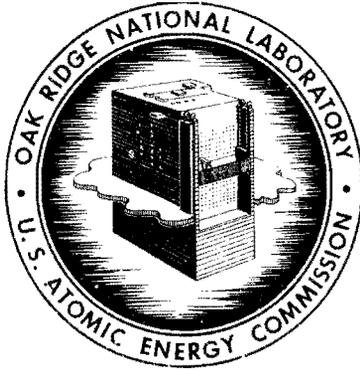


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**MEASUREMENT OF XENON POISONING IN THE HRT**

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**ABSTRACT**

Measurements obtained during three periods of HRT operations indicate that the xenon poison fraction was approximately 0.010. The technique used was based on mass spectrographic analyses of the stable xenon isotopes in the reactor off-gas stream. Models proposed to explain the measurements show that xenon, which is formed primarily by decay of iodine adsorbed on the pipe walls, is held up on the walls, out of the circulating stream, for an average period of about eight hours.

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## 1.0 SUMMARY

The xenon poison fraction in the HRT was measured on three occasions during extended periods of stable operation. The technique used was based on mass spectrographic analyses of the ratio of the stable xenon isotopes, Xe-136/Xe-134, in the reactor off-gas. Two measurements at 5 Mw operation, when approximately 55% of the power was produced in the core, indicated poison fractions of  $0.0096 \pm 0.0014$  and  $0.0120 \pm 0.0020$  at the 95% confidence level. A single measurement at 3.1 Mw with only 36% of the power produced on the core gave a value of  $0.010 \pm 0.0027$ .

Two models were proposed to explain the results in conjunction with other studies of iodine behavior in the reactor. A simplified theory of an adsorption equilibrium between xenon in solution and on pipe walls clearly shows that xenon retention in the high pressure system outside the core flux acted to reduce xenon poisoning. In a more refined model, xenon, which is formed by decay of iodine adsorbed on the walls, is assumed to be retained for some average lifetime until diffusion mechanisms return it to the circulating stream. An analysis of the poison fraction data indicated this average lifetime to be 8 to 12 hours. Uncertainties in the exact behavior of iodine and the dependence of iodine and xenon behavior on reactor power probably account for some unresolved discrepancies in the various methods of analyzing iodine and xenon behavior.

## 2.0 INTRODUCTION

Xenon poisoning is normally measured by noting reactivity changes, either through control rod position or temperature changes, during reactor startup and shutdown transients. In the Homogeneous Reactor Test, which had no control rods, reactivity changes due to xenon transients were reflected as temperature changes of only a few degrees. Since several other system parameters, such as average solution temperature, change during startup and shutdown, temperature variations resulting from xenon buildup and decay were almost completely obscured.

In the original HRT design xenon was removed by gas stripping. Aven showed that poison fractions as low as 0.005 should be easily achieved (1). Prior to operation, decisions to modify the low pressure system to include

an iodine removal trap and to eliminate any gas let-down considerably altered the concept of xenon control. While the iodine trap was installed primarily to prevent poisoning of the platinum recombiner catalyst, it acted to lower xenon concentrations in the high pressure system by removing the precursor, I-135. The gaseous let down was eliminated by adding sufficient  $\text{CuSO}_4$  to the fuel solution for complete recombination of the  $\text{D}_2$  and  $\text{O}_2$  in the high pressure system. This was intended to avoid the problem of fuel instability if oxygen were preferentially stripped from the fuel. Gift (2) estimated that with iodine removal the poison fraction would be 0.006, assuming that (1) the iodine circulated quantitatively with the fuel; (2) it was let down to the dump tank where, (3) it was also stripped quantitatively and retained on the iodine trap.

Extensive studies of the behavior of iodine in the reactor showed conclusively that it was not removed as effectively as predicted (3). Approximately 90% of the iodine in the high pressure system did not circulate with the fuel. However, that which was let down was effectively stripped and retained on the iodine trap. The xenon production in the fuel circuit was thus higher, making concentrations in solution higher and increasing the xenon poison fraction.

After formation of the hole in the core wall, iodine and xenon removal was rendered even less effective by the relatively slow interchange of solution between core and blanket and the long blanket processing cycle time which resulted.

### 3.0 METHOD OF MEASUREMENT

A scheme for measuring the xenon poison fraction was devised based on mass spectrographic analyses of the stable xenon isotopes in the reactor off-gas. Quantitative sampling, i.e., sampling a known volume of gas, related to a known period of time, would have proved quite difficult, but was not necessary since a comparison of the ratio of two stable isotopes,  $\text{Xe-136}/\text{Xe-134}$ , is sufficient to permit the poison fraction calculation. Also, in mass spectrographic analyses, the ratio of two isotopes can be obtained much more precisely than the absolute quantity of either in a given sample.

Neutron capture in Xe-135 results in the production of stable Xe-136. By determining the number of captures in Xe-135 per fission, the poison fraction can be obtained. Xe-134 was used for the ratio comparison since its precursors had much shorter half-lives than the precursors of the other stable xenon isotopes.

