AIIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202

Centimeter

Inches

MANUFACTURED TO AIIM STANDARDS
BY APPLIED IMAGE, INC.

1 of 2

DECLASSIFIED

HW-73700

SERIES AND COPY NO.

PATIE

December 20, 1956

HANFORD ATOMIC PRODUCTS OPERATION - RICHLAND, WASHINGTON

RESTRICTED
THIS DOCUMENT CONTAINS RESTRICTED DATA
DEFINED BY THE ATOMIC ENERGY ACT OF 1954.
IT IS TRANSMITTED UNDER DISCLOSURE OF ITS
CONTENTS IN ANY MANNER TO AN UNAUTHORIZED
PERSON IS PROHIBITED.

TITLE

TRANSIENT CALCULATION TECHNIQUES

☐ OTHER OFFICIAL CLASSIFIED INFORMATION
THIS MATERIAL CONTAINS INFORMATION AFFECTING
THE NATIONAL DEFENSE OF THE UNITED STATES
WITHIN THE MEANING OF THE ESPIONAGE LAWS,
TITLE 18, U. S. C., SECS. 793 AND 794, THE TRANS-
MISSION OR REVELATION OF WHICH IN ANY MANNER
TO AN UNAUTHORIZED PERSON IS PROHIBITED BY
LAW.

AUTHOR

R.O. Brugge
S.R. Stamp
J.T. Worthington

CIRCULATING COPY
RECEIVED 100 AREA

MAY 31 1963
~~JUL 5 1962~~

RETURN TO

THIS DOCUMENT MUST NOT BE LEFT UNATTENDED OR WHERE AN UNAUTHORIZED PERSON MAY HAVE ACCESS TO IT. WHEN NOT IN USE, IT MUST BE KEPT IN AN APPROVED STORAGE REPOSITORY WITHIN AN APPROVED SECURED AREA. WHILE IT IS YOUR RESPONSIBILITY AND OBLIGATION TO HAVE OBTAINED A SIGNATURE RECEIPT FROM THE CLASSIFIED OFFICE, IT IS YOUR RESPONSIBILITY TO MAINTAIN IT AND ITS CONTENTS WITHIN THE LIMITS OF THIS REPOSITORY AND FROM AN UNAUTHORIZED PERSON. NO TRANSMITTAL TO, OR STORAGE AT YOUR PLACE OF BUSINESS IS PERMITTED. IT IS NOT TO BE REPRODUCED, IF ADDITIONAL COPIES ARE REQUIRED, OBTAIN THEM FROM THE OFFICE ISSUING THEM. ALL PERSONS READING THIS DOCUMENT ARE REQUESTED TO SIGN IN THE SPACE PROVIDED BELOW.

TECHNICAL INFORMATION FILES

ROUTE TO:

PAYROLL NO.

LOCATION[illegible]

SIGNATURE AND DATE

R. D. Carter

17352

1760-18

5-31-63

Q4 Quarter 6-4-03

R. V. Pae

14095

3729

SEP 3 '63

NP 3-20-64

THIS DOCUMENT HAS BEEN SCANNED
AND IS STORED ON THE OPTICAL DISK DRIVE

DECLASSIFIED

(CLASSIFICATION)

DECLASSIFIED

HW-73700

Table of Contents listed on Page 133.

~~The [redacted] is defined in the [redacted]
Energy Act of 1954. [redacted]
[redacted] person is [redacted]~~

This document classified

by:

J. P. Chasley

This document consists of
133 pages. No. 2 of
16 copies. [redacted]

Distribution

1. DG Albertson	9. AW Medcalf
2. RD Carter ←	10. WS Nechodom
3. RA Chitwood	11. DE Newbrough
4. DW Constable	12. GF Owsley
5. JR Fredsall	13. ER Perl
6. GC Fullmer	14. AD Vaughn
7. LL Grumme	15. 300 File
8. JW Hagan	16. Record Center

Classification Cancelled and Changed To

DECLASSIFIED

By Authority of *DS Lewis*

CG-PR-2, 3-8-94

By *J. E. Savelly 3-25-94*

Verified By *McHanson, 3-30-94*

December 20, 1956

TRANSIENT CALCULATION TECHNIQUES

DECLASSIFIED

DECLASSIFIED

HW-73700
Page 2

Section I authored by

R. O. Brugge

XENON

Date of issue December 20, 1956

The Xenon Problem
Historical

Even before the Hanford piles were built the existence of a fission product nuclide with a very large neutron absorption cross-section was considered a real possibility. To cover this eventuality the original Hanford piles were built with considerable excess reactivity. The identity and characteristics of the Xe^{135} isotope were not discovered until after the B Pile had operated at 9 MW with a partial loading and had become sub-critical because of the formation of this "poison".^{1,2} Subsequent operation, observation, and calculations revealed that the new poison was the daughter of a non-poisonous isotope with a half-life of about 6.7 hours and that the poison also decayed with a half-life of about 9.2 hours to another non-poisonous isotope. To fit the observed reactivity changes it was necessary to assume a cross-section more than ten times larger than any previously known. This was initially estimated to be approximately 2.4×10^6 barns and the fission yield to be approximately 7%.

A great deal of work has gone into determining the xenon cross-section, and relatively complete information has been available only recently.^{3,4} The cross-section data in BNL-325 is much more complete than any available before, but the curve is not significantly different from that given in ORNL-325 and BNL-250; therefore, the recommendations made by Gast⁵ and the work of Goertzel and Oppenheim⁶ are still valid. Erkman^{7,8,9,10} and McDaniels¹¹ have each used Gast's recommended values to calculate the xenon in a Hanford pile. Their results for the zero flattening case differ slightly (~2%) because of minor differences in the simplifying assumptions made by each. The differences become larger as the flux distribution is flattened because McDaniels used an approximated 87% flattening efficiency,* whereas Erkman averaged tube-by-tube reactivity weightings permitting him to assume a 100% flattening efficiency. Whenever the actual pile accounting data provided include individual tube reactivity weightings, the Erkman method is preferable. This section supplies equations and curves for calculating the xenon effect by the two different methods.

* See paragraph 1-Page 5 for definition of "flattening efficiency".

1. 3-1435, "Memo - Report, Production Test 105-11-P-3, Reactivity of 105-B," G. L. Weil, 12-16-44, Secret.
2. HW-25076, "Calculation of Xenon in a Hanford Pile," 6-11-52, R. O. Brugge, p. 8, Secret.
3. ORNL-1715, "Semi-Annual Program Report for Period Ending 3-10-55", A. H. Snell, 7-14-54, See page 22.
4. BNL-325, "Neutron Cross Sections," D. J. Hughes, J. A. Harvey, 7-1-55, Not Classified.
5. HW-23729, "Review of the Xenon Problem", P. F. Gast, 3-12-52.
6. Y-491 "Temperature Dependence of the Xenon Cross Section", Goertzel and Oppenheim, 11-29-50.
7. HW-28729, "Xenon Poisoning Calculations Based on Tube Power", J. O. Erkman, 7-15-53.
8. HW-29502, "Weighting Factors for Radially Flattened Piles", JO Erkman, 10-1-53.
9. HW-31135, "Notes on Xenon Reactivity Effects in Hanford Reactors", J. O. Erkman, 7-26-54.
10. HW-32543, "Repetition of Information in Xenon Tables", J. O. Erkman, 7-26-54.
11. HW-30282, "K-Pile Xenon Constants", D. K. McDaniels, 12-23-53.

XENON**DECLASSIFIED**

The Xenon Problem

The Xenon Effect on Operation

The effects of xenon transients influence pile operation in many ways; only some of the more pronounced effects will be mentioned here. The poisoning of the pile at equilibrium is a major effect, causing reactivity loss of 2 to 2½% k in the pile power range of interest. The equilibrium pile power level does not change much from one operating period to the next and the equilibrium value of xenon tends to saturate at higher power levels; therefore, the variation in the saturation value is less important. The actual value does indirectly affect the pile power level through its effect on the reactivity available for flattening purposes.

The xenon reactivity transients are currently the largest operating reactivity transients encountered and the most complex. Since about 95% of the xenon is first formed as iodine which later decays to xenon, the xenon changes lag from minutes to hours behind the power changes. Since the xenon half-life is longer than the iodine half life, and xenon burnout is a significant factor, the xenon at first changes in the direction opposite to the power change. Note that since xenon is a poison the pile reactivity change is of opposite sign to the xenon change. A power reduction from equilibrium produces an initial increase in xenon and a corresponding reactivity loss. The reverse is also true. When the power is reduced to zero from normal operating equilibrium level the reactivity loss is great enough to make the pile sub-critical for 1-1½ days; the actual time varies with the power level, temperature coefficients, flattening, discharges, and the excess reactivity available in the control rods at shutdown.

If the pile is started after the sub-critical time has passed and before the xenon has decayed essentially to zero, there will be an initial reactivity gain due to xenon burnout as well as further decay. When sufficient I^{135} has been produced so that its decay to Xe^{135} balances the xenon decay plus burnout the reactivity absorbed by xenon passes through a minimum or "turnaround", and then increases steadily toward the equilibrium value if a constant power is maintained. Changes in power produce changes in the rate at which equilibrium is approached; if a power increase is large enough another transient reactivity gain involving another "turnaround" will result. The three sketches below illustrate the xenon changes for (1) a start-up to a constant power with an initially xenon-free pile (2) a shutdown from equilibrium, and (3) a start-up to constant power with some initial xenon. Note again, from the xenon values given, that the pile reactivity change is always opposite to the xenon change.

DECLASSIFIED

EW-73700
Page 4

XENON (Continued)

The effect of xenon and temperature coefficients on pile reactivity immediately after a shutdown is covered in a separate section on scram transients. The initial reactivity loss rate may be of the order of 1-2% β k per hour. In general recovery must be made within a few minutes or else xenon buildup will cause the pile to remain subcritical for 1 - 1½ days. The calculation of reactivity changes during outages in which scram recovery was not made is the subject of Section 1200.

The Xenon Problem
Definitions

1. Flattening efficiency is a term used to describe how closely the actual tube power distribution approaches the value which is possible with a given amount of excess reactivity available for flattening. In Reference 17, per cent flattening efficiency is defined as $\frac{\text{observed effective central tubes}}{\text{theoretical effective central tubes}} \times 100$, where the value of the denominator is supplied from a theoretical cosine curve derived from tube-by-tube reactivity weighting factors.
2. The term effective central tubes is defined as the quotient of the pile power divided by the maximum tube power. In practice the average of the ten most productive tubes is used because individual tube data are quite variable as a result of flow and temperature measuring problems.
3. Turnaround is a term applied to maxima and minima in the curve of pile reactivity vs. time. The term is used almost exclusively for reference to the reactivity maximum that occurs a few hours after start-up which is a summation of the effects of xenon burnout and build-up and the temperature coefficient of reactivity of the graphite.
4. F_1 is defined as $\frac{\text{the power of the } i\text{th tube}}{\text{average tube power}}$.¹⁴
5. F_1^2 is the square of F_1 .
6. F_1^3 is the third power of F_1 .
7. $\sum_{\text{pile}} F_1^2$ is defined as the sum over all tubes in the pile of the F_1^2 values. Where only the uranium-loaded tubes are considered this is usually indicated by $\sum^N F_1^2$ and the value of N is given.
8. $\sum^N F_1^2$ is defined as the sum over-all tubes in a discharge of the F_1^2 values.
9. The extension to $\sum^N F_1^3$, $\sum^N F_1^3$ are self-explanatory.

---

14. HW-26210, "Effective Pile Fractions", 12/1/52, R. O. Brugge.

17. HW-37917, "A Reactivity Accounting Method," 7-18-55, R. O. Brugge.

DECLASSIFIED

HW-23700
Page 6

XENON

Xenon-Iodine Calculations Formation and Decay

The following schematic diagram shows the significant steps in the xenon build-up and decay scheme.

The chain of fission products of mass number 135 could begin with tellurium; however, this nuclide has not been definitely found, and if it exists, the half-life is less than two minutes. For the purposes of this calculation any Te^{135} production can be included with the Iodine. The total fission yield of I^{135} and Xe^{135} is taken as 6.4%(5) and the ratio of Xe^{135} formed directly to total formation of Xe^{135} is taken as 0.05.(5)

The existence of an isomeric state of Xe^{135} is of little consequence to the xenon problem. The Xe^{135} is the only member of the chain with a significant cross-section, and it is removed either by beta decay or by neutron capture. The xenon cross section for neutron capture is given in detail in BNL-325.

DECLASSIFIED

XENON

Xenon and Iodine Calculations
Equations Based on Flattening

One transient xenon equation now in use is based on a knowledge of the relationship between the reactivity absorbed by flattening columns and rods and the degree of flattening of the flux distribution. The number of effective central tubes is one measure of the degree of flattening. The equations for xenon and iodine are:

$$L = \frac{AW}{1 - BW} \left[\frac{AWX(1-s) - M_0 I}{I - X(1 - BW)} \right] e^{-It} \left[I_0 - \frac{AW}{1 - BW} - \frac{AWX(1-s) - M_0 I}{I - X(1 - BW)} \right] e^{-X(1 - BW)t}$$

$$M = \frac{(1-s) AXW}{I} (1 - e^{-It}) + M_0 e^{-It}$$

After about three days at a constant power level the values approach saturation and the above equations reduce to:

$$L_s = \frac{AW}{1 - BW}$$

$$M_s = \frac{(1-s) AXW}{I}$$

The notation used is:

L = concentration of xenon in reactivity units at any given time, t- to be calculated.

M = concentration of iodine in reactivity units of potential xenon at any given time t- to be calculated.

I = decay constant of iodine, 0.1038 hr.⁻¹ (6.68 hr. half-life).

X = decay constant of xenon, 0.0753 hr.⁻¹ (9.2 hr. half-life).

s = fraction of xenon formed directly = 0.05..

W = pile power in megawatts.

A = a constant dependent upon flattening or flux distribution and pile size.

B = another constant also dependent on flattening and pile size.

t = time in hours.

DECLASSIFIED

HW-73700
Page 8

The constants A and B contain the ratio of the xenon capture cross-section to the U-235 fission cross-section and several physical constants. The first is dependent upon neutron energy distribution and varies through the pile; Reference 5 discusses this major assumption of neutron energy distribution in some detail as well as other necessary approximations. A and B also depend upon the gross flux distribution; this dependence was treated differently by McDaniels than by Erkman. McDaniels approximated a "reasonable" flux distribution, whereas Erkman set up a method to use digital pile data. McDaniels' results are presented in this section and Erkman's in 1102.3. The work leading to these results is given in References 7 and 9 and in the personal notebook of McDaniels¹⁸.

The values of A and B given in Reference 2, requiring that the flattening be known in inhours, cause the values of M and L to be underestimated at higher values of flattening. McDaniels provided values of A and B for the 2004 tube piles and the 3220 tube piles in Reference 11 which incorporated the recommendations of Gast (5) and are based on actual flux distributions; however, knowledge of the flattening in inhours is still required. These values are repeated here for completeness; however, it should be emphasized that they include the following approximation: The production was calculated on the basis of a "flat" zone and a buckled region outside of the flat zone; the total production was assumed to be 87% of the flat zone production plus 100% of the outer or buckled region. The values given in Reference 11 are listed below:

FLATTENING IN INHOURS	3220 TUBE PILES		2004 TUBE PILES	
	A	B	A	B
0	2.0914	0.0017371	3.8060	0.0032161
100	1.9447	0.0016153	3.6721	0.0031030
200	1.8657	0.0015497	3.4900	0.0029491
300	1.8150	0.0015075	3.3930	0.0028671
400	1.7736	0.0014732	3.3205	0.0028058
500	1.7479	0.0014518	-----	-----
600	1.7303	0.0014372	3.2204	0.0027212
700	1.7228	0.0014310	-----	-----
800	1.7163	0.0014256	3.1642	0.0026738
∞	1.6721	0.0013888	3.0600	0.0025858

2. HW-25076, "Calculation of Xenon in a Hanford Pile," 8/11/52, R. O. Brugge, p. 8, Secret.
5. HW-23729, "Review of the Xenon Problem", P. F. Gast, 3/12/52.
7. HW-28729, "Xenon Poisoning Calculations Based on Tube Power", JO Erkman, 7/15/53.
9. HW-31135, "Notes on Xenon Reactivity Effects in Hanford Reactors", J. O. Erkman, 3/15/54.
11. HW-30282, "K-Pile Xenon Constants", D. K. McDaniels, 12/23/53.
18. HW-6530-T and HW-5362-T, Personal Notes, D. K. McDaniels.

DECLASSIFIED

HW-73700

Page 9

It will be noted that the ratio between A_0 and A_1 is the same as between B_0 and B_1 where the A_0 refers to the zero flattening and the A_1 refers to some given

value of flattening. In the equations $L_s = \frac{AW}{1 - BW}$ and $M_s = (1-s) \frac{AXW}{I}$ the A

and B terms appear only as multipliers of the power W; this is also true of the transient equations. If $(A_0/A_1) = (B_0/B_1)$ it is then possible to use one set of A and B values (zero flattening for example) and use one value of an "equivalent" power level W^* such that $A_0W^* = A_1W$ and $B_0W^* = B_1W$. This means that only one xenon table is necessary; xenon for all degrees of flattening can be calculated by using a value W^* in a zero flattening table, which is always less than the true power. A curve can be drawn of A_1/A_0 vs. flattening; when the flattening is known, the fraction can be read from this curve and can then be multiplied by the actual pile power to find the "equivalent" power (W^*) for which the zero flattening xenon table will correctly give the xenon and iodine values. This was done in Reference 12 for the K Pile xenon tables. (In this reference A^*/A was used for A_1/A_0 .)

The xenon tables for the older piles (13) were calculated from the xenon equation as given above with the values of I, X, s, Y and σ_x/σ_f in use before Reference 5 was issued. The constants A and B were determined by the relationships $A = 4.43 (1 - 0.000625F)$ and $B = 0.00399 (1 - 0.000625F)$, where F was the pile flattening in inhours. These tables are incorrect for zero flattening, and the variation of A and B with flattening is also incorrect. The tables will be replaced in the near future.

