasonable mode of continuous xenon removal by stripping included in the calculations all the effects would be practically eliminated.

3. Reactivity Effects Produced by Sudden Xenon Removal.

No calculations were made concerning this type of operation, but some observations may be made based on what has been done. Suppose a reactor were partially shut down and no means of gradually increasing the concentration were employed. The reactor would become subcritical due to xenon buildup, and the temperature would fall. If the reactor

temperature fell 10°C , rapid reduction of the xenon concentration to its original level by sparging, or other means, would be equivalent to introducing a Δk_{eff} of about 0.03 over a short-time interval. Thus, only gradual removal of the xenon should be permitted in order to restore the reactor to criticality. Equation (13) may be used to compute the fractional rate of xenon removal corresponding to a certain rate of change of k_{eff} near criticality:

$$\frac{1}{N(\text{Xe})} \frac{dN(\text{Xe})}{dt} = - \frac{\eta \Sigma_a(25)}{(1 + \tau B^2) \Sigma(\text{Xe})} \frac{dk_{\text{eff}}}{dt} \quad (20)$$

If dk_{eff}/dt is not to exceed 0.005 sec.^{-1} , then at typical values of $1 + \tau B^2 = 1.5$ and $\Sigma(\text{Xe})/\Sigma_a(25)$ of 0.2, the xenon concentration would have to be reduced at a rate less than about 3.3% per second. A fairly rapid removal rate such as this suggests that it should usually be safe to remove xenon intermittently without severe restrictions. Each case would have to be judged individually, however.

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CONCLUSIONS

The growth and decay of xenon concentration resulting from power level changes appears to offer no serious problems in reactor operation even if no continuous xenon removal is employed. Changes in reactivity and temperature appear to occur at sufficiently low rates so that the reactor may be kept under control by concentration or temperature adjustments or by intermittent stripping. While no one of these methods may be suitable if used alone, it should be possible to find a simple and adequate combination of approaches.

The equations and results suggest that the effects of xenon upon reactivity have only moderate dependence upon either temperature or the amount of absorbers other than fuel or xenon. As the reactor size increases (i.e., the buckling decreases) the effects for a given initial flux appear to decrease when power is lowered and to increase when the initial power is restored.

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TABLE II

Nuclear Constants

1. Properties of U-235

$$\eta(25) = 2.08$$

$$\sigma_f(25) = 358 \text{ barns } (280^\circ)$$

$$\sigma_a(25) = 424 \text{ barns } (280^\circ); \quad 419 \text{ barns } (285^\circ)$$

2. Properties of Xenon

$$\sigma_a = 3 \times 10^6 \text{ barns (assumed temperature independent)}$$

$$\lambda(\text{Xe}) = 2.09 \times 10^{-5} \text{ secs.}^{-1}$$

$$y(\text{Xe}) = 0.003$$

3. Properties of Iodine

$$\lambda(\text{I}) = 2.87 \times 10^{-5} \text{ secs.}^{-1}$$

$$y(\text{I}) = 0.056$$

4. Slow Diffusion Constant, Age, and Absorption Cross Section of Heavy Water

	$D_2, \text{ cm}$	$\tau, \text{ cm}^2$	$\Sigma_a(\text{D}_2\text{O}), \text{ cm}^{-1}$
280°C	1.23	216	4.44×10^{-5}
285°C	1.25	222	4.37×10^{-5}

B^2	, buckling, cm^{-2}
D_2	, slow diffusion constant, cm.
k	, $\lambda(\text{Xe}) + \sigma(\text{Xe}) \bar{\phi}$
k_{eff}	, effective multiplication constant
Δk_{eff}	, excess multiplication constant
K	, fissions per megawatt-second
$N(\text{I}), N(\text{Xe})$	, concentration of iodine and xenon, atoms/ cm^3
$N(25)$	, concentration of U-235, atoms per barn-centimeter
$N_m(\text{Xe}), N_m(25)$	, maximum concentrations of xenon and U-235, atoms per cm^3 and atoms per barn-cm, respectively.
$N(\text{I})_0, N(\text{Xe})_0$	, initial iodine and xenon concentrations, atoms per cm^3
P	, power, megawatts
$P(0)$	, initial power, megawatts
t	, time, seconds
t_{min}	, time required to reach minimum xenon concentration following a return to original power, hours
T	, temperature, $^{\circ}\text{C}$.
ΔT_{max}	, maximum temperature rise, $^{\circ}\text{C}$.
V_s	, total system volume, cubic centimeters
$y(\text{Xe}), y(\text{I})$	, fission yield of xenon and iodine atoms, atoms per fission
$\Sigma_a(25)$	, macroscopic absorption cross section in U-235, cm^{-1}
Σ	, macroscopic cross section of reactor material other than fuel or xenon, cm^{-1}
$\Sigma(\text{Xe})$	, macroscopic cross section of xenon, cm^{-1}
Σ_f	, macroscopic fission cross section, cm^{-1}

$\sigma(\text{Xe})$, microscopic absorption cross section of xenon, cm^2

$\sigma_f(25), \sigma_a(25)$, microscopic fission and absorption cross sections of
U-235, barns

η , fission neutrons per absorption in fuel

$\lambda(\text{Xe}), \lambda(\text{I})$, decay constants of xenon and iodine, secs^{-1}

$\bar{\phi}$, average neutron flux over entire system volume,
 $\text{neutrons/cm}^2/\text{sec.}$

τ , Fermi Age, cm^2

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Figure 1
Xenon and I-135 Transient for a 4-ft³ Core-Region
200 MW Reactor at 250°C. Original Power
200 MW. Power Reduced to 10 MW at $t = 0$.

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