Mathematically, the poison fraction may be expressed as:

$$\begin{aligned} \text{Poison fraction} &= \left[ \frac{\text{Xe-136/fission}}{\text{Xe-134/fission}} - \frac{\text{Direct fission yield of Xe-136/fission}}{\text{Xe-134/fission}} \right] \\ &= \left[ \frac{\text{Xe-134}}{\text{fission}} \right] \left[ \frac{\text{U-235 fission}}{\text{U-235 adsorption}} \right] \\ &= \left[ \text{Measured } \frac{\text{Xe-136}}{\text{Xe-134}} - \frac{.0646}{.0806} \right] (.0806) \left[ \frac{582}{683} \right] \\ &= \left[ \frac{\text{Xe-136}}{\text{Xe-134}} - 0.802 \right] (.0806)(0.85) \end{aligned}$$

where the fission yields compiled by Katcoff (4) were used in the calculations. A similar calculation, using another standard reference source for fission yields (5) give poison fractions somewhat lower. While the uncertainty in these fission yields cannot be resolved, the former data are thought to be more accurate (6), and some samples obtained from very low power operation in this study tended to confirm the yields of Katcoff. Calculated poison fractions are plotted in Fig. 1 as a function of the Xe-136/Xe-134 ratio.

#### 4.0 SAMPLING AND ANALYTICAL TECHNIQUE

Samples for xenon poison measurements were obtained during three periods of reactor operation. In all cases, a period of stable operation was specified at constant power for a period of at least two days prior to sampling. In Reactor Run 21, with the reactor at 5.03 Mw, a sample of reactor off-gas was routed to a spare charcoal bed for a period of 50 hours from October 17 to October 19, 1959. This gas was subsequently purged through the bed and samples of the stable xenon isotopes were obtained by equilibrating approximately 20 g of charcoal at 0°C with the exit gas stream in a purge-type sample bomb. The xenon was transferred in a helium atmosphere to an evacuated sample flask after first purging

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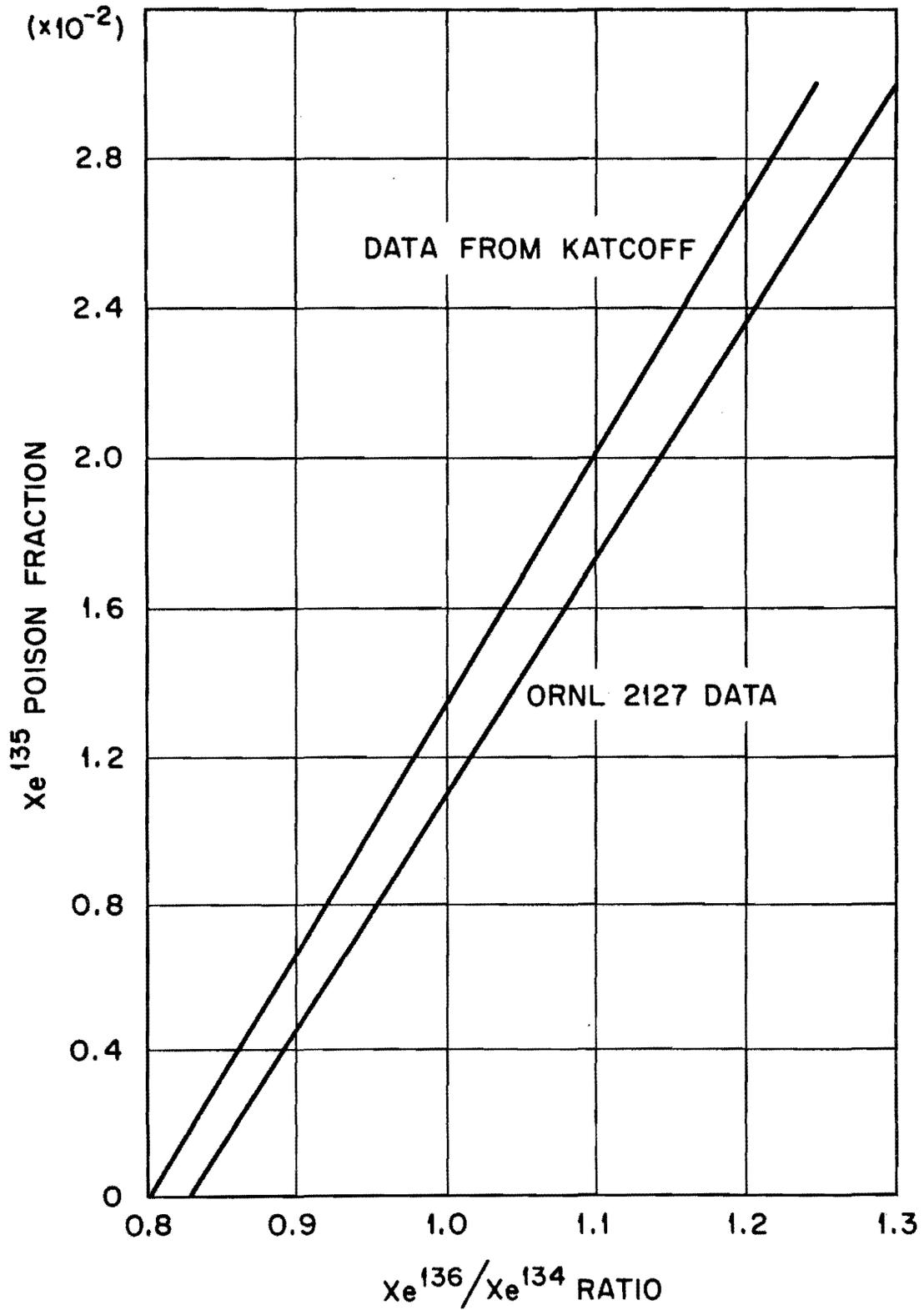


Fig.1. Poison Fraction as a Function of  $Xe^{136}/Xe^{134}$  Ratio.

oxygen from the original sample with helium. Dry ice and Ascarite traps were used to trap moisture and  $\text{CO}_2$ , respectively, from the gas stream during the transfer operations. Samples containing up to 1.6% xenon were thus obtained in a relatively clean helium atmosphere, from which mass spectrographic analyses were readily obtained.