The term flattening efficiency as applied to McDaniels' 87% flat zone production efficiency is at variance with the previous definitions. This term has been used loosely and with a variety of meanings by different people. McDaniels treated the problem as follows. In cylindrical geometry he calculated the radius of the flattened zone for a particular amount of flattening, say 600 ih. This then gave a central region of radius R containing N tubes operating at a tube power P surrounded by an annular buckled region containing $3220 - N$ or $2004 - N$ tubes where the power was described by the J_0 function. This would then yield a total power W^* for a given central tube power P. The actual power is always less than any power calculated as above because of individual tube power differences caused by exposure differences and "dimpling" due to flattening by discrete columns or rods. McDaniels made this correction by assuming the actual power W was equal to the sum of 0.87 NP and the theoretically calculated power in the buckled region. Thus at zero flattening, where $N = 0$, no correction is made and at an infinite flattening the correction is exactly 0.87.

5. HW-23729, "Review of the Xenon Problem", P. F. Gast, 3/12/52.
12. HW-33537, "Xenon Tables for the K Reactors, Zero Inhours Flattening, Zero to 8000 Mega Watts," 10/26/54, R. E. McGrath.
13. HW-25565, "Xenon Tables" Parts I through 7.

DECLASSIFIED

HW-73700
Page 10

XENON

Xenon and Iodine Calculations Equations Based on Flux Distribution

Erkman proposed a method of calculating xenon and iodine effects that takes into account the actual power distribution existing in the pile.^{7,8,9,10} The results are essentially identical with those of McDaniel's¹¹ when the same flattening efficiency assumptions and flattening vs. flux distribution assumptions are made; however, they offer the distinct advantage that no assumptions need be made since the use of the actual power distributions makes these corrections. The equations for M and L are identical with those on page 7 except that A and B are defined as follows:

$$A = \frac{5.46 \times 10^6 f \sum F_1^3}{DN \sum F_1^2}$$

$$B = \frac{3954 \sum F_1^3}{DN \sum F_1^2}$$

where: f = thermal utilization

D = effective pile length in cm. which includes augmentation distances.

(L is the common symbol for this value; D is used here to avoid confusion with L meaning xenon)

N = number of tubes loaded with uranium

and where F_1^2 and F_1^3 have the meaning given on page 1101.3-1. For particular piles the equations above reduce to constants multiplied by the flux distribution ratios. The values of A and B for 2004 and 3220 tube Hanford piles are given in the Table.

VALUES OF A AND B FOR THE 2004 and 3220 TUBE PILES

	<u>2004 TUBE PILES</u>	<u>3220 TUBE PILES</u>
D	810 cm.*	918 cm.**
f	0.865 (11)	0.880 (21)
A =	$2.910 \frac{\sum_{pile} F_1^3}{\sum_{pile} F_1^2} \left(\frac{2004}{N} \right) = 4.068$ (Unflattened)	$1.625 \frac{\sum_{pile} F_1^3}{\sum_{pile} F_1^2} \left(\frac{3220}{N} \right) = 2.325$ (Unflattened)
B =	$0.002439 \frac{\sum_{pile} F_1^3}{\sum_{pile} F_1^2} \left(\frac{2004}{N} \right) = 0.003410$ (Unflattened)	$0.001338 \frac{\sum_{pile} F_1^3}{\sum_{pile} F_1^2} \left(\frac{3220}{N} \right) = 0.001917$ (Unflattened)

* 285" charge of 32 slugs with 87 cm. total augmentation distance taken from HW-29034, 19.

** 337" charge of 38 slugs with 62.7 cm. total augmentation distance taken from HW-37158-P120.

XENON (Continued)

The xenon values calculated in this manner at zero flattening are a little larger than those obtained by section 1102.2. Some of the disagreement is caused by using the "as measured" augmentation distance in this section whereas in Reference 11 a value was anticipated which turned out to be approximately 23 cm ($2\frac{1}{2}\%$) too long.

Values of the ratio $\left(\frac{\sum_{\text{pile}} F_1^3}{\sum_{\text{pile}} F_1^2} \right)$ as a function of the radius of the flattened zone,

may be obtained from either Reference 8 or 15 so that a curve of (A_1/A_0) vs. $\left(\frac{\sum_{\text{pile}} F_1^3}{\sum_{\text{pile}} F_1^2} \right)$ may be made, by also using flattened zone radius as a function of

flattening in inhours. Reference 8 was used to produce Figure 3 in this section which shows (A_1/A_0) vs. $\left(\frac{\sum_{\text{pile}} F_1^3}{\sum_{\text{pile}} F_1^2} \right)$; this curve is duplicated as Figure 7 in Section 1105.

The curves in Figure 3 permit calculating the xenon with a single zero-flattening table. In most cases $N \approx 2004$ or 3220, and the minor correction of

$\left(\frac{2004}{N} \right)$ or $\left(\frac{3220}{N} \right)$ can be omitted; this was done in making the figures in this section. The value of $\left(\frac{\sum F_1^3}{\sum F_1^2} \right)$ as a function of the theoretical flattening in

inhours is given in Figure 4 for the 2004 tube piles and the 3220 tube piles. The values at zero flattening are 1.396 and 1.433 respectively.

-
7. HW-28729, "Xenon Poisoning Calculations Based on Tube Power," J. O. Erkman, 7/15/53.
  8. HW-29502, "Weighting Factors for Radially Flattened Piles," J. O. Erkman, 10/1/53.
  9. HW-31135, "Notes on Xenon Reactivity Effects in Hanford Reactors," J. O. Erkman, 3/15/54.
  10. HW-32543, "Repetition of Information in Xenon Tables," J. O. Erkman, 7/26/54.
  11. HW-30282, "K Pile Xenon Constants," D. K. McDaniels, 12/23/53.
  15. HW-31848, "Slug and Tube Factors", M. R. Moon & R. O. Brugge, 5/13/54.
  19. HW-29034. C-Pile Start-Up Technical Data, D. K. McDaniels and G. C. Fullmer, 9-1-53.
  20. HW-37158-P1, K-Pile Start-Up Experiments, Part I - Critical Size Determination of Lattice Characteristics, 11-1-55, C. L. Miller.
  21. HW-38738, Determination of Lattice Parameters from Experimental Neutron Distribution in Rod Fuel Elements at KW Pile Start-Up, 6-15-56, W. E. Niemuth.

Figure 1
Saturated Iodine and Xenon Values with Zero Flattening
Vs. Power Level
2004 Tube Pile

DECLASSIFIED

BN-73700
Page 13

Figure 2
Saturated Iodine and Xenon Values with Zero Flattening
Vs. Power Level
3220 Tube Pile

DECLASSIFIED

HW-73700
Page 14

DECLASSIFIED

Figure 4

DECLASSIFIED

HW-73700
Page 16

XENON

Xenon and Iodine Calculations Discharge Effects

The reactivity effect of the discharged xenon has long been calculated as a fraction $\left(\frac{\sum_{n=1}^N F_1^3}{\sum_{n=1}^N F_1^2}\right)$ of the total xenon and iodine where n represents the tubes of uranium discharged and N represents the total tubes of uranium in the pile.²

Reference 9 shows that this is not true unless $\left(\frac{\sum_{n=1}^N F_1^2}{\sum_{n=1}^N F_1^3}\right) = \left(\frac{\sum_{n=1}^N F_1^2}{\sum_{n=1}^N F_1^3}\right)$.

The difference is ordinarily very small but may be significant for large discharges which are strongly preferential to either the fringe or the central region. The true values of xenon discharged, provided the piles was at equilibrium, are:

$$L \text{ (discharged)} = \frac{1194 \left(\frac{\sum_{n=1}^N F_1^2}{\sum_{n=1}^N F_1^3} \right)}{1 + \frac{410.7}{W} \left(\frac{\sum_{n=1}^N F_1^2}{\sum_{n=1}^N F_1^3} \right)} \quad \text{for 2004 tube piles}$$

and for the 3220 tube piles:

$$L \text{ (discharged)} = \frac{1214 \left(\frac{\sum_{n=1}^N F_1^2}{\sum_{n=1}^N F_1^3} \right)}{1 + \frac{747.9}{W} \left(\frac{\sum_{n=1}^N F_1^2}{\sum_{n=1}^N F_1^3} \right)}$$

The fraction of potential poison (iodine) discharged is:*

$$\frac{\sum_{n=1}^N F_1^3}{\sum_{n=1}^N F_1^2}$$

-
- * The more simple expression for iodine discharge is applicable because there is no iodine burnout.
2. HW-25076, "Calculation of Xenon in a Hanford Pile," 8/11/52, R. O. Brugge, P. 8, Secret.
  9. HW-31135, "Notes on Xenon Reactivity Effects in Hanford Reactors", J. O. Erkman, 3/15/54.

DECLASSIFIED

HW-73700
Page 17

XENON(Continued)

These values should be subtracted from the saturation values of M and L to find M_0 and L_0 , the effective amount of xenon at time of shutdown corrected for discharge effects. If the pile was not at equilibrium, the fraction

$\left(\frac{\sum_{i=1}^N F_i^3}{\sum_{i=1}^N F_i} \right)$ will probably provide the best approximation; although the fraction

available from production scheduling data will probably be based on a flux distribution that was not in existence at the time of the outage.

DECLASSIFIED

Xenon and Iodine Calculations Effects of Flux Distribution Changes

The information so far presented assumes that the xenon reactivity value is measured in the same flux distribution as existed to form the xenon. This is an idealized case, and one can reasonably ask about the effect of a sudden change in the neutron flux distribution. This section will treat the question rather generally and by some simplified examples. It will also be shown that it is neither practical nor necessary from a safety standpoint to consider this effect for routine pile reactivity calculations. A review of Chapter 2100 and the calculation of effective reactivity values may help the reader.

Consider a pile with a fixed flux distribution - any distribution except the perfectly flat case will do. At equilibrium every volume-element of fuel will contain some xenon atoms, and, to a close approximation, the quantity will be proportional to the thermal neutron flux in the volume-element.* The reactivity value of the xenon in each element will be proportional to the volume-fraction of the total flux-squared-volume; therefore, if the total reactivity value of the xenon is known, the effective reactivity value of the xenon in any volume-element may be found. This will be the volume-fraction of the total flux-cubed volume, or -

$$Re_1 \approx \frac{L_8 F_1^3}{\sum F_1^3}$$

The nominal reactivity value is then -

$$\begin{aligned} Rn_1 &\approx \frac{Re_1 \sum F_1^2}{K F_1^2} \\ &\approx \frac{L_8 F_1^3}{K \sum F_1^3} \left(\frac{\sum F_1^2}{F_1^2} \right) \end{aligned}$$

where K is a constant dependent on pile size.

If we let the flux-distribution change from the fixed equilibrium value assumed up to now we can calculate the new effective reactivity values by weighting the above nominal values by the new flux-squared volume-fractions. Let the subscript j represent the new flux distribution.

---

* This is not strictly true as pointed out on pages 11 and 12, since there is a higher percentage of burnout in the higher flux regions.

DECLASSIFIED

HW-73700
Page 19

XENON CALCULATIONS

Xenon and Iodine Calculations Effects of Flux Distribution Changes

Then

$$Re_j \approx \frac{Rn_1 K F_j^2}{\sum F_j^2}$$

$$\approx \left(\frac{L_s F_1^3}{\sum F_1^3} \right) \left(\frac{\sum F_1^2}{F_1^2} \right) \left(\frac{F_j^2}{\sum F_j^2} \right)$$

(Note that the Ks cancel)

The new total effective xenon value can be found by summing the Re_j values over all volume-increments considered - call the new value L_s' . The problem to be considered is how L_s' is related to L_s when the flux distribution is suddenly changed, slightly or radically. We will not consider the transient that occurs after the sudden flux change. There will be a reactivity transient, but the calculation of this is too complex and the benefit of the knowledge too small to make it worth the effort. This is especially true if there is a power change associated with the flux distribution change, which would be the normal case with, say, a scram recovery.

It is apparent that the calculation for a large pile would be practical only with a computer. To avoid the mental-block of considering the whole problem at once, consider a much-simplified two-dimensional case to illustrate the effects. Let the flux distribution be as shown below by ϕ_1 . Let this suddenly change

to the curve ϕ_2 . The maximum values of Rn_1 will be at the peak of the ϕ_1 curve, but the maximum reactivity-weighting will be at the peak of the ϕ_2 curve. This lies over values of Rn_1 which are considerably smaller; it is intuitively apparent that L_s' is then smaller than L_s .

Consider more radical flux changes such as below:

DECLASSIFIED

HW-73700
Page 20

XENON CALCULATIONS

Xenon and Iodine Calculations Effects of Flux Distribution Changes

Distributions II and III are merely more extreme examples of that shown in I. Using the same reasoning, it can be seen that L_S'/L_S for Case II is very small and that L_S'/L_S for Case III is zero. Consider just one more case.

IV

In this case the maximum Rn_1 values will have an even larger flux-squared weighting in distribution ϕ_2 than in ϕ_1 and L_S'/L_S will be greater than one. From these simplified considerations it can be seen that L_S'/L_S can vary from >1 down to zero. Practical considerations make Case IV extremely unlikely. Because the new effective reactivity values of the xenon would be so very large at the peak of ϕ_2 , they will tend to depress the flux there, and this distribution could be maintained only by additions of large quantities of poison at the fringe of the distribution or a great deal of enrichment at the center. The first of these could be done in a pile with a large PCCF installation but only if there was already a reactivity excess.

The examples above show qualitatively what will happen to L_S'/L_S when there is a sudden flux change. To show some quantitative results, a small reactor will be assumed. This will keep the arithmetic volume low enough to permit a few numerical examples. Assume a 32-tube reactor with a 6 x 6 square array as below:

6		3	4	4	3	
5	3	6	7	7	6	3
4	4	7	10	10	7	4
3	4	7	10	10	7	4
2	3	6	7	7	6	3
1		3	4	4	3	
	A	B	C	D	E	F

Figure 5.

DECLASSIFIED

HW-73700
Page 21

XENON CALCULATIONS

Xenon and Iodine Calculations Effects of Flux Distribution Changes

Let the numbers inside the array correspond to relative tube powers; the numbers outside will be used to identify the tubes.

To further simplify the problem we can assume that the front-to-rear flux distribution remains constant for the first 2-3 examples.

Let F_1 represent the relative tube power and $\sum_{j=1}^{32} F_j$ represent the pile power.

Now find the values F_1^2 , F_1^3 , and $\sum_{j=1}^{32} F_j^2$, and $\sum_{j=1}^{32} F_j^3$.

F_1	N	NF_1	F_1^2	NF_1^2	F_1^3	NF_1^3
3	8	24	9	72	27	216
4	8	32	16	128	64	512
6	4	24	36	144	216	864
7	8	56	49	392	343	2744
10	4	40	100	400	1000	4000
$\sum_{j=1}^{32}$		176		1136		8336

Now assume some arbitrary amount of xenon while this pile is at equilibrium; 833.6 ih is a convenient value. Assume the xenon in each column is just

$\frac{F_1^3}{\sum_{j=1}^{32} F_j^3}$ (833.6) which is very nearly true and the difference will not

affect the validity of the examples. Then the effective xenon value in each column is just $0.1 F_1^3$. To find the effective value in some new flux distribution it will be necessary to find the nominal value of the xenon in each column and then apply the flux-squared weighting of the new flux distribution.

To find the new effective reactivity values (Re') we must use the F_j^2 and $\sum_{j=1}^{32} F_j^2$ values of that distribution as developed earlier in this section:

$$Re' = \left(\frac{F_1^3}{\sum_{j=1}^{32} F_j^3} \right) (833.6) \left(\frac{\sum_{j=1}^{32} F_j^2}{F_1^2} \right) \left(\frac{F_1^2}{\sum_{j=1}^{32} F_j^2} \right)$$

The total xenon effect can be found by simply summing Re' over all 32 tubes in this pile. To further simplify the arithmetic we can assume flux changes which have mirror symmetry about one centerline; the following cases will be used:

XENON CALCULATIONS

Xenon and Iodine Calculations Effects of Flux Distribution Changes

1. Shift the flux so that it peaks on the near-side - See Figure 6.
2. Flatten the distribution relative to Figure 5 - See Figure 7.
3. Peak the flux more sharply in the center than in Figure 5 - See Figure 8.

Figure 6

6		4	4	3	1	
5	4	7	7	5	3	1
4	7	10	10	7	4	2
3	7	10	10	7	4	2
2	4	7	7	5	3	1
1		4	4	3	1	
	A	B	C	D	E	F

F_j	N	F_j^2	NF_j^2
1	4	1	4
2	2	4	8
3	4	9	36
4	8	16	128
5	2	25	50
7	8	49	392
10	4	100	400
Σ	32		1018

Figure 7

6		1	1	1	1	
5	1	2	2	2	2	1
4	1	2	2	2	2	1
3	1	2	2	2	2	1
2	1	2	2	2	2	1
1		1	1	1	1	
	A	B	C	D	E	F

1	16	1	16
2	16	4	64
Σ	32		80

DECLASSIFIED

HW-73700
Page 23

XENON CALCULATIONS

Xenon and Iodine Calculations
Effects of Flux Distribution Changes

Figure 8

6		1	2	2	1	
5	1	3	4	4	3	1
4	2	4	10	10	4	2
3	2	4	10	10	4	2
2	1	3	4	4	3	1
1		1	2	2	1	
	A	B	C	D	E	F

F_j	N	F_j^2	NF_j^2
1	8	1	8
2	8	4	32
3	4	9	36
4	8	16	128
10	4	100	400
Σ	32		604

Figure 9

DECLASSIFIED

XENON CALCULATIONS

Xenon and Iodine Calculations
Effects of Flux Distribution Changes

TABLE I

Values of Re_1 and Re'_1

Tube No.	Re_1	Case 1		Case 2		Case 3	
		$\left(\frac{F_1^2}{F_1^2}\right)_1$	$\times Re_1$	$\left(\frac{F_1^2}{F_1^2}\right)_2$	$\times Re_1$	$\left(\frac{F_1^2}{F_1^2}\right)_3$	$\times Re_1$
1-B	2.7	16/9	4.8	1/9	0.3	1/9	0.3
C	6.4	16/16	6.4	1/16	0.4	4/16	1.6
D	6.4	9/16	3.6	1/16	0.4	4/16	1.6
E	2.7	1/9	0.3	1/9	0.3	1/9	0.3
2-A	2.7	16/9	4.8	1/9	0.3	1/9	0.3
B	21.6	49/36	29.4	4/36	2.4	9/36	5.4
C	34.3	49/49	34.3	4/49	2.8	16/49	11.2
D	34.3	25/49	17.5	4/49	2.8	16/49	11.2
E	21.6	9/36	5.4	4/36	2.4	9/36	5.4
F	2.7	1/9	0.3	1/9	0.3	1/9	0.3
3-A	6.4	49/16	19.6	1/16	0.4	4/16	1.6
B	34.3	100/49	70.0	4/49	2.8	16/49	11.2
C	100.0	100/100	100.0	4/100	4.0	100/100	100.0
D	100.0	49/100	49.0	4/100	4.0	100/100	100.0
E	34.3	16/49	11.2	4/49	2.8	16/49	11.2
F	6.4	4/16	1.6	1/16	0.4	4/16	1.6
Σ	416.8		358.2		26.8		264.2

$$Xe_2 = \Sigma Re' = 2 \Sigma x R_1 \frac{\Sigma F_1^2}{\Sigma F_1^2} = 2(358.2) \left(\frac{1136}{1018} \right) = 800 = 95.7\% \text{ of } \Sigma Re$$

$$Xe_3 = \Sigma Re' = 2 \Sigma x R_1 \frac{\Sigma F_1^2}{\Sigma F_1^2} = 2(26.8) \left(\frac{1136}{80} \right) = 768 = 92.2\% \text{ of } \Sigma Re$$

$$Xe_4 = \Sigma Re' = 2 \Sigma x R_1 \frac{\Sigma F_1^2}{\Sigma F_1^2} = 2(264.8) \left(\frac{1136}{604} \right) = 1000 = 120\% \text{ of } \Sigma Re$$

DECLASSIFIED

EW-73700
Page 25

XENON CALCULATIONS

Xenon and Iodine Calculations Effects of Flux Distribution Changes

Table I shows the results of the three new flux-squared weightings. Reference to Figure 9 shows that these are all rather severe changes with the situation in Figure 6 as the most probable sort of change following a scram recovery. Two further considerations should illustrate that this 4-5% decrease in the effective xenon value should be near an upper limit for the case of an approach to critical for a scram recovery. First - the equilibrium flux distribution in a Hanford pile is ordinarily "flatter" than our reference case; the flatter the original distribution is, the smaller will be the effect of a flux distribution change. In the limit, if all values of Re_i were equal, the immediate effect of a flux change is zero. Second - on a scram recovery, critical is normally reached with 100 or more in of rod still in the pile which reduces the degree of skewness at that time. Of course, the skewness is increased as the recovery level is attained and rods are withdrawn further to cover the metal-heating effect. From a safety standpoint this last part is unimportant; the added available reactivity may help assure recovery.

While the effect of a flux change does not appear to be important safetywise for the routine scram recovery from equilibrium, it can be important for certain tests and selected non-equilibrium scrams. Consider the scram transient test first; assume that the equilibrium flux distribution was less than optimum. For example, we could have an excess of control rod in the pile with the flux skewed toward the far-side. When the technique of holding critical at 1-10 MW is used as described in Chapter 1300 the falling reactivity transient should be a smooth curve - See Figure 10. If a severe flux shift occurs the poison value of the xenon is reduced and a "flat-spot" or a "break" will occur in the curve.* Note that this will always be such as to produce more reactivity than "expected" and that it will be most severe when the flux was skewed away from the rods while at equilibrium.

Figure 10

As a final example, consider a pile operated such as to produce flux skewing toward the front and with an initial tube power distribution as shown in Figure 5. After a scram we will assume that the tube power distribution is

XENON CALCULATIONS

Xenon and Iodine Calculations Effects of Flux Distribution Changes

as shown in Figure 6 and that the front-to-rear skewing is reversed by radical changes in the rod configuration as shown below:

Before					Rel. Pwr. Slug No.
.1	.2	.3	.4	.3	
s_1	s_2	s_3	s_4	s_5	

After				
.3	.4	.3	.2	.1
s_1	s_2	s_3	s_4	s_5

Figure II

The degree of front-to-rear skewing is quite severe and one would intuitively expect that L_s'/L_s would be considerably smaller than shown for cases 1 and 2. The details of the slug-by-slug calculation will not be shown. It was found that:

$$\sum_{i=1}^{i=160} F_i^2 = 442.04, \quad \sum_{i=1}^{i=160} F_i^3 = 1058.672$$

$$\sum_{j=1}^{j=160} F_j^2 = 397.02$$

where the i's and j's refer to slug, not tube volumes. The net result was that $\Sigma Re'/\Sigma Re = 0.655$.

The calculated 35% reduction in the xenon value is not realistic for the practical case since such a radical change in the front-to-rear flux distribution probably cannot be achieved unless deliberate efforts are made.

A compensating effect not mentioned up to this point is that the reactivity contribution caused by the graphite coefficient would be similarly affected by a sudden change in the flux distribution, and the sign would be opposite.

DECLASSIFIED

XENON CALCULATIONS

Xenon and Iodine Calculations

Effects of Flux Distribution Changes

Since the magnitude of the graphite contribution is normally 60-90% of the xenon value, the net effect on pile reactivity, in the hot pile case, would always be smaller than the values suggested by these examples. It is concluded that the reactivity effects of flux distortions need not be considered for the routine hot start-up reactivity prediction. For the cold start-up case it would be possible to have sizeable errors in xenon evaluation if large changes in flux distribution were produced. Such errors would affect the evaluation of the graphite coefficient (see Chapter 2600) but it is most unlikely that they could be large enough to produce a serious prediction error unless very large distortions were deliberately introduced.

DECLASSIFIED

The Xenon Tables
Development of the Tables

It was recognized early by the area physicists that calculating the xenon transient by use of the equation in section 1102.2 and a desk calculator was unnecessarily laborious. The equation can be arranged so that the time and power level dependent variables can be calculated in advance and listed in tables¹⁶. Then the iodine and xenon values can be calculated quickly using these tables and values of iodine and xenon known at some earlier time. The known values are usually the saturation values for the particular power level, the end result of some previous calculation, or zero.

The development of the values which are given in the various xenon tables is shown on the following page.

The factors on the following pages which are identified as (A), (B), (F), (G), and (H) contain only time and power (t & W), the decay constants (I and X), and the direct yield (s) plus the flux distribution and pile size factors A and B. The values of A and B can be calculated for any thermal reactor using Erkman's equations shown in 1102.3; therefore, new tables for thermal reactors of different length, number of tubes, thermal utilization, or frontal area can be produced by information in this Section, Section 1102.3 and HW-29502.⁸

-
8. HW-29502, "Weighting Factors for Radially Flattened Piles", J. O. Erkman, 10-1-53.
16. HW-9761 "Tables of Constants of the Repeating Functions for the Calculation of Iodine and Xenon," 5-6-58, P. M. Thompson.

DECLASSIFIED

The xenon equation on page 7 was:

$$(1) L = \frac{AW}{1 \neq BW} \neq \left[\frac{AWX(1-s) - M_0 I}{I - X(1 \neq BW)} \right] e^{-It} \neq \left[L_0 - \frac{AW}{1 \neq BW} - \frac{AWX(1-s) - M_0 I}{I - X(1 \neq BW)} \right] e^{-X(1 \neq BW)t}$$

This can be rewritten by recombining terms to yield:

$$(2) L = \left(\frac{AW}{1 \neq BW} \right) \left[1 - e^{-X(1 \neq BW)t} \right] \neq \left[\frac{(1-s)AXW}{I - X(1 \neq BW)} \right] \left[e^{-It} - e^{-X(1 \neq BW)t} \right] \neq$$

$$M_0 \left[\frac{I}{I - X(1 \neq BW)} \right] \left[e^{-X(1 \neq BW)t} - e^{-It} \right] \neq L_0 e^{-X(1 \neq BW)t}$$

Separate the second term into the two exponentials and multiply each by $\left(\frac{1 \neq BW}{1 \neq BW} \right)$:

$$(3) L = \left(\frac{AW}{1 \neq BW} \right) \left[1 - e^{-X(1 \neq BW)t} \right] \neq \left(\frac{1 \neq BW}{1 \neq BW} \right) \left[\frac{(1-s)AXW}{I - X(1 \neq BW)} \right] e^{-It} -$$

$$\left(\frac{1 \neq BW}{1 \neq BW} \right) \left[\frac{(1-s)AXW}{I - X(1 \neq BW)} \right] e^{-X(1 \neq BW)t} \neq M_0 \left[\frac{I}{I - X(1 \neq BW)} \right] \left[e^{-X(1 \neq BW)t} - e^{-It} \right]$$

$$L_0 e^{-X(1 \neq BW)t}$$

Re-arrange the second and third terms to separate out the factor $\left(\frac{AW}{1 \neq BW} \right)$; Note that $\left(\frac{AW}{1 \neq BW} \right) = L_s$:

$$(4) L = L_s \left[1 - e^{-X(1 \neq BW)t} \right] \neq L_s \left[\frac{(1-s)X(1 \neq BW)}{I - X(1 \neq BW)} \right] e^{-It} -$$

$$L_s \left[\frac{(1-s)X(1 \neq BW)}{I - X(1 \neq BW)} \right] e^{-X(1 \neq BW)t} \neq M_0 \left[\frac{I}{I - X(1 \neq BW)} \right] \left[e^{-X(1 \neq BW)t} - e^{-It} \right]$$

$$\neq L_0 e^{-X(1 \neq BW)t}$$

Re-arrange to factor out L_s :

$$(5) L = L_s \left[1 \neq \left(\frac{(1-s)X(1 \neq BW)}{I - X(1 \neq BW)} \right) e^{-It} - \left(1 \neq \frac{(1-s)X(1 \neq BW)}{I - X(1 \neq BW)} \right) e^{-X(1 \neq BW)t} \right] \neq$$

$$M_0 \left[\frac{I}{I - X(1 \neq BW)} \right] \left[e^{-X(1 \neq BW)t} - e^{-It} \right] \neq L_0 e^{-X(1 \neq BW)t}$$

Make a substitution of variables where:

$$X_w = X(1 \neq BW); \quad Z = \frac{I}{I - X(1 \neq BW)}; \quad Y = \frac{(1-s)X_w}{I - X_w} = \frac{(1-s)X(1 \neq BW)}{I - X(1 \neq BW)}$$

Then:

$$(6) L = L_s \left[1 \neq Y e^{-It} - (1 \neq Y) e^{-X_w t} \right] \neq M_0 Z \left[e^{-X_w t} - e^{-It} \right] \neq L_0 e^{-X_w t}$$

DECLASSIFIED

Let us now define: $(F) = Ls \left[1 - Y e^{-It} - (1 - Y) e^{-Xwt} \right];$

$$(G) = Z \left[e^{-Xwt} - e^{-It} \right]; \quad (H) = e^{-Xwt}$$

Then at any time t the value of I_t is:

$$(7) \quad I_t = (F)_t + M_0(G)_t + L_0(H)$$

The values of (F) , (G) , and (H) can be calculated by machine for a range of power levels and times. This has been done in a series of xenon tables starting with HW-9761 by P. M. Thompson. The calculated values of (F) , (G) , and (H) are normally listed for one power level and for a series of times on one page.

The iodine equation was given in 1102.2 as:

$$(8) \quad M = \frac{(1-s) AXW}{I} (1 - e^{-It}) + M_0 e^{-It}$$

Again we define: $(A) = \frac{(1-s) (AXW)}{I} (1 - e^{-It}) = M_s (1 - e^{-It})$

$$(B) = e^{-It}$$

Then at any time t the value of M_t is:

(9) $M_t = (A)_t + M_0(B)_t$ and the values of (A) and (B) are listed with (F) , (G) , and (H) for a range of times at each power level W of interest.

DECLASSIFIED

Xenon Tables
Use of the Tables

Examination of equations (7) and (9) in 1103.1 show that the xenon or iodine for any time can be calculated by use of the tables if L_0 and M_0 are known. In actual practice it is necessary to find some time of operation when L_0 and M_0 are close enough to L_s and M_s that the saturation values may be used to begin the calculation. Once this has been done, the tables permit following the changes through the most tortuous ups and downs of power level. Note that they are so arranged that any pair of M & L values calculated can become M_0 and L_0 for a subsequent calculation. Note carefully however that prior calculations, such as for prediction charts, can never be any more accurate than the assumptions

made regarding flattening or the equivalent, $\left(\frac{\sum F_1^3}{\sum F_1^2} \right)$.

Two very simple examples of table use will be given here; more complex examples are given in section 1104. Use the K pile table (HW-33537) and assume that the flattening is zero. In this way the table can be used directly without a flattening correction. For the first example, assume equilibrium zero power level as the reference point. M_0 and L_0 are then zero. Assume W is changed to 100 MW; see p. 15 of HW-33537. At $t = 1$ hr.

$$L = F \lambda G M_0 \lambda H L_0$$

$$L = 1.63 \text{ ih}$$

$$\text{and } M = A \lambda M_0 B$$

$$= 14.06 \text{ ih (potential poison)}$$

The values at 1.1 hr. for example may be found now by using the table for 0.1 hr. and the 1 hr. values as M_0 and L_0 .

$$\text{Then @ 1.1 hr. } L = 0.10 \lambda (0.01028)(14.06) \lambda (0.99120)(1.63)$$

$$= 1.87 \text{ ih}$$

$$\text{and } M = 1.47 \lambda (0.98967)(14.06)$$

$$= 15.38 \text{ ih (potential poison)}$$

Another simple example might start with the power level at an equilibrium 2000 MW. ($M_s = 2852.28$ $L_s = 934.87$; see page 145 of HW-33537) Assume a shutdown to zero level for 0.7 hours, followed by a value of 1500 MW for 1, 2, & 4 hours after the rise to 1500 MW (1500 MW table on p. 135, HW-33537).

DECLASSIFIED

SAMPLE XENON TRANSIET

<u>TIME</u>	<u>W</u>	<u>M</u>	<u>L</u>
0	2000	2852	935 (rounded off)
0.5	0	2708	1042 (see p. 5, HW-33527)
0.7	0	2652	1082 (Use 0.2 values operation on 0.5 values)
1.7	1500	2601	1076
2.7	1500	2556	1067
4.7	1500	2478	1044

The tables in current use for the 2004 tube piles (HW-25565) use the lower case notation a, b, f, g, and h except for the part extended beyond 1000 MW. The meaning is the same. The oldest table (HW-9761) covers 0-300MW in 1 MW steps and lists the values under headings of A, B, & C for xenon and F and G for iodine.

DECLASSIFIED

HW-73700

Page 33

XENON

Routine Calculations (The method of Section I is used in every example).

Example 1: Shutdown

For the purpose of examples the following conditions are assumed:

Type of Pile	3220 Tube
W, Power level	2000 MW (equilibrium)
n, (number of tubes discharged)	200
N, (number of active tubes)	3205
$\sum_{i=1}^N F_i^2$	3640
$\sum_{i=1}^N F_i^3$	4401
$\sum_{i=1}^n F_i^2$	376
$\sum_{i=1}^n F_i^3$	511

From $\frac{\sum_{i=1}^N F_i^3}{\sum_{i=1}^N F_i^2} = 1.204$ and figure 7 of Section 1105 the zero flattening power level

to use is $(0.845) \times (2000) = 1690$ MW. From HW-33537 the closest tabulated power is 1700 MW and the saturated values are: (Interpolation could be used but uncertainties in other values makes this of little value.)

$$M_s = 2424$$

$$L_s = 899$$

Method on page 16 used to evaluate the discharge of L and M:

$$L(d) = \frac{1194 \left(\frac{376}{3640} \right)}{1 - \left(\frac{410.7}{2000} \right) \left(\frac{376}{511} \right)} = \frac{123.3}{1 - 0.151} = 107 \text{ ih}$$

$$M(d) = 2424 \left(\frac{511}{4401} \right) = 281 \text{ ih}$$

The resulting M_0 and L_0 values are then $2424 - 281 = 2143$ and $899 - 107 = 792$. Using the zero power level page in HW-33537 the values at times (t) are:

DECLASSIFIED

XENON (Continued)

SAMPLE XENON TRANSIENT

t	M	L
0	2143	792
1	1932	938
2	1741	1053
3	1570	1142
4	1415	1208
5	1275	1255
8	934	1305 (Max.)
10	759	1285
15	452	1133
20	269	928
25	160	726
30	95	551
40	34	300
50	12	156
60	4	78
80	1	19
100		4

Note the increase in xenon with time following shutdown for about eight hours. While at equilibrium the xenon value was at equilibrium with the decay from I^{135} , the decay of Xe^{135} and xenon burnout. As soon as the power level is reduced to zero the burn-out factor becomes zero; however, the decay from I^{135} remains essentially unchanged until the iodine backlog is materially reduced. The calculation is plotted on page 35.

DECLASSIFIED

HW-73700
Page 35

FIGURE
XENON CHANGES FOLLOWING SHUTDOWN. SEE EXAMPLE 1 CONDITIONS:
SHUTDOWN FROM EQUILIBRIUM @ 2000 MW, K PILES

DECLASSIFIED

HW-73700
Page 36

XENON

Routine Calculations

Example 2 - Simple Start-Up

A simple start-up might be considered as one in which the power level did not change once the start-up was accomplished. Ordinarily this is not a practical type of start-up, but it will illustrate the method. Assume that a start-up can be made 25 hours after the shutdown in Example 1, and that the power level can be brought immediately to 2000 MW. The values of M_0 and L_0 are then 160 and 726, and the values of M_t and L_t are calculated below using the 1700 MW table from HW-33527. Note that here it has been tacitly assumed that the flattening or flux distribution is essentially that which existed before shutdown.