A less time-consuming sampling system was installed in which two additional samples were obtained in the final reactor run (25). The sample consisted of a needle block assembly and appropriate valving to permit transfer of gas from one chemical plant decay tank to the other. The chemical plant vent system was evacuated to less than one-half atmosphere after which reactor off-gas was routed to it until the pressure was approximately one atmosphere. Samples were removed into 10 cc diaphragm top glass bottles filled with charcoal. The quantity of xenon obtained from this sampler was smaller than from the previous system, and required much greater care in subsequent handling steps to ensure samples free from  $\text{CO}_2$  and moisture.

On April 17, 1961, a sample was isolated following a period of operation at 5.09 Mw, from which 6 aliquot samples were withdrawn and analyzed. One week later on April 24, after a considerably altered period of operation which resulted following the loss of the patch from the upper core hole, a third sample was isolated and four aliquots were subsequently analyzed. Power level was 3.10 Mw, 66% of which was produced in the blanket instead of the normal 45-50%.

Initial mass spectrographic analyses revealed that natural xenon was present in the samples up to the extent of 25% of the total xenon in the sample. Since natural xenon contains 10.4% Xe-134 and 8.9% Xe-136, corrections were required to gross ratios. These were made using as a reference Xe-129 which is present to the extent of 26.4% in natural xenon, but which does not have a significant fission yield.

## 5.0 EXPERIMENTAL RESULTS

Results of the mass spectrographic analyses and the calculated poison fractions are listed in Table 5.1 for the three samples obtained. In section 6.0 the poison fraction measurements are compared with calculated

results based on independent information about the behavior of iodine and xenon in the HRT.

Table 5.1

Sample No. 1 - Isolated October 19, 1959

Reactor Power Level 5.03 Mw;  $P_c/P_t = 0.53$

<u>HRT Aliquot No.</u>	<u>CPM-21-85</u>	<u>CPM-21-77</u>	<u>CPM-21-83</u>	<u>CPM-21-89</u>	<u>CPM-21-90</u>	<u>CPM-21-97</u>
Xe-136	100	100	100	100	100	100
Xe-134	106	107	106.9	106.2	105.1	107.8
Xe-129	30	15.2	12.9	5.76	5.83	18.9
Fission Product <u>Xe-136</u> <u>Xe-134</u>	0.954	0.939	0.940	0.953	0.943	0.934

Calculated poison fraction at 95% confidence level =  $0.0096 \pm 0.0014$

Sample No. 2 - Isolated April 17, 1961

Reactor Power Level 5.09 Mw;  $P_c/P_t = 0.56$

<u>HRT Aliquot No.</u>	<u>RM-25-451</u>	<u>RM-25-454</u>	<u>RM-25-465</u>	<u>RM-25-473</u>	<u>RM-25-474</u>	<u>RM-25-475</u>
Xe-136	98	98	98	96.4	98.5	99.1
Xe-134	100	100	100	100	100	100
Fission Product <u>Xe-136</u> <u>Xe-134</u>	0.98	0.98	0.98	0.964	0.985	0.991

Calculated poison fraction =  $0.0120 \pm 0.0019$

Sample No. 3 - Isolated April 24, 1961

Reactor Power Level 3.10 Mw;  $P_c/P_t = 0.36$

<u>HRT Aliquot No.</u>	<u>RM-25-436</u>	<u>RM-25-438</u>	<u>RM-25-447</u>	<u>RM-25-448</u>
Xe-136	100	100	94	97
Xe-134	107	105	100	100
Xe-129	~2			
Fission Product <u>Xe-136</u> <u>Xe-134</u>	0.935	0.953	0.94	0.97

Calculated poison fraction =  $0.010 \pm 0.0027$

The quantity of xenon isolated in the last two samples was approximately a factor of 10 less than in the first sample, making the mass spectrographic analyses somewhat less precise. This is reflected by more scatter in the data and a somewhat larger uncertainty in the poison fraction calculations. However, the natural xenon content of the final two samples was also very low, making corrections unnecessary. The natural xenon in the samples presumably was present in the oxygen which is continuously injected into the reactor system and vented with the fission gases through the charcoal adsorbers.

The method of isolating the first sample provided a convenient means for obtaining an elution curve for xenon from a large charcoal bed using the 5.27 day Xe-133 as a tracer. This curve is presented in Fig. 2. The total volume of gas purged through the bed during the time the xenon was placed on the bed was only about 4000 liters, so that in comparison to the total elution volume, the activity was added almost as a single spike. The break-through time and shape of the elution curve show that the bed performance was typical of such charcoal adsorber systems (7). The total Xe-133 eluted (obtained by integrating under the curve) agreed within 26% of the quantity calculated to have been added to the bed.