SIMPLE START-UP XENON TRANSIENT

<u>TIME</u>	<u>M</u>	<u>L</u>
0	160	726
1	383	578
2	585	487
3	766	437
4	929	415
5	1076	413 Minimum
6	1210	423
10	1622	523
15	1947	656
20	2140	750
25	2255	810
30	2324	846
40	2389	880
50	2412	893
75	2423	899
100	2424	899

For the first five hours after start-up the xenon decay and burnup exceeds the decay from iodine to xenon. The two rates become equal at about five hours; this normally coincides closely with the reactivity "turnaround" of the pile during start-up, although this turnaround time is also strongly affected by the graphite temperature coefficient and the effective moderator conductivity. The results are plotted on Page 37.

FIGURE

XENON CHANGE FOLLOWING SHUTDOWN AND STARTUP
 EXAMPLE 2 CONDITIONS: SHUTDOWN K FROM 2000 MW EQUILIBRIUM
 STARTUP @ 25 HOURS TO 2000 MW

DECLASSIFIED

DECLASSIFIED

HW-73700
Page 38XENON

Routine Calculations

Example 3 - Complex Start-Up

A pile start-up and the associated xenon calculations can be about as complex as the imagination will permit. For this example a situation will be chosen which approximates some start-ups that have occurred. The starting point will be the forty hours case from Example 1 where $M = 34$ and $L = 300$. The power level will be 1500 MW for three hours, then reduced to 1000 MW for four hours, increased to 1500 MW for eight hours, shutdown for four hours and returned to 1500 for eight hours. The table used was HW-33537 and $\frac{\sum_{i=1}^N F_i^3}{\sum_{i=1}^N F_i^2}$ was assumed to be 1.209; there-

fore, the "equivalent" power levels in the tables would be 1268 and 840 in place of 1500 and 1000 MW respectively.

MORE COMPLEX START-UP XENON TRANSIENTS

<u>TIME</u>	<u>PILE POWER</u>	<u>TABLE POWER</u>	<u>M</u>	<u>L</u>
0	1500	1270	34	300
1	1500	1270	209	250
2	1500	1270	367	240
3	1500	1270	509	240
3	1000	840	509	240
4	1000	840	577	258
5	1000	840	638	280
6	1000	840	693	303
7	1000	840	743	327
7	1500	1270	743	327
8	1500	1270	848	341
9	1500	1270	943	362
11	1500	1270	1106	412
15	1500	1270	1346	521
15	0	0	1346	521
16	0	0	1213	611
17	0	0	1094	682
18	0	0	986	736
19	0	0	889	776
19	1500	1270	889	776
20	1500	1270	980	707
21	1500	1270	1062	660
23	1500	1270	1202	614
25	1500	1270	1316	606
27	1500	1270	1409	618

In this case note that xenon turn-around occurs first at about 2.5 hours. A power cut might be made at this time for any one of several reasons, but note that xenon growth continues. A power cut might be made purposely to cause a xenon turn-around. The return to 1500 MW at seven hours only slowed the growth of xenon for a few hours, but the 4 hour shutdown allowed the xenon to increase by 250 ih. The subsequent operation at 1500 MW caused another xenon turn-around at 25 hours. The transient is plotted on Page 39.

FIGURE

XENON CHANGES FOLLOWING SHUTDOWN AND TYPICAL STARTUP
EXAMPLE 3 CONDITIONS: SHUTDOWN FROM 2000 MW EQUILIBRIUM, STARTUP
AFTER 40 HOURS, STARTUP LEVELS AS INDICATED
IN GRAPH.

DECLASSIFIED

DECLASSIFIED

HW-73700
Page 40

XENON

Routine Calculations

Example 4 - Scram Recovery

If a pile is shutdown from equilibrium power for a short time the xenon starts to increase rapidly but changes only slowly after a recovery to power is made. Other considerations together with the xenon effect make minimum required recovery power levels of the order of $2/3$ to $3/4$ of the equilibrium power level. In this example assume a scram from 2000 MW with conditions as in Example 1, except that there is no discharge. Assume a recovery is made to 1500 MW (1270 MW Table) and calculate the xenon transient.

SCRAM AND RECOVERY XENON TRANSIENT

<u>TIME</u>	<u>PILE POWER</u>	<u>TABLE POWER</u>	<u>M</u>	<u>L</u>	<u>ΔL START-UP</u>
0	2000	1700	2424	899	
0	0	0	2424	899	
0.5	0	0	2301	986	
0.5	1500	1270	2301	986	0
1.0	{	{	2276	991	- 5
1.5			2252	995	- 9
2.0			2230	997	-11
2.5			2209	998	-12
3.0			2189	998	-12
4	1500	1270		992	- 6
6		{		977	+ 9
8				959	+27

The transient is plotted on Page 41.

FIGURE :
 XENON CHANGE FOLLOWING A SCRAM WITH AND WITHOUT RECOVERY
 EXAMPLE 4 CONDITIONS: K PILE SCRAM FROM 2000 MW, RECOVERY TO 1500 MW.

DECLASSIFIED

DECLASSIFIED

XENON

Useful and Descriptive Curves

General Use of Curves

The following curves serve two purposes: They illustrate the functional relationships as an aid in training new personnel. Equally important, they are reproduced in such a way that values can be read with sufficient precision that the curves may be used in calculations. Some of the figures were included in Section 1102 but are repeated here to provide a complete set in one place.

DECLASSIFIED

XENON

Useful and Descriptive Curves

Saturated Iodine and Xenon Values for a 2004 Tube Pile

Figure 1 gives the saturation values of iodine and xenon in a 2004 tube unflattened pile as a function of power level. The fact that the xenon asymptotically approaches a limiting value, whereas the iodine increases without end, explains why the pile sub-critical time (minimum down time) increases generally as the pile power level does. When the pile is shut down all xenon burnup ceases, but the decay from iodine to xenon continues unabated. Figure 1 may be used with Figure 7 to give M_0 and L_0 values for any degree of flattening and any power level in one of the older Hanford reactors.

DECLASSIFIED

Figure 1
Saturated Iodine and Xenon Values with Zero Flattening
Vs. Power Level
2004 Tube Pile

DECLASSIFIED

XENON

Useful and Descriptive Curves

Saturated Iodine and Xenon Values for a 3220 Tube Pile

Figure 2 provides saturation values of Iodine and Xenon for the unflattened 3220 tube pile for power levels up to 10,000 MW. Figure 8 should be used in conjunction with Figure 2 to find M_s and L_s values for any degree of flattening and any power level in one of the K Piles.

DECLASSIFIED

HW-73700
Page 46

Figure 2
Saturated Iodine and Xenon Values with Zero Flattening
Vs. Power Level
3220 Tube Pile

DECLASSIFIED

XENON

Useful and Descriptive Curves

Rate of Change in Saturation Xenon with Power Level - 2004 Tube Pile

Ultimate changes in reactivity for small power changes can be readily estimated at any level in a 2004 tube pile from Figure 3. Note that this curve gives no information about the transient values; it merely lists the rate of change in the saturation value in terms of inhours per megawatt.

DECLASSIFIED

FIGURE 3
The Rate of Change of the Saturation Xenon Value with Power Level
(The Value at Zero is 4.06 ih/MW)
2004 Tube Piles

$$\frac{d(L_s)}{dw} = \frac{A}{(1+Bw)^2}$$

DECLASSIFIED

XENON

Useful and Descriptive Curves

Rate of Change in Saturation Xenon with Power Level - 3220 Tube Pile

Figure 4 provides information for the K piles similar to that described by Figure 3 for the older piles.

DECLASSIFIED

FIGURE 4

THE RATE OF CHANGE OF THE SATURATION
XENON VALUE WITH POWER LEVEL
(THE VALUE AT ZERO IS 2.32 ih/MW)
3220 TUBE PILES

$$\frac{d(L_g)}{dW} = \frac{A}{(1+BW)^2}$$

DECLASSIFIED

XENON

Useful and Descriptive Curves

Xenon Transients Following Shutdown from Various Power Levels - 2004 Tube Pile:

Figure 5 illustrates how the xenon buildup following an outage changes with power level. These curves could be qualitatively inferred from Figure 1; however, these curves now permit quick estimation of the rate at which the pile loses reactivity when first shut down. The average loss-rate for the first hour is given in the inset as a function of the equilibrium level with zero flattening. The figures may be used also to approximate quickly the rate of change of reactivity at the time of approach to critical during a hot start-up. Figure 7 may be used to find the equivalent power for a flattened case.

DECLASSIFIED

FIGURE 5
XENON CHANGE FOLLOWING SHUTDOWN FOR
VARIOUS POWER LEVELS IN A 2004 TUBE PILE

DECLASSIFIEDXENON

Useful and Descriptive Curves

Xenon Transients Following Shutdown from Various Power Levels - 3220 Tube
Piles

Figure 6 shows K Pile xenon build-up rates immediately following shutdown as described on Page 51 for the old pile case in the previous figure. Figure 8 indicates the equivalent power to be substituted to take account of flattening.

DECLASSIFIED

HW-73700
Page 54

FIGURE 6
XENON CHANGE FOLLOWING SHUTDOWN FOR
VARIOUS POWER LEVELS IN A 3220 TUBE PILE

DECLASSIFIED

XENON

Useful and Descriptive Curves

Equivalent Pile Power Ratio vs. Weighted Flux Distribution

Only one xenon table is necessary for all degrees of flattening for a given pile with the use of Figure 7. The values required may be obtained by taking the summations indicated over the uranium-loaded tubes (or over all tubes in the reactor without significant difference since the ratio is used rather than the absolute values). The value of A_1/A_0 read from the curve is the ratio of the A or B values in the xenon and iodine equations for different degrees of flattening. Since A & B change in the same way with flattening, an equivalent power level zero flattening table may be used. The known actual power level is multiplied by the A_1/A_0 value determined from the ratio of $\sum F_1^3 / \sum F_1^2$; this yields an equivalent lower power level at which the zero flattening xenon table provides the correct xenon and iodine information.

DECLASSIFIED

DECLASSIFIED

XENON

Useful and Descriptive Curves

Weighted Flux Distribution vs. Inhours in Flattening

These curves permit transferring from one method of xenon calculation to the other. Since the constants (A and B) in section 1102.2 were derived by calculating

$\frac{\sum F_1^3}{\sum F_1^2}$ for various degrees of flattening, nothing is gained by the use of these

curves if $\sum F_1^3$ is already known. Flattening efficiency uncertainties make it

undesirable to correct from flux distribution to effective flattening since the constants on page 7 assume an arbitrary flattening efficiency; the definition of flattening efficiency in this case is given on page 1102.2-3.

DECLASSIFIED

FIGURE 8

$\left(\frac{\text{Pile } \sum F_i^3}{\text{Pile } \sum F_i^2} \right)$ VS. Effective Flattening in Inhours

DECLASSIFIED

Section 1200 Authored by

SR Stamp

Date of Issue _____.

COLD START-UP PREDICTIONS*

SECTION 2

CONTENTS

	<u>PAGE NO.</u>
Purpose	60
Transient Changes of Reactivity	
Xenon Reactivity Transient	61
Graphite Reactivity Contribution	62
Metal Reactivity Loss	66
Other Transient Effects	67
Loading Changes	
Natural Uranium	70
Flattening	72
Enrichment	73
Other Loading Changes	74
Calculation of Pile Reactivity Changes	
List of Symbols	76
Calculation of R_{∞}	77
Transient Calculations	78
Types of Start-Ups	
High Level Start-Up	80
Low Level Start-Up	87
Cutback Start-Up	89
Temporary Poison Start-Up	93
Forced Poison Start-Up	95
Form of Prediction Presentation	99

*This section replaces HW-24975.

DECLASSIFIED

HW-73700
Page 60

COLD START-UP PREDICTIONS

Purpose

Accurate reactivity predictions are necessary for safe and efficient operation of the reactors. Cold-start-up predictions inform operating personnel (1) when the shutdown pile can be started, (2) what the most productive start-up is as a function of downtime, (3) what the magnitude of the excess reactivity is during the anticipated start-up interval and as the reactivity transient passes through its initial maximum following start-up, and (4) when hot start-up procedures apply following the initial cold start-up. (For differentiation between hot and cold start-ups see the Process Standards, HW-46000).

A critical prediction is necessary for a controlled rise to the start-up power level. Should a start-up be attempted without an accurate critical prediction, too much control rod might be withdrawn. The resulting rapid power rise could cause damage to the reactor.*

During operation the pile reactivity is not permitted to exceed the control capacity of the horizontal rods and available supplementary control. The predicted reactivity transient following start-up is provided for comparison with the observed transient. Should the comparison indicate that at its maximum the reactivity of the pile might be greater than the capacity of the horizontal rods plus supplementary control, remedial action could be initiated in time to avoid a shutdown, which undesirably reduces production efficiency.

A prediction is prepared by the Area Physicist for each cold and planned secondary cold start-up. Predictions are presented in the form of graphs of excess reactivity versus time with accompanying recommendations for their use.

---

* Start-ups could be made safely without accurate predictions, provided control rods were withdrawn more slowly; however, decreased production efficiency would result.

DECLASSIFIED

COLD START-UP PREDICTIONS

Transient Changes of Reactivity
Xenon Reactivity Transient

The reactivity effect of xenon is discussed in Section 11 of this manual, and detailed examples under Item 1104 show how the reactivity changes following shutdown and start-up are calculated.

COLD START-UP PREDICTIONS

Transient Changes of Reactivity Graphite Reactivity Contribution

With the exception of reactivity losses associated with uranium heating and xenon poisoning, all other short term reactivity changes are lumped in the graphite contribution. These changes are caused by changes in material densities with material temperatures and by variations of neutron cross sections with neutron energy.^{1,2,3,4,5} The energy spectrum of neutrons impinging upon the slug is related to the graphite temperature which in turn is related to the local power. Thus, for simplicity the graphite temperature coefficient of reactivity is treated as a power coefficient. The composition of the reactor atmosphere, a mixture of helium and carbon dioxide, governs the conductivity across the gap between the graphite and the tube and thereby affects the graphite temperature and determines the graphite contribution; therefore, the graphite contribution is corrected for the reactor gas composition. In addition, the magnitude of the coefficient depends strongly on the plutonium concentration. The plutonium concentration is proportional to exposure, and since the reactivity effect varies as the square of the local flux, the graphite coefficient is usually expressed as a linear function of the flux-squared weighted uranium exposure in MWD/T - called E. (See Chapter 1400, HW-46100, Vol. 2)

Following a shutdown or power cut, the graphite reactivity contribution decays on a characteristic exponential period, T_f , which is affected by the reactor gas composition. The value of T_f should be the flux squared weighted average of the cooling periods for each element of lattice rather than the cooling period for a particular thermocouple location or the simple average for a few locations. This is particularly true at the K Reactors where the tube channels are overbored near the edges of the pile to minimize tube distortion caused by graphite growth. Although such weighted averages were obtained during early operation of the K Reactors, lack of sufficient thermocouples prevents this approach at the present. Instead, the value used is the one usually found by trial and error to best fit observed scram transient data. A single value seems to work well over a rather wide range of helium concentrations. After a power cut from one level, W_0 , to another, W_1 , the graphite contribution, C_g , varies as the following expression:

$$C_g(t) = C_g(W_0 - W_1) e^{-t/T_f} + C_g W_1,$$

where C_g is the graphite coefficient in inhours per megawatt, W_0 and W_1 are pile power levels in megawatts, t is the time in hours following the power change, and T_f is the falling period.

1. HW-23548, "Temperature Coefficients of Hanford Type Lattice", G. E. Duvall, 2-14-52.
2. 7-6428, "Samarium Temperature Coefficient", P. F. Gast, 6-19-47.
3. HW-32934, "The Dependence of Long Term Gains on Neutron Temperature and the Variation of the Graphite Temperature Coefficient With Exposure", R. E. Heineman, 9-2-54.
4. HW-35786, "Reactivity Dynamics of a Thermal Reactor", R. E. Heineman, 4-15-55.
5. HW-38532, "The Determination of Temperature and Exposure Coefficients of Reactivity From Pile Data", R. E. Heineman, 8-8-55.

DECLASSIFIED

COLD START-UP PREDICTIONS (Continued)

When the reactor power is raised from an initial level, W_0 , to a new level, W_1 , the graphite contribution, which may not have been at equilibrium for W_0 , rises on an exponential period which observation indicates is nearly independent of gas composition. This change progresses according to the following expression:

$$C_G(t) = [C_G W_1 - C_G(t_0)] (1 - e^{-t/T_r}) + C_G(t_0)$$

where T_r is the rising period in hours and t_0 is the time the power is raised from W_0 to W_1 .

For convenience tables of $e^{-t/T}$ and $(1 - e^{-t/T})$ versus time are provided for the range of periods normally encountered. See Table I.