## 6.0 XENON BEHAVIOR AND REMOVAL MECHANISMS IN THE HRT

In aqueous homogeneous reactors, three mechanisms can act to reduce the amount of Xe-135 which is exposed to the reactor flux and thus reduce the xenon poison fraction. These are:

1. Removal of the precursor, I-135, which was done in the HRT by let down of fuel to the low pressure system where the iodine was stripped and retained on a silver-plated mesh trap.
2. Removal of Xe-135 by let down as a dissolved gas in liquid, as was the case in the HRT, or by gaseous stripping and gas let down.
3. Retention of Xe-135 in the high pressure system, but outside the core where it decays to Cs-135. The mechanism for this retention is not fully understood, but the fact that it existed was clearly demonstrated by these measurements.

It has been shown previously (8) that in high flux aqueous reactors, removal of I-135 on a 1-hour cycle effectively reduces xenon poisoning

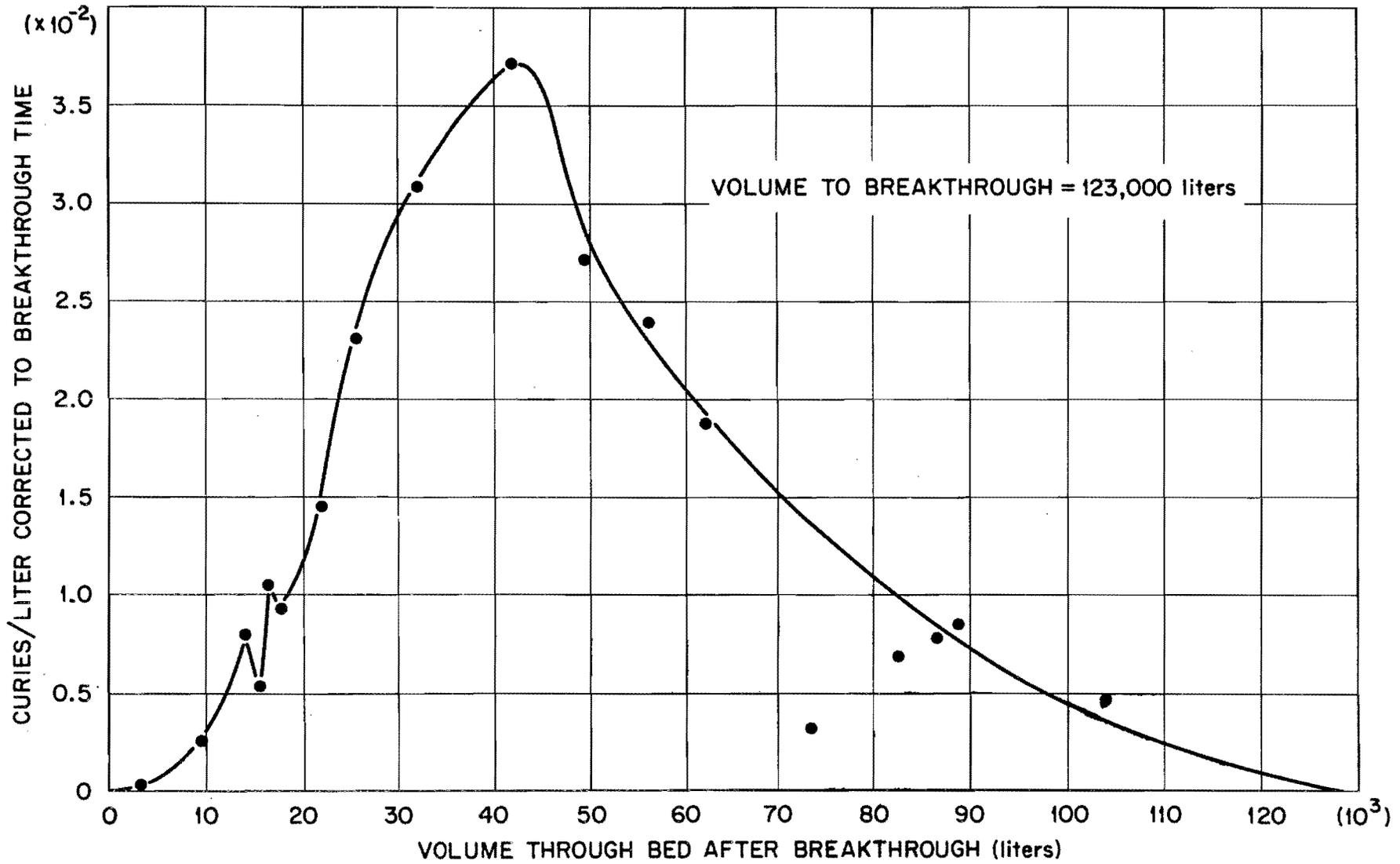


Fig.2. Elution of  $Xe^{133}$  from Bed D.

below 1%, while gas stripping of Xe-135 must be done on a much shorter cycle to realize the same low poisoning. In studies of iodine behavior in the HRT (3), iodine was found to be held up in the high pressure system, presumably because of radiation induced reduction of iodine to iodide. A model which postulated that a pseudo-equilibrium existed between iodine in solution and that adsorbed on the walls fit most of the data obtained when it was assumed that only 10% of the iodine in the high pressure system was circulating, the other 90% being adsorbed on the walls. However, the interpretations were primarily based on I-133/I-131 activity ratios, and the data were not sufficient to show that the model adequately described the behavior of the shorter-lived isotopes, including I-135. Qualitatively, at least, the fraction circulating can be identical for all isotopes only if the equilibrium is instantaneous, while, for example if the time to establish equilibrium is as long as one hour, the fraction of I-135 circulating may be twice as high as that of I-131. This holdup of iodine on the walls significantly increased the quantity of I-135 remaining in the high pressure system, but iodine removal was still the primary mechanism for reducing xenon poisoning in the HRT.

Xenon retention in the high pressure system was first noted indirectly in connection with the iodine removal studies (3) through a comparison of the Cs-135 accumulated in the fuel solution over an extended period of time with that expected from iodine and xenon removal mechanisms. Using any reasonable assumptions about iodine holdup, the quantity of Cs-135 found was considerably greater than if xenon were circulating quantitatively and being let down with the fuel solution. The poison fraction measurements confirm the xenon retention. The Cs-135 measurements appear to indicate somewhat less xenon holdup than do the poison fraction measurements. However, both methods give consistent results if the fraction of I-135 circulating were 25% instead of 10%. While this fraction is somewhat higher than indicated from the iodine studies, it does not appear completely unreasonable. Unfortunately, comparisons are complicated by the fact that the poison fraction measurements were made at a constant high power while the Cs-135 was accumulated over a long period of variable power operation and meager evidence indicates that iodine behavior varies with reactor power (3).

Two models were developed in attempts to explain the poison fraction measurements. The first is an extension of the iodine pseudo-equilibrium model applying the same assumption of equilibrium between xenon in solution and that on the walls. Calculations of the xenon poison fraction were made for a number of assumed fractions circulating using this model to show clearly that only a small fraction of xenon can be circulating. The results of these calculations, presented in Fig. 3, indicate that no more than 10-15% of the Xe-135 can be circulating to realize a poison fraction as low as was obtained. The equations derived for these calculations are given in the appendix. All constants employ the actual HRT conditions of flow rate, uranium concentrations and power levels which existed on the three occasions when poison fraction measurements were made, and a fast fission correction of 0.94 recommended by D. Vondy.\*

This model probably does not satisfy the actual physical system since no reasonable mechanism can be postulated which would maintain an equilibrium between xenon on the walls and that in solution. A somewhat more satisfying model was developed by assuming that xenon formed by decay of iodine, which is adsorbed on the wall, is retained for some period on the walls. The xenon ultimately diffuses back into the circulating stream where it is removed by the let down stream, by decay or by neutron capture in the core. Xenon formed directly in solution is assumed to remain circulating until removed by one of the three removal mechanisms. Calculations using this model are plotted in Fig. 4. To fit the poison fraction measurements, the removal rate constant must fall in the range of 0.05 to 0.1 hr<sup>-1</sup>, indicating an average lifetime on the wall of 6 to 12 hours.

The calculations were extended to permit a prediction of the HRT poison fraction level for 5 Mw power production in the core region only. A poison fraction of 0.006 is indicated for the actual let down rates used in the HRT. No measurements of xenon poisoning were made in the brief interval of operation before the hole was burned in the core.

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\* i.e., actual poison fraction = 0.94 times the poison fraction obtained using thermal cross sections convected to 280°C operating temperature.