DECLASSIFIED

TABLE I

RISE AND FALL PERIODS
(Calculated from tables of e^{-x} and $1 - e^{-x}$)

DECLASSIFIED															
	1	2	.25	.3	.4	.5	.75	1	2	3	4	5	6	7	8(Hours)
30 R	.181	.330	.393	.451	.551	.632	.777	.865	.982	.998					
F	.819	.670	.607	.549	.449	.368	.223	.135	.018	.002					
35 R	.158	.290	.349	.402	.496	.576	.724	.820	.968	.994	.999				
F	.842	.710	.651	.598	.504	.424	.276	.180	.032	.006	.001				
40 R	.139	.259	.313	.362	.451	.528	.675	.777	.950	.989	.998				
F	.861	.741	.687	.638	.549	.472	.325	.223	.050	.011	.002				
45 R	.125	.234	.283	.330	.413	.487	.632	.736	.931	.982	.995	.999			
F	.875	.766	.717	.670	.587	.513	.368	.264	.069	.016	.005	.001			
50 R	.113	.213	.259	.302	.381	.451	.593	.699	.909	.973	.992	.998			
F	.887	.787	.741	.698	.619	.549	.407	.301	.091	.027	.008	.002			
55 R	.103	.196	.239	.279	.354	.420	.559	.664	.887	.962	.987	.995	.998		
F	.897	.804	.761	.721	.646	.580	.441	.336	.113	.038	.013	.005	.002		
60 R	.095	.181	.221	.269	.330	.393	.528	.632	.865	.950	.982	.993	.998		
F	.905	.819	.779	.741	.670	.607	.472	.368	.135	.050	.018	.007	.002		
65 R	.088	.169	.206	.242	.309	.370	.500	.603	.842	.938	.975	.990	.996	.998	
F	.912	.831	.794	.758	.691	.630	.500	.397	.158	.062	.025	.010	.004	.002	.001
70 R	.082	.157	.193	.227	.290	.349	.474	.576	.820	.924	.968	.986	.994	.997	.999
F	.918	.843	.807	.773	.710	.651	.526	.424	.180	.076	.032	.014	.006	.003	.001
75 R	.077	.148	.181	.213	.274	.330	.451	.551	.798	.909	.959	.982	.992	.997	.999
F	.923	.852	.819	.787	.726	.670	.549	.449	.202	.091	.041	.018	.008	.003	.001
	.1	.2	.25	.3	.4	.5	.75	1	2	3	4	5	6	7	8(Hours)

Period in Minutes

DECLASSIFIED

REF-73708
Page 65

TABLE I (Continued)

	1	2	.25	.3	.4	.5	.75	1	2	3	4	5	6	7	8 (Hours)
80 R	.072	.139	.171	.201	.259	.313	.430	.528	.777	.895	.951	.977	.989	.995	.998
F	.928	.861	.829	.799	.741	.687	.570	.472	.223	.105	.049	.023	.011	.005	.002
85 R	.069	.132	.162	.191	.246	.297	.411	.506	.756	.880	.940	.970	.985	.992	.996
F	.931	.868	.838	.809	.754	.703	.589	.494	.244	.120	.060	.030	.015	.008	.004
90 R	.065	.125	.153	.181	.234	.283	.393	.487	.736	.865	.930	.964	.981	.990	.995
F	.935	.875	.847	.819	.766	.717	.607	.513	.264	.135	.070	.036	.019	.010	.005
95 R	.061	.119	.146	.173	.223	.271	.377	.468	.717	.850	.920	.958	.977	.988	.993
F	.939	.881	.854	.827	.777	.729	.623	.532	.283	.150	.080	.042	.023	.012	.007
100 R	.058	.113	.139	.165	.213	.259	.362	.451	.699	.835	.909	.950	.973	.985	.992
F	.942	.887	.861	.835	.787	.741	.638	.549	.301	.165	.091	.050	.027	.015	.008
105 R	.056	.108	.133	.158	.204	.249	.349	.435	.681	.820	.898	.942	.967	.981	.989
F	.994	.892	.867	.842	.796	.751	.651	.565	.319	.180	.102	.058	.033	.019	.011
110 R	.053	.103	.127	.151	.196	.239	.330	.420	.664	.805	.887	.935	.963	.979	.988
F	.947	.897	.873	.849	.804	.761	.664	.580	.336	.195	.113	.065	.037	.021	.012
115 R	.051	.099	.122	.145	.188	.230	.324	.406	.648	.791	.876	.926	.956	.974	.985
F	.949	.901	.878	.855	.812	.770	.676	.594	.352	.209	.124	.074	.044	.026	.015
120 R	.049	.095	.117	.139	.181	.221	.313	.393	.632	.777	.865	.918	.950	.970	.982
F	.951	.905	.883	.861	.819	.779	.687	.607	.368	.223	.135	.082	.050	.030	.018
125 R	.047	.092	.113	.134	.175	.213	.302	.381	.617	.763	.853	.903	.944	.965	.979
F	.953	.908	.887	.866	.825	.787	.698	.619	.383	.237	.147	.091	.056	.035	.021
130 R	.044	.088	.109	.129	.169	.206	.293	.370	.603	.750	.842	.901	.937	.960	.975
F	.956	.912	.891	.871	.831	.794	.707	.630	.397	.250	.158	.099	.063	.040	.025
135 R	.043	.085	.105	.125	.163	.199	.283	.359	.589	.736	.831	.892	.931	.955	.971
F	.957	.915	.895	.875	.837	.801	.717	.641	.411	.264	.169	.108	.069	.045	.029
140 R	.042	.082	.102	.121	.158	.193	.275	.349	.576	.724	.820	.883	.924	.950	.968
F	.958	.918	.898	.879	.842	.807	.725	.651	.424	.276	.180	.117	.076	.050	.032
	.1	.2	.25	.3	.4	.5	.75	1	2	3	4	5	6	7	8 (Hours)

Percent in Minutes

DECLASSIFIED

HW-73700
Page 66

COLD START-UP PREDICTIONS

Transient Changes of Reactivity
Metal Reactivity Loss

A nearly instantaneous reactivity increase accompanies every power cut, and likewise, a power increase causes a reactivity loss. This phenomenon, which is known as the metal effect, is caused primarily by Doppler broadening of the U-238 resonance capture cross section as the metal temperature increases.⁶ All available information indicates that the metal coefficient, C_m , in inhours per megawatt is a constant over the entire range of power experienced; however, values of the coefficient should differ with lattice size, thickness of the water annulus, the amount of uranium in the pile, and to a small degree with coolant flow rate. The metal loss, C_M , equals $\Delta W C_m$, where ΔW is the power change and C_m is the metal coefficient, a negative quantity, in inhours per megawatt.

6. HW-235-8, "Temperature Coefficients of Hanford Type Lattices", G. E. Duvall, 2-14-52.

DECLASSIFIED

HW-73700
Page 67

COLD START-UP PREDICTIONS

Transient Changes of Reactivity Other Transient Effects

Four additional transient effects are important. Three of these are associated with long term gains, described more fully in chapter 1400, and the fourth occurs during an abnormal operating condition. The three main effects which compose the net long term gains are: (1) U^{235} depletion, (2) samarium build-up, and (3) plutonium build-up. The depletion of U^{235} and build-up of Sm^{149} poison cause the reactivity of freshly charged uranium to decrease. At about 60 MWD/ton, as the Samarium approaches saturation, the rate of reactivity gain from plutonium build-up begins to exceed the rate of reactivity loss caused by the U^{235} depletion and Sm^{149} build-up. The reactivity continues to increase until the effects of U^{235} and plutonium burn-out begin to exceed the effect of plutonium build-up at about 600 MWD/ton. Beyond this exposure the metal continues to lose reactivity.

Atoms of U^{235} are consumed in the fission process. Their rate of depletion is proportional to their concentration and to power. Since the average power generally remains nearly constant during the normal in-pile residence of a natural uranium column, the U^{235} depletion rate depends primarily on U^{235} concentration which decreases with exposure; therefore, the U^{235} depletion rate gradually decreases with exposure. At the current goal exposure of 500 MWD/ton about 9 per cent of the U^{235} has been consumed.⁷

Promethium-149, produced by the fission of U^{235} , decays on a 2.2 day half life to Sm^{149} which is a stable nuclide with an absorption cross section of 66,000 barns.⁸ Under steady-state conditions the reactivity absorbed reaches a maximum which is independent of power.⁹ Thus the build-up of Sm^{149} is primarily responsible for the initial dip in the long term gains curve. Following shutdown, the Pm^{149} present at shutdown decays to Sm^{149} and causes a reactivity loss.⁸ This additional samarium loss gradually disappears as the samarium comes to equilibrium again after start-up.

Plutonium is produced primarily by the following chain:

7. HW-31285, "Product Yield and Quality and U^{235} Depletion in Irradiated Natural Uranium", R. O. Gumprecht, 11-10-55.
8. HW-46377, "Long Term Reactivity Data from Irradiated Slugs - Final Report IT-105-553-A", C. E. Bowers & R. O. Gumprecht, 2-15-57.
9. Glasstone and Edlund, "The Elements of Nuclear Reactor Theory", New York: D. Van Nostrand Co., 1952, p.338.

DECLASSIFIED

HW-73700
Page 68

COLD START-UP PREDICTIONS (Continued)

Although Pu^{239} build-up does not replace U^{235} burn-out atom for atom, it does provide a reactivity increase since Pu^{239} yields more neutrons per fission than U^{235} . However, above 600 MWD/ton the burn-out of both U^{235} and Pu^{239} overrides this effect, and reactivity decreases with exposure. Following shutdown the decay Np^{239} to Pu^{239} produces a reactivity increase.⁸ When equilibrium operation is resumed, this reactivity gain gradually disappears.

Magnitudes of the Pm-Sm and Np-Pu transients are power dependent and almost equal, and the half lives of Pm^{149} and Np^{239} are nearly equal; therefore, these transients are not calculated in actual practice since they very nearly cancel each other.

The fourth type of transient occurs occasionally when water enters the moderator through a process tube break and when this water is removed following the tube repair. Water in the moderator acts as a nuclear poison, and the size of its effect on pile reactivity will depend on its quantity and location. Since generally it is not possible to determine the amount of water in the moderator or its exact location, it is virtually impossible to calculate the reactivity loss caused by a water leak.

8. HW-46377, "Long Term Reactivity Data from Irradiated Slugs - Final Report - PT-105-553-A", C. E. Bowers & R. O. Gumprecht, 2-15-57.

DECLASSIFIED

HW-73700
Page 69

COLD START-UP PREDICTIONS

Loading Changes

The main objective in operating the Hanford reactors is to produce the required amount of plutonium as cheaply as possible. Since the rate at which plutonium is produced affects its cost and is proportional to the reactor power level, it is desirable to operate the largest possible number of tubes at the maximum permissible tube power. The practice of loading neutron absorbers and uranium enriched in the U^{235} isotope or enriched uranium alloys to achieve this result is called flattening. In general the enriched material, called enrichment, is loaded in an annular ring near the edge of the pile to raise the lower tube powers in that region, while neutron absorbent material called flattening is loaded near the center of the reactor to depress the higher tube powers usually located there. Flattening is also adjusted to compensate for local reactivity effects caused by replacing irradiated uranium with fresh material. This section describes the influence of loading changes on reactivity predictions. See Chapter 2200, 2300, 3100, and 3200 for more information on flattening and enrichment.

COLD START-UP PREDICTIONSLoading Changes
Natural Uranium

Natural uranium columns are discharged when they reach a goal exposure either corresponding to a fuel element rupture limit or to a desired product quality which is determined by the ratio of Pu-240 to Pu-239 present. At present tube powers the irradiated column is more reactive in both the hot and cold pile than the fresh column replacing it, except at very low exposures where the plutonium build-up has not yet compensated for U²³⁵ burn-out and Sm¹⁴⁹ buildup. As tube powers are increased the long term gains curve is displaced downward, and eventually unexposed uranium will be more reactive than irradiated uranium in the cold pile.⁸ The temperature dependent portion of the effect of irradiated uranium is taken into account with the graphite coefficient, which varies with the flux-squared weighted exposure and the composition of the reactor atmosphere. Note that this change in coefficient does not affect the prediction of pile reactivity while the reactor remains cold. The net loss of cold pile reactivity caused by discharging irradiated natural uranium columns is described by a function of the flux-squared weighted exposure, $\bar{E}$, of the discharge:

$$\Delta R = -(A + B \bar{E} + C \bar{E}^2 - D \bar{p}) \frac{\sum_{i=1}^n f_i^2}{\sum_{i=1}^N f_i^2}$$

where: n is the number of columns being discharged,
 N is the total number of active columns,
 f_i is the tube factor of the i th column,
 $(A + B \bar{E} + C \bar{E}^2)$ represents the difference between the cold clean reactivity of a zero exposure pile and a pile at the same weighted exposure as the discharge,

$$\frac{\sum_{i=1}^n f_i^2}{\sum_{i=1}^N f_i^2} \text{ is the reactivity fraction being discharged,}$$

$$\bar{E} \text{ discharge} = \frac{\sum_{i=1}^n E_i f_i^2}{\sum_{i=1}^n f_i^2}$$

$$\bar{p} = \frac{W}{N} \frac{\sum_{i=1}^n f_i^3}{\sum_{i=1}^n f_i^2} = \frac{\sum_{i=1}^n (kw_i) f_i^2}{\sum_{i=1}^n f_i^2} = \text{weighted average tube power}$$

8. HW-46377, "Long Term Reactivity Data from Irradiated Slugs - Final Report - PT-10-53-A", C. E. Bowers and R. O. Gumprecht, 2-15-57.

COLD START-UP PREDICTIONS (Continued)

A corresponds to the value of saturated samarium poisoning,⁸

B & C are constants which determine the shape of the long term gains curve,⁸ and

D is the displacement of the gains curve⁸ per unit flux squared weighted tube power which is caused by the hold-up of plutonium in the form of Np^{239} by virtue of the Np^{239} half life. D is most conveniently evaluated by stating tube power units in kilowatts.

For more information on A, B, C, and D see Chapter 1400.

---

8. HW-46377, "Long Term Reactivity Data from Irradiated Slugs - Final Report - PT-105-553-A", C. E. Bowers and R. O. Gumprecht, 2-15-57.

DECLASSIFIED

COLD START-UP PREDICTIONS

Loading Changes
Flattening

As the residual exposure of the reactor changes, flattening column strengths may be varied to maintain a flat radial distribution of tube powers and to regulate the reactivity controlled by horizontal rods during equilibrium operation. The reactivity effect of a flattening column is determined by the type of neutron absorbing material used, the amount and location of the poison in the tube, and the location of the tube in the reactor tube power pattern. Tables of nominal reactivities, based on an assumed cosine flux distribution along the tube axis, are available for several poison charge lengths with various displacements from the front-to-rear centerline. (See chapters 2200 and 3100) If tube factor data are available the effective reactivities of flattening columns can be calculated for the given tube power distribution. The tube power distribution following loading changes can not be predicted accurately in advance; therefore, the nominal reactivity changes are normally converted to effective reactivities with an average nominal-to-effective ratio. These nominal values are based largely on the critical pile test data reported in HW-29034, "C Pile Start-Up Technical Data", D. K. McDaniels and G. C. Fullmer, 9-1-53 and "K Pile Start-Up Experiments, Part III, Reactivity Effects of Fuel and Target Materials", C. L. Miller, 4-2-56.

DECLASSIFIED

HW-73700
Page 73

COLD START-UP PREDICTIONS

Loading Changes
Enrichment

The term enrichment includes all materials which are more reactive than natural uranium and which are loaded specifically to increase pile reactivity or the number of tubes operating at maximum power. In general enrichment consists of two types - an Al-U²³⁵ alloy or natural uranium enriched in the U²³⁵ isotope. An Al-U²³⁵ alloy containing about 4 per cent U²³⁵ by weight, called C material, has been used as standard enrichment material for several years. Currently, this is being replaced by E material which is uranium containing 0.94 per cent of the U²³⁵ isotope. (Natural uranium contains 0.71 per cent U²³⁵) Enrichment column reactivities are calculated in the same manner as flattening column reactivities except the nominal reactivity of a C column varies with exposure.¹⁰ The reactivity contributed by three E columns is equivalent to that of one new C column, and the nominal reactivity of an E column remains nearly constant up to exposures of about 600 MWD/ton since plutonium build-up nearly compensates for U²³⁵ burn-out.

10. HW-36104, "C Column Power and Reactivity Calculations", R. O. Brugge, 4-15-55.

DECLASSIFIED

HW-73700
Page 74

COLD START-UP PREDICTIONS

Loading Changes

Other

Other loading changes which influence pile reactivity are: (1) special requests and plant assistance, (2) temporary poison, (3) non-standard uranium columns, (4) special power-producing columns, and (5) splines.

Special requests and plant assistance are special irradiations performed under particular production tests. Special requests include materials irradiated for other AEC sites for isotope production or materials testing. Plant assistance irradiations provide information for the improvement of the Hanford production process. Nominal reactivities generally specified in the production tests are used with pile fractions data (See Chapter 2100) to predict the effective reactivities of these loadings.

Temporary poison columns consist of Pb-Cd (3-4% Cd) slugs which are contained in aluminum cans. These slugs are essentially 100 per cent "black", which means the slug absorbs all the thermal neutrons which enter it. Temporary poison is used primarily for supplementary reactivity control during start-up; however, it is also charged into poison column control tubes for flattening during equilibrium operation. These tubes are specially equipped to permit the charge or discharge of poison during operation. Since the irradiation of temporary poison material produces no useful product, there is no restriction on the length of the irradiation. Thus it is called a flexible poison. When an outage is sufficiently long, tubes in addition to the poison column control tubes must be loaded with temporary poison. To discharge temporary poison from standard tubes requires a special shutdown. It is not possible to predict accurately the reactivity effect of a given temporary poison column. During start-up the flux distribution varies, and consequently the effect of an individual column can change ± 35 per cent. Average values have been determined from past experience for various temporary poison loadings, and in actual practice these average values are used.

Cored and I & E slugs are non-standard uranium charges under test for use in the future. Cored slugs are solid slugs with an axial void, and I & E slugs are cored slugs fabricated to permit coolant flow through the axial hole and along the outside of the slug. Enriched slugs could be either cored or I & E, but it is probable that only I & E slugs will be used since they should be the more rupture resistant type at high slug powers. Reactivity effects of each type of non-standard uranium charge must be evaluated separately since in general reactivity coefficients, long term gains, and xenon poisoning will differ.

Special power producing columns include J-N, J-Q, and E-N columns. These consist of poisonous isotope-producing slugs loaded alternately with enriched slugs to compensate for the reactivity they absorb. The types are defined below:

J material - an Al-U²³⁵ alloy containing about 7 per cent U²³⁵ by weight.

N material - a Li-Al alloy used for tritium production.

Q material - thorium used for U²³³ production.

E material is defined on page 73.

Each of these types must be evaluated separately just as the types of non-standard uranium.

DECLASSIFIED

COLD START-UP PREDICTIONS (Continued)

Poison splines are being tested as a supplement to the horizontal rod system. A spline is a long, thin strip of aluminum which forms an envelope containing B_4C powder. Splines are inserted into process tubes through specially designed caps on the front nozzle. The spline, which fits between the tube wall and the bottom of the slug, may be used in tubes containing regular uranium slugs. Tube location of the spline in a given flux pattern and the amount of spline in the pile will determine its reactivity effect. Thus the effective reactivities of splines and poison columns are calculated in the same manner.