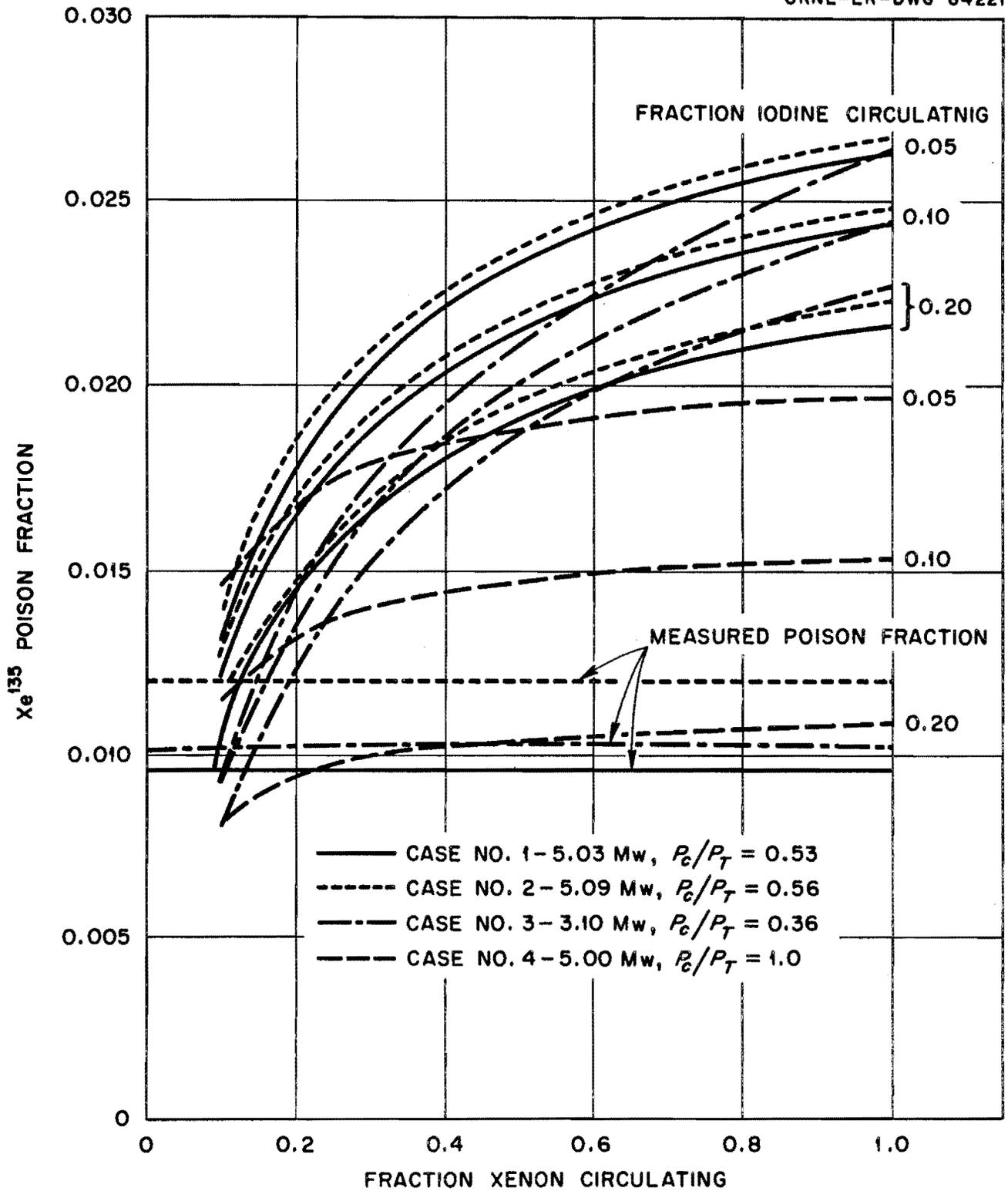


Fig. 3. Calculated Xenon Poison Fraction Determined by  $I^{135}$  and  $Xe^{135}$  Behavior.

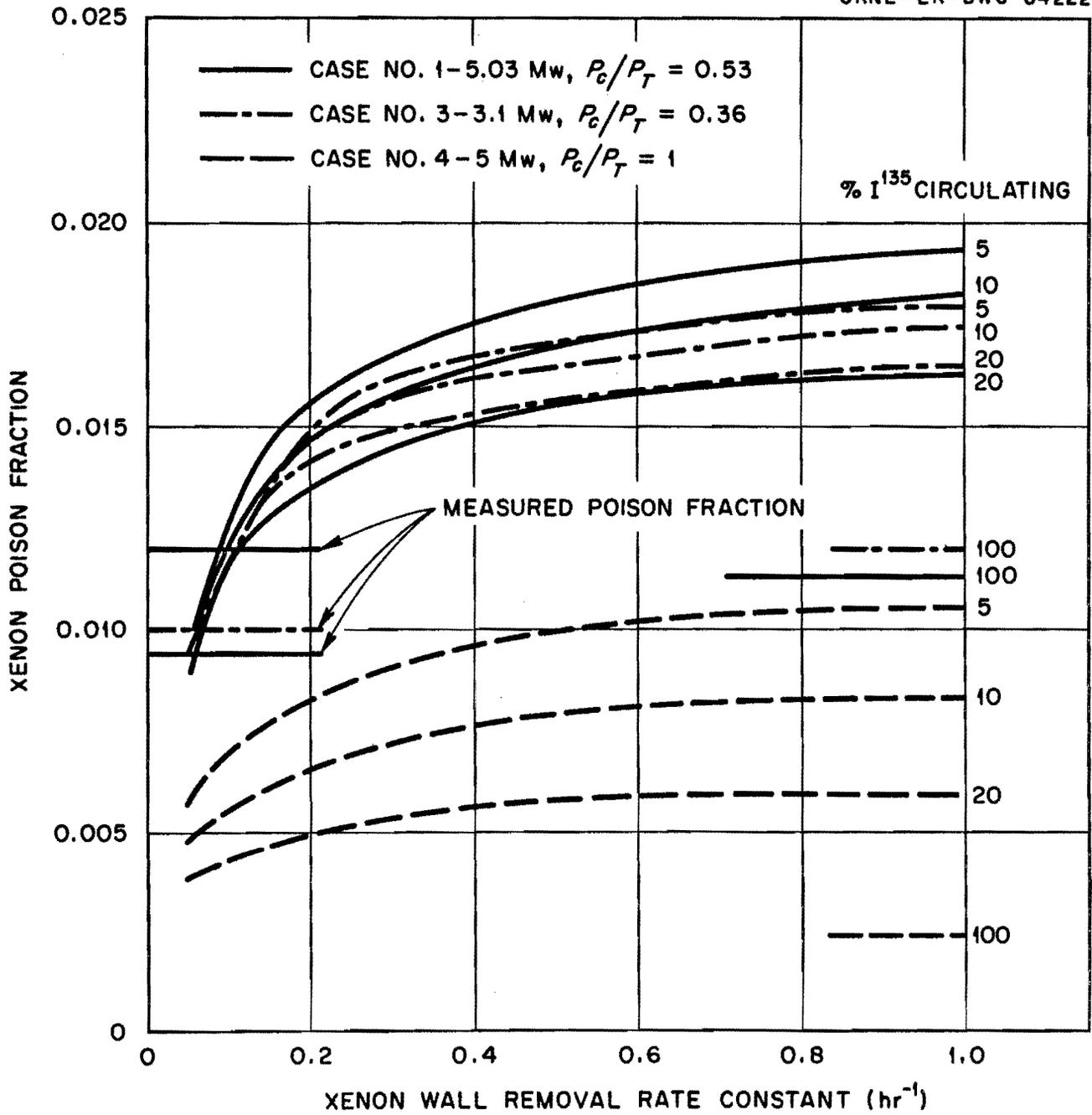


Fig. 4. Calculated Xenon Poison Fraction Determined by I<sup>135</sup> and X<sup>135</sup> Behavior.

## 7.0 CONCLUSIONS

1. The xenon poison fraction under HRT conditions of 5 Mw power, with 53% of the power produced in the core, was found to be approximately 0.010, dependent to a minor degree on exact operating conditions. At 3.1 Mw with only 36% of the power produced in the core, the poison fraction was also 0.010.

2. The precision of measurement of the poison fraction, using mass spectrographic analyses of the stable xenon isotopes in the off-gas ( $\pm .0015$  at the 95% confidence level), is somewhat better than the absolute accuracy of the calculated number because of some uncertainty in the fission yield of the xenon isotopes.

3. Retention of xenon outside the reactor core acts to reduce xenon poisoning. Only about 10-15% of the xenon in the high pressure system circulates with the fuel.

4. The xenon holdup outside the core can probably be explained by the fact that a substantial fraction of the xenon is formed by decay of iodine which is adsorbed on the walls outside the core. After an average life of about 8 hours on the walls, the xenon diffuses back into the circulating stream.

5. Xenon retention outside the core was previously discovered from Cs-135 measurements and analyses of iodine behavior. These analyses indicated slightly less xenon retention than the poison measurements. The discrepancy between the quantity retained on the walls as determined from the poison fraction measurements and that indicated by the cesium measurements cannot be fully resolved, but may be due either to power dependent variations in iodine and xenon behavior which are not fully understood, or slight differences in the behavior of the various iodine isotopes.

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## 9.0 APPENDIX

### 9.1 Equations for Equilibrium Adsorption Model

Nomenclature:

$N_I^C$  = Total I-135 population in core high pressure system

$N_I^B$  = Total I-135 population in core blanket

$N_{Xe}^C, N_{Xe}^B$  = Total Xenon population in core and blanket

$P_I^C, P_I^B$  = Production rate of I-135 in core and blanket

$r_1$  = blanket to core processing rate constant

$r_2$  = core to blanket processing rate constant

$r_4$  = core to let down rate constant

$\lambda_I, \lambda_{Xe}$  = I-135, Xe-135 decay constants

$\epsilon_I, \epsilon_{Xe}$  = fraction of iodine or xenon of total in high pressure system which is circulating with the fuel

$P_{Xe}^C, P_{Xe}^B$  = direct fission production of xenon in core and blanket

$\bar{\phi}_C, \bar{\phi}_B$  = Total volume average thermal fluxes in core and blanket respectively

$\sigma_{Xe}$  = xenon cross section =  $2.36 \times 10^6$  b, averaged over thermal distribution

Iodine

$$\frac{dN_I^C}{dt} = P_I^C + N_I^B r_1 \epsilon_I - N_I^C \left[ (\lambda_I + r_2 \epsilon_I + r_4 \epsilon_I) \right] \quad (\text{Eq. 1})$$

$$\frac{dN_I^B}{dt} = P_I^B + N_I^C r_2 \epsilon_I - N_I^B (\lambda_I + r_1 \epsilon_I) \quad (\text{Eq. 2})$$

at equilibrium:

$$N_I^B = \frac{P_I^B + N_I^C r_2 \epsilon_I}{\lambda_I + r_1 \epsilon_I} \quad (\text{Eq. 3})$$

$$N_I^C = \frac{P_I^C + N_I^B r_1 \epsilon_I}{\lambda_I + r_2 \epsilon_I + r_4 \epsilon_I} \quad (\text{Eq. 4})$$