DECLASSIFIED

HW-73700
Page 76

COLD START-UP PREDICTIONS

Calculation of Pile Reactivity Changes

List of Symbols

C_g	graphite coefficient in inhours per megawatt
C_G	graphite reactivity contribution in inhours, $C_g W$
C_m	metal coefficient in inhours per megawatt
C_M	metal reactivity loss, $C_m W$
$\bar{E}$	flux-squared weighted uranium exposure in MWD/ton
f	tube factor (tube power/avg. tube power = $\frac{\text{tube power}}{W}$)
Δ^F	net effect of loading changes other than exposed uranium
HM	regular uranium - number of natural uranium charges
L	xenon poisoning in inhours
M	iodine, potential xenon poison, in inhours
n	number of HM columns discharged during outage.
N	number of power producing tubes in the reactor
Δ^R	reactivity change caused by discharge of exposed uranium
t	time in hours
T_f	graphite cooling period in minutes
T_r	graphite heating period in minutes
W	pile power level in megawatts

DECLASSIFIED

COLD START-UP PREDICTIONS

Calculation of Pile Reactivity Changes

Calculation of R_{∞}

Calculations of pile reactivity variations must be referred to some base reactivity. Although the equilibrium reactivity of the pile just before shutdown may be used, the most convenient base is R_{∞} , the pile reactivity after sufficient time down for complete metal and graphite cooling, full xenon and iodine decay, and completion of loading changes. The pile reactivity reaches R_{∞} about three days after shutdown. As in nearly all other instances, it is assumed the flux distribution does not change. R_{∞} is calculated in the following manner:

+ Rods	pile reactivity compensated by control rods during equilibrium
+ L	reactivity gain provided by complete decay of xenon
+ WC_m	reactivity gain provided by metal cooling; W is pile power in megawatts and C_m is the metal coefficient in inhours/megawatt.
- WC_g	reactivity loss due to graphite cooling; W is pile power in megawatts and C_g is the graphite coefficient in inhours/megawatt before the outage.
- ΔR	reactivity loss (except at very low exposures or very high tube powers) caused by discharge of exposed natural uranium.
+ ΔF	net effect of loading changes other than exposed uranium
R_{∞}	total -- reactivity after an infinite time down.

COLD START-UP PREDICTIONS

DECLASSIFIED

Calculation of Pile Reactivity Changes
Transient Calculations

Since R_{∞} represents the ultimate xenon decay and pile cooling, the reactivity of the pile, $R(t)$, at any time, t , is obtained by correcting R_{∞} for xenon and temperature effects:

$$R(t) = R_{\infty} - L(t) + C_G(t) - C_M,$$

where $R(t)$ is the amount of control rod necessary to hold the pile critical at the given power level, $L(t)$ is the xenon poisoning, $C_G(t)$ is the graphite contribution, and C_M is the metal loss.

Following shutdown from equilibrium or near-equilibrium conditions, the reactor gains reactivity from the metal effect nearly instantaneously, and it loses reactivity as the graphite cools to room temperature and xenon builds up in the absence of burn-out. Approximately 12 hours after shutdown the reactivity of the sub-critical pile reaches a minimum as xenon build-up reaches a maximum, then decay alone provides the reactivity gain. Approximately three days after shutdown the reactivity of the pile becomes R_{∞} . The interval between the time the reactor power is half down from its value before shutdown and the time it can just be started following a reactivity minimum is called the minimum downtime (MDT). A shutdown of this length is called a minimum outage.

After the pile is started and its power is held at some level, its reactivity will increase for a period of several hours until xenon production balances, and finally overrides, xenon burn-out and decay, and graphite heating effects. The point of maximum reactivity is called turnaround, and the magnitude of the reactivity transient from start-up to turnaround will depend primarily on the power level, the amounts of iodine and xenon present at start-up, and the size of the overall contribution, C_0 , which is the algebraic sum of the metal and graphite contributions. Thus, the start-up level, and hence start-up efficiency, will be determined by the amount of variable control available for controlling the transient.

Detailed sample calculations are included on pages 79-93 under the various types of start-ups.

DECLASSIFIED

HW-73700
Page 79

COLD START-UP PREDICTIONS

Types of Start-Ups

It would be desirable from the production standpoint to raise the power level to its equilibrium maximum when starting a reactor after an outage; however, the magnitude of the ensuing reactivity transient, the capacity of the horizontal control system, and tube power distribution control problems preclude such a start-up at any of the reactors. The start-up production loss is defined as the difference between the actual production accumulated during the rise to equilibrium power and the production which could have been made if it were possible to raise the power immediately to the maximum level. In general it is desirable to keep start-up losses to a minimum, and this is accomplished by selection of the proper type of start-up.

Four types of start-ups are commonly used; they are the high level, low level, cutback, and temporary poison start-ups. In addition the forced poison start-up is a type which is used infrequently. The start-up level, and hence the start-up loss, will be determined exclusively by reactivity control considerations during low level start-ups, and by both reactivity control and tube power distribution considerations during cut-back, high level, temporary poison and forced poison start-ups. See the following sections for individual descriptions and examples.

Currently a new type of start-up which is a variation of the high and low level types is being used on a limited scale, and it is anticipated that this type will be used almost exclusively within a couple of years. This is the start-up with supplementary control. In addition to the horizontal rods, the poison column control facility and poison splines will be used for variable control, and start-up losses will depend only on the rate at which control can be added or removed while maintaining a reasonably flat tube power distribution.

COLD START-UP PREDICTIONSTypes of Start-Ups
High Level Start-Up

If a power level over 50 percent of the previous equilibrium level is held until turnaround, the start-up is called a high level start-up. Generally this type of start-up is used immediately after a minimum outage since nearly the full capacity of the horizontal system is available for controlling the large reactivity transient caused by operation at the high start-up level. In addition to reactivity control limitations the level may be limited by high tube powers caused by distorted tube power distributions. Early in the operation when little rod is in the pile, the hottest tubes are found in the center-near, while near turnaround when nearly all rods are in, the hot tubes are located outside the rod and normal flattening patterns. As outage length increases past a minimum downtime, reactivity control considerations become predominant, and the start-up level must be reduced accordingly. Eventually the start-up level for which turnaround can be controlled with horizontal rods becomes low enough that the start-up automatically becomes a low level start-up.

EXAMPLE I

Assumptions listed below are for a 9-rod, 2004 tube reactor. These conditions will apply to examples given in following sections. The problem is to calculate the shutdown reactivity transient and the reactivity transient following start-up after a minimum outage.

Equilibrium Operation

These are the data necessary to compute the reactivity status of the pile before shutdown; they are sufficient for calculating R_{∞} for outages during which no loading changes are made.

W = pile power level = 1200 megawatts) Obtained from
Rods = reactivity held by horizontal rods = 316 inhours) reactor control
Reactor Gas Composition = 30 per cent helium) room.

$$N = 1960$$

$$\sum_{i=1}^N f_i^2 = 2210$$

$$\sum_{i=1}^N f_i^3 = 2630$$

$$\sum_{i=1}^{HM} E_i f_i^2 = 92,900 \text{ MWD}$$

Obtained approximately once a month
from Computing and Machine Records
of the Production Operation

DECLASSIFIED

EXAMPLE I (Continued)

Equilibrium Operation (cont.)

$$C_m = -.20 \text{ ih/MW}$$

$$C_g @ x\% \text{ helium} = (1-.004x)(.50 + .0008 \bar{E}) \text{ ih/MW}$$

$$\text{Graphite heating period} = T_r = 55 \text{ minutes}$$

$$\text{Graphite cooling period} = T_f = 110 \text{ minutes}$$

$$\text{Number of standard uranium columns per ton of uranium} = 7.86$$

Graphite Coefficient

$$\bar{E} = \frac{\sum_{i=1}^N E_i f_i^2}{\sum_{i=1}^N f_i^2} (7.86) = \frac{92900}{2210} (7.86) = 330 \text{ MWD/ton}$$

$$C_g @ 30\% \text{ helium} = [1-.004(30)] [.50 + .0008(330)] = .67 \text{ ih/MW}$$

Xenon

$$\frac{\sum_{i=1}^N f_i^3}{\sum_{i=1}^N f_i^2} = \frac{2630}{2210} = 1.19 \text{ This is used to find } \frac{A_1}{A_0} \text{ in Section 1105.8-2.}$$

$$\frac{A_1}{A_0} = .852 \quad W^* = (.852)(1200) = 1020 \text{ MW.}$$

Interpolating between $W^* = 1000$ and 1025 in HW-49690,

$$L_g = 927 \text{ ih and } M_g = 2860 \text{ ih.}$$

R_{eo} Without Loading Changes

$$R_{eo} = \text{Rods} + L_g + WC_m - WC_g = 316 + 927 + 240 - 804 = 679 \text{ ih}$$

Shutdown Changes

HM Discharge

$$n = 175$$

$$\sum_{i=1}^n f_i^2 = 221$$

$$\sum_{i=1}^n f_i^3 = 257$$

$$\sum_{i=1}^n E_i f_i^2 = 15,500$$

Sent to Operations with the discharge lists by Computing and Machine Records.

EXAMPLE I (Continued)

Shutdown Changes (cont.)

DECLASSIFIED

HM Discharge (cont.)

Long Term Gains Discharged

$$\bar{E} = \frac{15,500}{221} (7.86) = 550 \text{ MWD/ton}$$

$$\bar{P} = \frac{W}{N} \frac{\sum_{i=1}^n f_i^3}{\sum_{i=1}^n f_i^2} = \left(\frac{1200 \times 10^3}{1960} \right) \left(\frac{257}{221} \right) = 712 \text{ kw}$$

$$\Delta R = \left(-.116 \bar{P} + 175 - 1.49 \bar{E} + 2.14 \times 10^{-3} \bar{E}^2 \right) \frac{\sum_{i=1}^n f_i^2}{\sum_{i=1}^n f_i^2} =$$

$$\left[-.116(712) + 175 - 1.49(550) + (2.14 \times 10^{-3})(550)^2 \right] \left(\frac{221}{2210} \right) = -8 \text{ ih.}$$

Iodine and Xenon Discharge

Assuming for the convenience of calculation that the discharge is accomplished instantaneously at the time of shutdown,

$$M(0) = \left(1 - \frac{\sum_{i=1}^n f_i^3}{\sum_{i=1}^n f_i^3} \right) M_B = \left(1 - \frac{257}{2630} \right) (2860) = 2580 \text{ ih and}$$

$$L(0) = \left(1 - \frac{\sum_{i=1}^n f_i^3}{\sum_{i=1}^n f_i^3} \right) L_B = (.902)(927) = 836 \text{ ih.}$$

Change of Graphite Coefficient

The discharge will cause the weighted exposure of the pile to change, and consequently, the graphite coefficient will change. However, this change of C_g does not affect the shutdown pile; it applies only to the reactivity status of the operating reactor following the discharge.

$$\bar{E} \text{ pile (after discharge)} = \left(\frac{92900 - 15500}{2210} \right) (7.86) = 275 \text{ MWD/ton.}$$

$$C_g \text{ at 30\% helium} = \left[1 - .004(30) \right] \left[.50 + .008(275) \right] = (.88)(.72) = .63 \text{ ih/MW.}$$

$$\text{Loss of graphite coefficient caused by the discharge} = .67 - .63 = .04 \text{ ih/MW.}$$

DECLASSIFIED

EXAMPLE I (Continued)

Shutdown Changes (cont.)

Change of Graphite Coefficient (cont.)

This corresponds to a loss of $(1200)(.04) = 48$ ih of graphite contribution during equilibrium operation at 1200 MW with 30% helium.

Flattening Changes

It is assumed that the cold long term gains discharged (-8 ih) can be satisfactorily compensated with 8 ih less in rods at equilibrium and 308 ih in rods $(316 - 8)$ is a desirable minimum at equilibrium. The 48 ih loss of graphite contribution is compensated by discharging 48 ih of flattening.

$$\Delta F = + 48 \text{ ih}$$

R_∞ After Loading Changes

$$R_{\infty} (\text{after loading changes}) = R_{\infty} (\text{before loading changes}) + \Delta R + \Delta F = 679 - 8 + 48 = 719 \text{ ih.}$$

Critical Curve Calculation (See Figure 1)

The reactivity of the pile t hours after the pile power level is half down is

$$R(t) = R_{\infty} - L(t) + C_G(t) - C_M(t).$$

<u>t</u>	<u>W</u>	<u>M</u>	<u>L</u>	<u>C_G</u>	<u>C_M</u>	<u>R</u>
0	0	2580	836	804	0	687
5	0		1430	52	0	-659
10	0		1490	0	0	-771
15	0		1325	0	0	-606
20	0		1091	0	0	-372
26	0	175	811	0	0	- 92
27	0	158	769	0	0	- 50
28	0	142	728	0	0	- 9
29	0	128	689	0	0	30
30	0	114	652	0	0	67
35	0	67	486	0	0	233
40	0	41	356	0	0	363
45	0	23	258	0	0	461
50	0	15	184	0	0	535
60	0	5	94	0	0	625
70	0	2	46	0	0	673
80	0	1	23	0	0	696
90	0	0	11	0	0	708
100	0	0	5	0	0	714

FIGURE - I
CRITICAL CURVE

Further instructions are included on page ____ of the Physicist's Log

DECLASSIFIED

DECLASSIFIED

EXAMPLE I (Continued)

Turnaround Calculation for a High Level Start-Up (See Figure 2)

Assumptions:

1. Half up to turnaround level at 29 hours down,
2. helium = 60%, *
3. horizontal rod available for control at turnaround = 590 ih,
4. start-up level limited only by available reactivity control at turnaround, and
5. $\frac{A_1}{A_0} = .852$ (same as for pre-shutdown distribution).

$$C_g \text{ @ start-up} = [1 - .004(60)](.72) = .55 \text{ ih/MW}$$

<u>W</u>	<u>W*</u>	<u>t</u>	<u>M</u>	<u>L</u>	<u>C_G</u>	<u>C_M</u>	<u>R</u>
0	0	29	128	689	0	0	30
785	670	0	128	689	0	157	-127
785	670	1	300	567	287	157	282
785	670	2	456	487	383	157	458
785	670	3	597	439	415	157	538
785	670	4	722	413	426	157	575
785	670	5	837	403	430	157	589
785	670	5.5	889	403	431	157	590 Turnaround
785	670	6	940	406	431	157	587
785	670	7	1032	417	431	157	576

* Increasing the helium concentration to 60% from a normal equilibrium value of 30% provides sufficient start-up reactivity control by reducing C_g , yet helium consumption is kept to a minimum.

FIGURE - 2
HIGH LEVEL START - UP

Further instructions are included on page ____ of the Physicist's Log

DECLASSIFIED

DECLASSIFIED

COLD START-UP PREDICTIONS

Types of Start-Ups
Low Level Start-Up

As outage length progresses beyond minimum downtime, more horizontal rod is needed to hold the shutdown pile just critical as the xenon decays, and consequently, less rod is available for controlling the reactivity transient induced by operation at the start-up level; therefore, the power level to be held until turnaround is reduced as the length of the outage increases. When the start-up level is less than 50 per cent of the equilibrium level, the start-up is called a low level start-up, and it differs from a high level start-up only in the magnitude of the start-up level. Eventually the permissible start-up level becomes so low that it becomes more efficient to use another type of start-up. The time to change is not clear cut since an alternative type of start-up may involve charging temporary poison columns which then require a short outage for discharge. Since operation does not always proceed according to plan during these short outages, it is not possible to base a choice of start-up type on calculated production loss alone.

EXAMPLE II

The problem is to calculate the turnaround reactivity transient for a downtime of 39 hours (from half down to half up to turnaround level). See Figure 3. Use the same assumptions used in Example I.

$$R_{\infty} = 719$$

<u>t</u>	<u>W</u>	<u>W*</u>	<u>M</u>	<u>L</u>	<u>C_G</u>	<u>C_M</u>	<u>R</u>
39	0	0	44	379	0	0	340
0	440	375	44	379	0	88	252
1	440	375	142	334	161	88	458
2	440	375	230	304	215	88	542
3	440	375	310	289	233	88	575
4	440	375	381	281	239	88	589
4.5	440	375	415	281	240	88	590 Turnaround
5.0	440	375	446	282	241	88	590
6.0	440	375	505	289	242	88	584

FIGURE - 3

LOW LEVEL START-UP

Further instructions are included on page ____ of the Physicist's Log

DECLASSIFIED

DECLASSIFIED

HW-73700
Page 89

COLD START-UP PREDICTIONS

Types of Start-Up Predictions

Cutback Start-Up

A cutback start-up is characterized by operation at a given level for a short period followed by a cut to a lower power to force a reactivity turnaround. The initial level is higher and the power after the cut is lower than the maximum power which could be held past turnaround with the horizontal rods for a high or low level start-up made at the same time. During operation before the power cut, iodine is accumulated faster than during the corresponding high or low level start-up. This increased rate of iodine production yields xenon at a faster rate following the cut and thereby helps force a turnaround and permits the power to be raised more rapidly after turnaround. When the amount of control available to follow the reactivity transient limits the power level to be held until turnaround for a high or low level start-up, a cutback start-up may provide greater production efficiency. Operation nearer tube power limits before the cut and an increase in the rate of rise possible after turnaround supply the additional production.

In general, following the power cut, xenon decay and burnout are still greater than the xenon build-up. The size of this difference will be determined by the amounts of iodine and xenon present at start-up and by the power level and length of time operated before the cut. The cut consists of three parts which perform three functions: (1) the part necessary to halt any further increases in the graphite contribution; (2) the amount which provides just enough loss of over-all contribution to compensate the net difference between xenon decay and burnout and xenon build-up, and (3) a small additional amount to assure turnaround. It would be most desirable to specify that the power should be cut to a definite level when the reactivity reached a definite value. However, since these quantities change considerably for a difference in start-up time of a few hours and since start-ups are not always accomplished at the times planned, it would be necessary to present a graph of cutback instructions versus time of start-up to assure maximum production. It is possible to construct a graph of cutback conditions which will provide maximum production and which for all practical purposes will be independent of time of start-up. This graph is developed as follows. Where t is the time after start-up,

$$WC_g (1 - e^{-t/T_r}) = \text{graphite contribution,}$$

$$\frac{WC_g (1 - e^{-t/T_r})}{C_g} = \text{level at which the graphite contribution would be at equilibrium, and}$$

W_{ac} = the additional cut to provide reactivity loss to compensate the net gain supplied by xenon decay, burnout, and build-up, and to assure turnaround.