Xenon:

$$\begin{aligned} \frac{dN_{Xe}^C}{dt} = P_{Xe}^C + N_I^C \lambda_I + N_{Xe}^B r_1 \epsilon_{Xe} - N_{Xe}^C \left[ \lambda_{Xe} \right. \\ \left. + \epsilon_{Xe} (r_2 + r_4 + \phi_C \sigma_{Xe}) \right] \end{aligned} \quad (\text{Eq. 5})$$

$$\begin{aligned} \frac{dN_{Xe}^B}{dt} = P_{Xe}^B + N_I^B \lambda_I + N_{Xe}^C r_2 \epsilon_{Xe} - N_{Xe}^B \left[ \lambda_{Xe} \right. \\ \left. + \epsilon_{Xe} (r_1 + \phi_B \sigma_{Xe}) \right] \end{aligned} \quad (\text{Eq. 6})$$

and at equilibrium:

$$N_{Xe}^C = \frac{P_{Xe}^C + N_I^C \lambda_I + N_{Xe}^B r_1 \epsilon_{Xe}}{\lambda_{Xe} + \epsilon_{Xe} (r_2 + r_4 + \phi_C \sigma)} \quad (\text{Eq. 7})$$

$$N_{Xe}^B = \frac{P_{Xe}^B + N_I^B \lambda_I + N_{Xe}^C r_2 \epsilon_{Xe}}{\lambda_{Xe} + \epsilon_{Xe} (r_1 + \phi_B \sigma)} \quad (\text{Eq. 8})$$

### 9.2 Equation for Xenon Wall-to-Solution Diffusion Model

Define  $\lambda_R$  = rate at which given xenon population on walls is returned to circulating solution, fraction per hour

Redefine  $N_{Xe}^C, N_{Xe}^B$  = xenon population circulating with fuel stream in core and blanket high pressure systems

Iodine:

Same as defined in Equations 1 through 4.

Xenon:

$$\begin{aligned} \frac{dN_{Xe}^C}{dt} = & P_{Xe}^C + N_I^C \lambda_I \epsilon_I + \frac{N_I^C \lambda_I (1-\epsilon_I) \lambda_R}{\lambda_{Xe} + \lambda_R} \\ & + N_{Xe}^B r_1 - N_{Xe}^C (\lambda_{Xe} + r_2 + r_4 + \phi_C \sigma) \end{aligned} \quad (\text{Eq. 9})$$

$$\begin{aligned} \frac{dN_{Xe}^B}{dt} = & P_{Xe}^B + N_I^B \lambda_I \epsilon_I + \frac{N_I^B \lambda_I (1-\epsilon_I) \lambda_R}{\lambda_{Xe} + \lambda_R} \\ & + N_{Xe}^C r_2 - N_{Xe}^B (\lambda_{Xe} + r_1 + \phi_B \sigma) \end{aligned} \quad (\text{Eq. 10})$$

At equilibrium:

$$N_{Xe}^C = \frac{N_I^C \lambda_I \left[ \epsilon_I + \frac{(1-\epsilon_I) \lambda_R}{\lambda_{Xe} + \lambda_R} \right] + N_{Xe}^B r_1 + P_{Xe}^C}{\lambda_{Xe} + r_2 + r_4 + \phi_B \sigma} \quad (\text{Eq. 11})$$

$$N_{Xe}^B = \frac{N_I^B \lambda_I \left[ \epsilon_I + \frac{(1-\epsilon_I) \lambda_R}{\lambda_{Xe} + \lambda_R} \right] + N_{Xe}^C r_2 + P_{Xe}^B}{\lambda_{Xe} + r_1 + \phi_B \sigma} \quad (\text{Eq. 12})$$

### 9.3 Poison Fractions

$$\text{Core Poison Fraction } PF_C = \frac{N_{Xe}^C \sigma_{Xe} \epsilon_{Xe}}{N_{25}^C \sigma_a^{25}} (0.94)^* \quad (\text{Eq. 13})$$

$$\text{Blanket Poison Fraction } PF_B = \frac{N_{Xe}^B \sigma_{Xe} \epsilon_{Xe}}{N_{25}^C \sigma_a^{25}} (0.94) \quad (\text{Eq. 14})$$

\*0.94 is fast fission correction calculated by D. Vondy

System averaged poison fraction

$$PF_{av} = PF_C \left( \frac{P_C}{P_T} \right) + PF_B \left( 1 - \frac{P_C}{P_T} \right) \quad (\text{Eq. 15})$$

where  $\frac{P_C}{P_T}$  = fraction of power produced in core

#### 9.4 Calculations

The above equations were coded for solution on the IBM-7090 by L. B. Shappert and the results plotted in Figs. 3 and 4. Constants employed for the four cases are tabulated below. The first three cases are for actual HRT run conditions during the time the xenon poison fraction measurements were made.

	<u>Core I</u>	<u>Core II</u>	<u>Core III</u>	<u>Core IV</u>
Core U-235 conc. g/liter at temp.	4.32	4.44	3.23	6.50
Blanket U-235 conc. g/liter at temp.	1.67	1.51	2.44	0
Total Power, $P_T$	5.03	5.09	3.10	5.00
$P_C/P_T$	0.53	0.56	0.36	1.00
$\sigma_f$ 25-b	375	375	375	375
$\sigma_a$ 25-b	444	444b	444b	444b
$\sigma_{Xe^{-b}}$	$2.36 \times 10^6$	$2.36 \times 10^6$	$2.36 \times 10^6$	$2.36 \times 10^6$
$r_1$ (1) $\text{hr}^{-1}$	0.11	0.071	0.084	0
$r_2$ (2) $\text{hr}^{-1}$	0.155	0.089	0.231	0
$r_4$ (3) $\text{hr}^{-1}$	0.904	0.842	0.893	0.904

(1) blanket to core processing rate constant

(2) core to blanket processing rate constant

(3) core let down processing rate constant

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