Then,

$$W (1 - e^{-t/T_r}) - W_{ac} = \text{the highest level to cut to and still cause turnaround, and}$$

$$\Delta W = W - [W (1 - e^{-t/T_r}) - W_{ac}] = W e^{-t/T_r} + W_{ac} = \text{the cut to force turnaround.}$$

If R = the maximum allowable reactivity in rods at turnaround, the power should be cut when there is just enough rod left to force turnaround, when the reactivity in rods = $R - \Delta W$. $C_m = R - (W e^{-t/T_r} + W_{ac}) C_m$. A graph is constructed which shows

COLD START-UP PREDICTIONS (Continued)

reactivity in rods before the power cut and the level to cut to versus time after startup. This graph plus the critical curve is the prediction, and it is accompanied with the instructions to (1) start up to a given level (the level for which the graph was constructed), (2) plot the reactivity in rods on the graph versus the time after start-up, and (3) when the reactivity in rods meets the curve on the graph, cut to the level given by the graph for that time. See Example 3. Cutback start-ups are effective over a rather narrow range of start-up times extending from the high level into the low level start-up regions. When adequate supplementary control becomes available, cutback start-ups will no longer be advantageous, and all start-ups will be of the high level type.

EXAMPLE III

The problem is to make a cutback prediction for a start-up between 38 and 43 hours down and to calculate the transient following half up to start-up level at 39 hours. Use the same assumptions listed in Example 1 (See Section 1205.1). The maximum start-up level varies considerably with time of start-up, and since to prepare the prediction for a fairly narrow time interval. The information in Table II is used to construct Figure 4.

TABLE II

$$W = 500 \text{ and } W_{ac} = 50$$

Columns four and five are plotted versus time after start-up in Figure 4. When the inhours in rods = $R - \Delta W_{cm}$, cut to $[W(1 - e^{-t/T_r}) - W_{ac}]$ megawatts.

t (HRS.)	ΔW	ΔW_{cm}	$R - \Delta W_{cm}$	$W(1 - e^{-t/T_r}) - W_{ac}$
.5	340	68	522	160
1	218	44	546	282
2	107	21	569	394
3	69	14	576	431
4	57	11	579	444

The transient following a start-up to 500 MW after 39 hours down is calculated below: R is plotted in Figure 4.

$R_{\infty} = 719$		$M_0 = 2580$		$I_0 = 836$		$C_g = .55$	
t	W	W^*	M	L	$C_g W$	$C_m W$	R
39	0	0	44	379	-	-	340
0	500	425	44	379	-	100	240
.5	500	425	103	352	116	100	383
1	500	425	159	331	183	100	471
1.5	500	425	212	313	221	100	527
2	500	425	262	300	244	100	563
2.1	500	425	271	292	247	100	568
2.2	500	425	281	296	250	100	573
2.3	500	425	291	294	253	100	578

DECLASSIFIED

HW-73700
Page 91

EXAMPLE III (Continued)

When this transient is plotted, Figure 4 indicates a cut to 395 MW 2.1 hours after start-up to 500 MW. The calculation below shows how the reactivity should change following the cut.

<u>t</u>	<u>W</u>	<u>W*</u>	<u>M</u>	<u>L</u>	<u>C_gW</u>	<u>C_mW</u>	<u>R</u>
2.1	500	425	271	298	247	100	568
0	395	335	271	298	247	79	589
.1	395	335	278	297	245	79	588
.2	395	335	285	295	244	79	589
.5	395	335	305	292	240	79	588
1	395	335	338	288	234	79	586
2	395	335	399	284	227	79	583

FIGURE - 4

CUTBACK START -UP

Further instructions are included on page ____ of the Physicist's Log

DECLASSIFIED

DECLASSIFIED

HW-73700
Page 93

COLD START-UP PREDICTIONS

Types of Start-Ups
Temporary Poison Start-Up

As outage length increases and the reactor approaches the xenon-free condition, less rod is available for controlling the reactivity after start-up, and eventually the reactivity of the pile exceeds the capacity of the horizontal rods. Thus additional control is necessary to keep the pile safely sub-critical during the outage and provide additional reactivity control during the post start-up transient. Additional control in the form of lead-cadmium slugs is charged into tubes located near the edge of the flattened zone outside the horizontal rod pattern. The reactor is operated for a few hours to build up the iodine and xenon concentrations necessary to replace the control provided by the temporary poison charges, then the reactor is shut down to discharge the temporary poison and recharge the tubes with natural uranium. The subsequent start-up is generally a high level start-up. Care must be exercised that the amounts of iodine and xenon accumulated during the operation with temporary poison are not great enough to force the reactor to be sub-critical with all controls removed following the discharge of the temporary poison columns. If the reactor becomes sub-critical four or five hours after shutdown, it will not become critical again for another 10 to 20 hours, and a sizable amount of production will be lost. The critical curve for the outage for the discharge of temporary poison is sensitive to the total production ($\sum$ power level x time) accumulated during the operation preceding the outage; it is not particularly sensitive to the time taken to accumulate the total production when there is less than 20 per cent difference between the actual and calculated times. When the tube power distribution is peaked in the center-near of the reactor during operation with temporary poison, the build-up of iodine and xenon will be greater than calculated, and the larger xenon transient during the temporary poison outage will cause the reactor to lose more reactivity than predicted. The prediction error can be as much as 100 inhours. Such cases should be anticipated, and the accumulated production goal for the temporary poison run should be reduced accordingly.

EXAMPLE V

The problem is to prepare a reactivity prediction for a temporary poison start-up after 70 hours down. Use the same assumptions used in Example 1 (See Section 1205.1). Results are presented in Figure 5.

$$M_0 = 2580 \quad L_0 = 836 \quad \% \text{ Helium} = 80 \text{ during start-up}$$

$$\bar{E} = 275 \text{ MWD/ton after the discharge.}$$

$$C_g = \left[1 - (.004)(80) \right] \left[.50 + (.0008)(275) \right] = .49$$

$$10 \text{ "P" columns} = 250 \text{ ih (25 ih/column).}$$

$$R_{\infty} = 719 \quad R = R_{\infty} - L(t) + C_g(t) - C_M - P$$

AIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202

Centimeter

Inches

MANUFACTURED TO AIM STANDARDS
BY APPLIED IMAGE, INC.

2 of 2

DECLASSIFIED

EXAMPLE IV (Continued)

<u>t</u>	<u>W</u>	<u>W*</u>	<u>M</u>	<u>L</u>	<u>Cg</u>	<u>CM</u>	<u>P</u>	<u>R</u>
70	0	0	2	46	0	0	250	256
0	835	710	2	46	167	167	250	519
1	835	710	198	55	272	167	250	519
2	835	710	375	79	363	167	250	586
2.5	835	710	457	94	382	167	250	590
3	835	710	534	113	393	167	250	582
4	835	710	677	152	404	167	250	554
5	835	710	807	195	407	167	250	514
6	835	710	924	240	408	167	250	470
7	835	710	1029	285	409	167	250	426
7.7	835	710	1096	316	409	167	250	395
0	0	0	1096	316	409	0	0	812
1	0	0	987	397	237	0	0	559
2	0	0	891	462	137	0	0	394
3	0	0	802	513	80	0	0	286
4	0	0	723	552	46	0	0	213
6	0	0	587	600	15	0	0	134
7	0	0	530	613	9	0	0	115
8	0	0	478	619	5	0	0	105
9	0	0	431	619	3	0	0	103
9.5	0	0	652	581	27	0	0	165
0	950	810	652	581	27	190	0	-25
1	950	810	811	516	318	190	0	331
2	950	810	956	479	416	190	0	466
3	950	810	1085	464	449	190	0	514
4	950	810	1202	465	460	190	0	524
5	950	810	1307	474	464	190	0	519
6	950	810	1402	491	465	190	0	503

Turn-around

ARCAD RICHARD, WASH.

FIGURE - 5
TEMPORARY POISON START - UP

Further instructions are included on page ____ of the Physicist's Log

DECLASSIFIED

DECLASSIFIED

COLD START-UP PREDICTIONS

Types of Start-Ups

Forced Poison Start-Up

A forced poison start-up consists of an initial high level operation and a shut-down to charge temporary poison followed by a regular temporary poison start-up. This type affords the greatest possible production for a near-minimum outage when two horizontal control rods are out of service at a nine rod pile; however, it has been used rather infrequently since all rods have been in service following the Project CG-558 rod changes and particularly since helium has been used for start-up reactivity control (See Section 1202.2). When two rods are out of service at a nine-rod pile and no additional flexible control is available, it is not possible to control the reactivity transient for a low level start-up even if the reactor is started immediately after a minimum time down. Through xenon burnout the initial operation provides additional excess reactivity to be absorbed by temporary poison, and the temporary poison provides enough additional control to permit a high level start-up. It is anticipated that this type of start-up will be used rarely, and not at all when supplementary control is available. Currently, when a pile is found to be much more reactive than predicted during a start-up without temporary poison, it may be more efficient to shut it down and charge temporary poison. Thus the start-up automatically becomes an unplanned forced poison start-up.

EXAMPLE V

The problem is to prepare a prediction for a forced poison start-up after 32 hours down. Use the same assumptions that were used for Example 4 (See Section 1205.4) with the following exceptions: (1) the helium concentration is 60 per cent; therefore, $C_g = .55$, and (2) rods available for control at turnaround = 490 ih (two rods are out of service).

During operation before temporary poison is charged, it is desirable to maintain enough horizontal control in reserve to shut the reactor down (enough to compensate the reactivity gain from metal cooling). Prediction curves are shown in Figure 6.

$$A1/A0 = .852$$

$$R_{\infty} = 719$$

$$C_g = .55$$

$$C_m = -.20$$

$$T_r = 55$$

$$T_f = 110$$

$$R = R_{\infty} \cdot L(t) + C_g(t) - C_m - P$$

CLASSIFIED

EXAMPLE V (Continued)

<u>t</u>	<u>W</u>	<u>W*</u>	<u>M</u>	<u>L</u>	<u>Cg</u>	<u>CM</u>	<u>P</u>	<u>R</u>
32	0	0	92	581			0	138
0	715	610	92	581	0	143	0	-7
1	715	610	252	486	261	143	0	351
0	0	0	252	486	261	0	150	344
1	0	0	227	474	151	0	150	246
2	0	0	205	462	88	0	150	195
3	0	0	184	448	51	0	150	172
4	0	0	166	433	29	0	150	165
0	715	610	166	433	29	143	150	22
1	715	610	319	375	271	143	150	322
2	715	610	456	342	352	143	150	436
3	715	610	580	327	379	143	150	478
4	715	610	691	327	388	143	150	487 Turnaround
5	715	610	791	337	391	143	150	480
6	715	610	882	353	392	143	150	465
7	715	610	963	374	393	143	150	445
7.1	715	610	971	376	393	143	150	443
0	0	0	971	376	393	0	0	736
1	0	0	875	441	228	0	0	506
2	0	0	789	492	132	0	0	359
3	0	0	711	531	77	0	0	265
5	0	0	578	580	26	0	0	165
6	0	0	520	593	15	0	0	141
7	0	0	470	600	8	0	0	127
8	0	0	423	601	5	0	0	123
4	0	0	641	560	44	0	0	203
0	715	610	641	560	44	143	0	60
1	715	610	747	517	276	143	0	335
2	715	610	842	493	354	143	0	437
3	715	610	927	481	380	143	0	475
4	715	610	1004	478	388	143	0	486 Turnaround
5	715	610	1073	485	391	143	0	482

FIGURE - 6
FORCED POISON START-UP

Further instructions are included on page ____ of the Physicist's Log

CLASSIFIED

UNCLASSIFIED

COLD START-UP PREDICTIONS

Form of Prediction Presentation

Information presented to Operations should include (1) graphs of pile reactivity versus time, (2) complete instructions for the most productive start-up as a function of time of start-up, and (3) the production which must be accumulated before hot start-up procedures may be used. The graphs of pile reactivity versus time should include critical curves for the intervals in which start-up is anticipated and a sample turnaround curve for the most stringent control requirement for each different type of start-up. It is recommended that the graphs show only the changes in reactivity with time and that all other instructions be entered in a classified notebook, called the Physicist's Log, which is kept in the control room.

Instructions entered in the log should show clearly how the start-up conditions change with the time of start-up. These include: (1) type of start-up, (2) start-up power level, (3) composition of reactor atmosphere, (4) production to be accumulated during operation with temporary poison, (5) temporary poison tube numbers, and (6) ample descriptions of control problems anticipated and of particular conditions to be avoided (such as a peaked tube temperature distribution in the center-near during a temporary poison run). These instructions should also specify the total production which must be accumulated following start-up before hot start-up procedures may be used in the event of a scram (See Process Standards C-060 and C-070 in HW-46000, "Process Standards Reactor"). Figure 6 in Section 1205.5 is an example of the recommended manner of presenting the reactivity prediction. In actual practice the prediction curves should be plotted on larger graphs so they can be read easily by Operations personnel. An example of the corresponding entries in the Physicist's Log is listed below.

"During this start-up No. 5 and No. 7 rods are out of service; therefore, only 490 ih are available for control at turnaround. No top-to-bottom heat balance problems are anticipated since the flattening pattern has been adjusted for operation with these rods out of service* The helium concentration should be maintained at 60 per cent throughout the start-up. If the reactor is half up to the start-up level between 31 and 33 hours from half down, operate at 715 MW until the reactivity in rods is 350 ih, then shut down and charge temporary poison. Tube numbers for temporary poison columns are: 1072, 1264, 1384, 3671, 3373, 3485. Start-up to 715 MW, operate for a total production of 5075 megawatt hours (MWH), then shut down and discharge temporary poison. Following the temporary poison discharge, start up to 715 MW and hold until turnaround. After turnaround maintain helium at 60 per cent and raise power at a rate which will permit the rods to come out slowly. As tube power limits are approached, hold the power level constant and let the rods come out. When the reactivity held by rods becomes 350 ih, begin adding CO₂. Add CO₂ and raise power gradually until equilibrium operation is achieved.

Hot start-up condition apply (with temporary poison in the reactor) after 4000 MWH before accumulated.

Hot start-up conditions apply after 3200 MWH have been accumulated during operation following the discharge of the temporary poison."

---

* A revised Rod Withdrawal Chart has been provided.

DECLASSIFIED

SCRAM RECOVERY PREDICTIONS

SECTION 2.1

CONTENTS

PAGE NO.

Purpose	101
Characteristics	102
Definition	102
Description of Transient Following a Scram	102
Recovery Level	102
Reasons for Differentiating Between Hot and Cold Start-ups	106
Problems	107
Means of Increasing Recovery Time	107
Rates of Rise	111
Tube Power Distribution Control	111
Critical Predictions	112
Calculations	113
Scram Transient Tests	126
Purpose	126
Description of Methods	127
Analysis of Data	129

DECLASSIFIED

Section 1300 authored by:

J. T. Worthington
by FIOE

Date of issue:

SCRAM RECOVERY PREDICTIONS

Purpose

Accurate reactivity predictions are necessary for safe and efficient reactor operation. A scram recovery prediction informs operating personnel of the reactivity status immediately following the shut-down of a reactor, so that a start-up can be accomplished during the short time that supercriticality exists. Otherwise, the reactor will go subcritical within 20 minutes to an hour and cannot start up for 25-30 hours. An accurate scram recovery prediction helps to insure a safe recovery in a minimum amount of time and avert the large production loss associated with a minimum outage.

DECLASSIFIED

SCRAM RECOVERY PREDICTIONS

Characteristics
Definition

A scram recovery is any start-up that is attempted while the pile reactivity is decreasing. Two types of scram recoveries are defined:

Secondary Cold Start-up*

A Secondary Cold Start-up is any start-up attempted while the pile reactivity is decreasing and, if the outage continued, the excess reactivity would eventually fall to not less than 40 inhours.

Hot Start-up*

A Hot Start-up is any start-up attempted while the pile reactivity is decreasing, and if the outage continued, the excess reactivity would eventually fall to less than 40 inhours.

---

*HW-116000 - Process Standards, Reactor.

DECLASSIFIEDSCRAM RECOVERY PREDICTIONS

Characteristics

Description of Transient Following a Scram

Scram from Equilibrium

Immediately following a scram there is a reactivity gain due to the uranium temperature decrease from a maximum of about 600°C to inlet water temperature. This change in metal temperature causes a reduction in the effective resonance capture cross section of U-238 by the inverse of the doppler broadening effect. The cooling period of the metal is of the order of seconds; for Pile Physics purpose the reactivity gain can be considered as instantaneous.

At the time of scram, the graphite moderator starts to cool, following an exponential cooling curve. As the graphite loses heat through a small gas annulus to the cooling tubes, the reactivity contributed by the heated moderator falls in a similar manner. The cooling rate and therefore the rate of reactivity loss from cooling, can be slowed down by introducing a low conductivity gas (CO₂) into the annulus to displace the higher conductivity gas (He) present during equilibrium operation.

The third effect on the excess reactivity following an equilibrium scram is buildup of Xe¹³⁵ from its parent I¹³⁵. During equilibrium operation, xenon and iodine are at steady state concentrations which depend on power level, degree of flux flattening, etc.* As soon as reactor power ceases, the following conditions occur:

- 1) formation of xenon and iodine directly from fission ceases,
- 2) burnout of xenon by thermal neutron absorption stops,
- 3) decay of iodine to xenon continues with a half-life of 6.7 hours, and
- 4) decay of xenon proceeds with a half-life of 9.2 hours.

Over the period of time during which an equilibrium scram recovery is possible (a maximum of one hour under present circumstances, depending upon individual pile conditions) the total effect is a nearly linear increase in xenon.

The total transient following an equilibrium scram is an instantaneous gain in reactivity equal to $C_m W$ (C_m = metal coefficient in inhours/MW, W = power previous to scram in MW), followed by a decrease in reactivity, nearly linear, of approximately 12 inhours per minute. This rate is power-level, exposure, and gas-dependent and is expected to increase with planned future operation to about 14 inhours per minute with a 33% power increase over present levels.

---

*See Section 1.00

DECLASSIFIED

SCRAM RECOVERY PREDICTIONS

Characteristics

Description of Transient Following a Scram

Scrams from Non-Equilibrium

The general description of a non-equilibrium scram is the same as that of an equilibrium scram; that is, there is an instantaneous, initial reactivity gain followed by a time-dependent decrease in reactivity, the decay rate depending on the amount of production since start-up, the length of the outage before the start-up, and the power levels reached. However, the decay may be slight enough, after a small production increment from initial start-up, that the excess reactivity will not decrease much and will start to increase after a very short time. (Para. 1304.1-2)

DECLASSIFIED

SCRAM RECOVERY PREDICTIONS

Characteristics

Recovery Level

Recovery level can be defined as the minimum power level necessary to sustain an excess reactivity of zero in hours following a scram recovery. Although recovery can theoretically be made under this circumstance (all control rods out), and in many actual cases recovery has been successful, flux shifts to the near-side can cause high enough localized tube temperatures in this region to force the insertion of rods in an attempt to stay below permissible limits. This, of course, reduces the power level and the recovery attempt fails. This is a common occurrence in reactors with heavy radial enrichment weighted to the near-side for equilibrium control stability. In any case, the calculation for minimum recovery level is an estimate only, since flux distribution and reactivity weighting are not well known before the fact. Considering a specific reactor with only small variations in loading and rod configuration at equilibrium conditions, experience with scrams is considerably better than purely theoretical calculations. (The foregoing discussion applies to equilibrium and near-equilibrium scrams only.)

Considering purely non-equilibrium scrams, the recovery level is not too important since sufficient reactivity is present to achieve the same power level previous to the scram, and in some cases, the loss of reactivity during the short outage results in the capability of even higher levels than before.

The ultimate success of a recovery attempt depends upon the presence of sufficient initial reactivity in rods to balance the reactivity loss due to metal heating, as the power level is raised to a point where the reactivity loss due to xenon buildup is just compensated by graphite heating and neutron "burnout" of Xe-135. Under present conditions at both the K piles and old piles, recovery level depends upon stopping the reactivity loss from the graphite cooling. If a sufficiently high power level is attained to "turn" graphite temperatures, this level is high enough to stop xenon buildup. However, as higher equilibrium power levels are reached, the steady state I-135 concentration becomes so great that during a recovery attempt, say to Xe-135 will exceed the burnout rate at a power level which would actually be high enough to turn the graphite temperatures. In other words, as equilibrium powers go up, the percentage of equilibrium power necessary for a successful recovery also increases. At present, minimum recovery levels are about 65% of equilibrium power. With increases in total pile power of 25%, a recovery level sufficient to cause both graphite and xenon turnaround will be about 80% of equilibrium. The flux shifts associated with a scram recovery decrease the effective flattening enough so that a scram recovery from proposed levels may be impossible without exceeding the outlet temperature limits.

DECLASSIFIED

SCRAM RECOVERY PREDICTIONS

Characteristics

Reasons for Differentiating Between Hot and Cold Start-ups

Reactor safety considerations constitute the criteria for categorizing critical approach conservatism. In the cold start-up case, predictions are subject to a variety of errors due to large loading changes and uranium discharges. Secondary cold start-ups are also subject to error since non-equilibrium operation requires stepwise evaluation of the xenon and iodine values and there are a wide variety of operating circumstances. The pile reactivity rate of change and direction of change are important in determining a safe rate for approaching critical.

The conditions inherent in initial cold start-ups are: 1) the pile reactivity is increasing slowly or at a dead standstill (infinite outage), 2) there may be temporary poison charged which constitutes a fair uncertainty in predicting critical, and 3) other changes in loading of some degree have usually taken place.

A secondary cold start-up involves an uncertainty in the poisoning effect of the xenon and the pile reactivity may be either slowly increasing or decreasing with a rate dependent upon past operating history. Only minor loading changes may be made during the outage.

A hot start-up has these two main characteristics: 1) pile reactivity is decreasing rapidly, and 2) the reactivity status will always be known well because only small loading changes may be made and the time interval is short.

Based on the ability of instruments to indicate a rising period at a low power and considering the effectiveness of reactor scram circuitry, together with human reaction time and judgement, the three types of start-ups were considered to allow the safest and still most efficient means of starting up. Improvements in instrumentation for detecting critical at low levels, measuring rate of rise, and monitoring proximity to limits can increase the efficiency of all start-ups.

DECLASSIFIED

SCRAM RECOVERY PREDICTIONS

Problems

Means of Increasing Recovery Time

Gas Composition

As previously mentioned (page 104) the reactivity decay rate following a scram can be reduced by purging the unit with a large volume of carbon dioxide; the introduction of this low conductivity gas serves as an insulation to retain the graphite heat, thus enhancing its moderating character. The overall effect of such a purge is a decreased rate of reactivity loss following the scram, and a faster gain in reactivity at recovery level; in other words, the slope of the transient is changed.

Since time is usually the deciding factor in scram recovery attempts, it is desirable to initiate a purge as soon as possible after a scram; timing and volume of the purge are significant in the success of the purge. These two factors cannot be strictly controlled nor estimated, since a multitude of incidents may easily affect volume or delay starting the purge.

It would be impossible to provide scram recovery curves for every conceivable set of scram conditions. The problem of gas purging is taken into account empirically; the assigned physicist routinely adjusts curves to fit normally observed conditions. Thus the curves will be accurate for the majority of scram recoveries; that is, in an area where a purge is normally initiated immediately after a scram, recovery curves will automatically take this into consideration; the curves will thus be accurate when a purge is taken, and conservative otherwise.

DECLASSIFIED

SCRAM RECOVERY PREDICTIONS

Problems

Means of Increasing Recovery Time

Poison Discharge and Spline Removal

The discharging of permanent flattening in the form of lead-cadmium in Poison Column Control Facility tubes or boron splines seems to be a straightforward way to gain excess reactivity during a scram outage. However, due to uncertainties in their poisoning effect with an unpredictable flux distribution, heavy conservatism is imposed by Process Standards in the rate of approach to critical depending on the amount of poison discharged if it is discharged while sub-critical. Usually, the use of this method is not attractive because of this conservatism and also for reasons of operational difficulties involved in discharging the poison.

Poison may be discharged quite easily, however, during the rise to power, and there are no restrictions imposed with this method other than those that apply for routine discharge.

DECLASSIFIED

SCRAM RECOVERY PREDICTIONS

Problems

Means of Increasing Recovery Time

Increased Reactivity in Rods at Equilibrium

Increasing equilibrium reactivity in rods may be done in two ways:
1) running with higher graphite temperatures, and 2) enrichment.

Since there is an undesirable reaction between graphite and carbon dioxide at elevated temperatures, this method is not too desirable at present. However, the substitution of a gas such as nitrogen which has essentially the same conductivity as carbon dioxide, and is inert, makes this method promising for future use.

Enriching for increased recovery time is partly an economic problem dependent upon scram frequency and enrichment costs. The use of enrichment is also restricted by the capacity of the VSR and Ball 3X systems and nuclear safety requirements.

DECLASSIFIED

SCRAM RECOVERY PREDICTIONS

Problems
Rates-of-Rise

The criteria for allowable rates-of-rise are based on reaction time, both human and mechanical, so that runaway reactions and fuel element damage from thermal stress do not occur. The amount of conservatism necessary again depends on the quality of instrumentation, both in the low-flux-level period region and in the megawatt region. At present, the K reactors because of refined instrumentation, (i.e., low-level period trip, octant monitor and full pile temperature monitor with a trip feature) and lower ΔT per MW (more metal and more flow) are allowed a greater rate-of-rise, in the megawatt region at least, than the older reactors which rely primarily on the under-pile Beckman chambers for automatic fail-safe back-up. The safety situation can be improved further by addition of sub-critical proportional counters and direct reading rate-of-rise instruments. Consequently, some of the more restrictive Standards on rate-of-rise and rod-withdrawal may be revised for more efficient start-ups.

DECLASSIFIED

SCRAM RECOVERY PREDICTIONS

Problems

Tube Power Distribution Control

Following an equilibrium scram and the ensuing hot start-up, the reactivity loss has proceeded to the point where tube temperature limits are reached with all rods out (or very nearly so). This may not be a sufficient total power for recovery. If not, the power level will start to fall and the reactor ultimately shuts itself down. In the case where recovery level is attained, a flux distortion peaked to the near-side generally results. As the pile gains reactivity, the control rods continue to go in to provide more adequate control. Often, as this insertion progresses, the heat may shift to the far-side as if it were pushed across the reactor ahead of the rods. In this case, control is nearly impossible, since to obtain more far-side poisoning, control rod must necessarily pass through the near-side to reach it, making the situation worse. When the flux shifts to the far-side it is more easily controlled with half-rods since a reactivity moment to the near-side can be created by pushing them full in. At the nine-rod piles it is usually the practice to insert a strong center rod first to quell the near-side problem, and then start the two half-rods in, swapping them for the center rod if necessary. Care must be taken not to "bottle-up" the heat between the half-rods or again a distortion problem will result. As time progresses and reactivity is regained, it is a relatively simple task to raise power back to equilibrium level.

It should be stressed here that a balanced rod insertion order and a general plan for rod manipulations be recommended by the Pile Physicist to insure against bad distortions during start-up.

DECLASSIFIED

HW-73700
Page 112

SCRAM RECOVERY PREDICTIONS

Critical Predictions

The basic assumptions generally used for scram recovery curves are as follows: A graphite coefficient is chosen which is representative for the average flux-squared-weighted-exposure ($\bar{E}$) of the reactor and it is corrected for the average gas composition. For example, if a reactor has a discharge goal of 500 MWD/T, the average $\bar{E}$ would be about 250. The gas composition correction would then be selected depending on whether the calculation was for non-equilibrium (high helium) or equilibrium conditions. Falling period values are obtained from scram transient tests and force-fit analyses of both equilibrium and non-equilibrium scram recoveries. The metal coefficient can be evaluated from scram transient tests. Rod calibrations, and xenon calculations are assumed to be correct.

DECLASSIFIED

SCRAM RECOVERY PREDICTIONS

Critical Predictions
Calculations (An example from KE File)

Equilibrium Recovery Curves

$$\bar{E} = 250 \frac{\text{MWD}}{T}; \quad C_g \text{ at } 80\% \text{ He} = 0.229 \text{ ih/MW}$$

$$W = 3000; \quad \frac{W^*}{W} = 0.8$$

$$C_m = -0.1 \text{ ih/MW}$$

$$T \text{ (falling)} = 60 \text{ min.}$$

Using these values, a scram recovery curve will be calculated
 $\Delta ih = -(\Delta C_g W + \Delta L)$.

t	W	W*	M	L	C _g W	C _m W	ΔL	ΔC _g W	Δih
0	3000	2400	3423	971	687	-300			
0	0	0		971	687	0	0	0	0
0.1				999	622		28	65	- 93
0.2				1026	563		55	124	- 179
0.3				1053	509		82	178	- 260
0.4				1079	460		108	227	- 335
0.5			3250	1105	417		134	270	- 404
0.6				1130	377		159	310	- 469
0.7				1155	341		184	346	- 530
0.8				1179	308		208	379	- 587
0.9				1202	280		231	407	- 638
1.0				1225	253		254	434	- 688

Δih represents the change in reactivity from equilibrium conditions before the scram so that (ih in rods + |C_mW|) at time 0 + Δih at time t = available excess reactivity at time t. Using the above numbers and assuming 240 ih in rods at time 0, critical at 24 minutes (0.4 hours) is equal to 240 + 300 - 335 or 205 inhours.

This recovery curve is valid for KE Reactor over a range of about 400 MW. Thus, this curve could safely be used from 2800 to 3200. It is suggested that the reader check this by calculating similar curves for 2800 and 3200 and checking the end results. Xenon values used throughout this chapter are from HW-33537.

By assuming a level of detection for critical (100 W) and by using an average period (30 sec. to 50 MW) and rate of rise (200 MW/min to ~75% of recovery level and 100 MW/min thereafter for K piles), an approximate allowable time-down can be plotted versus inhours held in rods before scram.

DECLASSIFIED

SCRAM RECOVERY PREDICTIONS

Critical Predictions Calculations

Equilibrium Recovery Curves (Continued)

(It should be stressed that this is a "best guess" calculation and depends on the validity of the recovery level figure.) The additional assumption made is that 100 inhours of excess reactivity are necessary at the time of one-half to recovery level in order that the recovery be successful.

SAMPLE CALCULATION

<u>Time (Min)</u>	<u>Level</u>	<u>Remarks</u>
0	100 Watts	First indication, 30 sec. period
7.5	50 MW	200 rate-of-rise
12.5	1050	~1/2 to recovery level
14.5	1450	100 rate-of-rise
20.0	2000	Calculated recovery level

With the information that it takes about 12.5 minutes from first indication to one-half to recovery level, we can use the scram recovery prediction curve to determine maximum downtime.

Assume: 300 inhours in rods at time of scram, power level is 3000.

Question: How long after scram is there 100 inhours of reactivity? This will be considered 1/2 up time.

Answer: $300 + 0.1 (3000) = 600$ ih excess at $t = 0$. At $t = 39$, excess = 100 (from curve).

Final Calculation: Since it takes 12.5 minutes from first indication to 1/2 up, the maximum available time with 300 ih in rods before scram is:
 $39 - 12.5 = 26.5$ min.

Another calculation can be made at a lower equilibrium rod value and a straight line drawn through the points to complete the graph. (See Figure 1)

DECLASSIFIED

SCRAM RECOVERY PREDICTIONS

Critical Predictions Calculations

Simple Non-Equilibrium Recovery Curves

As stated in Section 1302.2-2, the reactivity transient following a non-equilibrium scram is dependent on: 1) the length of the outage before the cold start-up, 2) the amount of production since the cold start-up, and 3) the power levels reached. For these reasons, it is necessary to set up from two to five families of curves for adequate coverage. As in the equilibrium case, the curves are reactivity loss plotted against time; however, each curve of a family of non-equilibrium recovery curves has megawatt hours of production since start-up as a parameter.

The number of sets of curves is determined by the adequacy of coverage a set will give; that is, the calculated error from one set of hypothetical conditions compared to the actual conditions calculated for the curve should not exceed about 40 inhours after three hours of decay. The criteria for classifying each set depend to a great extent on the start-up level. Hence, at a reactor with supplementary start-up control, such as splines or Poison Column Control Facility, start-up level will be essentially the same whether the preceding outage terminated at minimum time or much later. At a nine-rod pile with full supplemental control available, two sets of non-equilibrium curves are sufficient. The range of one is from rods-out minimum to about 50 hours downtime. The other covers any time after 50 hours. In contrast to this, a K pile, dependent on horizontal rods only for start-up transient control, requires four sets. They are classified as follows:

A. Non-Poison Start-up

- (1) Turnaround level between 1600 and 1900.
- (2) Turnaround level between 800 and 1600.

B. Poison Start-up.

C. Poison-Push Start-up.

Note: Decay rates from all types of these curves converge toward the equilibrium value. Consequently, after about 20,000 to 25,000 MWH since initial start-up one set may be used until equilibrium predictions apply.

Set A(1) above is used from minimum time to about five hours past minimum. Set A(2) is used from this point until an economical low-level start-up can no longer be made, after which poison must be charged and curves B and C apply.

In calculating the curves it is necessary to assume an average turnaround level and a rate-of-rise consistent with actual pile operation. Again,

DECLASSIFIED

SCRAM RECOVERY PREDICTIONS

Critical Predictions
Calculations

Simple Non-Equilibrium Recovery Curves (Continued)

the graphite coefficient is an average value as was the equilibrium case. It should probably be pointed out that the starting point (hours from minimum time) in beginning a set of recovery curves is quite arbitrary and involves trial and error calculation as do the production increments between the individual curves in a set.

SAMPLE CALCULATION

$\bar{E} = 250 \text{ MWD/T}$; C_g at 90% He = 0.202 1h/MW; T (falling) = 60 min. Previous Equilibrium Level = 3000 MW. Start-up, after 30 hours down, to 1700 MW for six hours, then a rate of rise of 80 MW/hr for six hours and 60 MW/hr for seven hours. (Included in this calculation is a natural uranium discharge of 5% f^3). Non-Equilibrium Curve A(1) will be calculated as an example. See Figures 2, 3, 4, 5, and 6 for the plotted results.

T	ΔT	W	W*	M	L	CgW	(MWH Since P Start-up)
0	0	0	0	145	808	0	0
0	0	1700	1360	145	808	0	0
1	1.0			322	661	217	1700
2	1.0			481	562	297	3400
3	1.0			625	499	326	5100
4	1.0			755	462	337	
5	1.0			872	445	341	8500
6	1.0			977	442	342	
7	1.0	1780	1424	1080	447	353	11,980
8	1.0	1860	1488	1183	457	368	
9	1.0	1940	1552	1284	471	383	
10	1.0	2020	1616	1386	487	399	17,800
11	1.0	2100	1680	1485	506	415	
12	1.0	2180	1744	1585	525	431	
13	1.0	2240	1790	1682	545	444	
14	1.0	2300	1840	1776	566	457	26,620
15	1.0	2360	1890	1868	587	470	
16	1.0	2420	1940	1958	607	482	
17	1.0	2480	1980	2043	627	494	
18	1.0	2540	2030	2126	646	506	
19	1.0	2600	2080	2208	664	518	39,020
29	10.0	2800	2240	2854	823	566	67,020
∞	--	3000	2400	3423	971	687	--

DECLASSIFIED

SCRAM RECOVERY PREDICTIONS

Critical Predictions
Calculations

Simple Non-Equilibrium Recovery Curves (Continued)

<u>t</u>	<u>Δt</u>	<u>W</u>	<u>W*</u>	<u>M</u>	<u>L</u>	<u>CgW</u>	<u>ΔL</u>	<u>ΔCgW</u>	<u>Δth</u>	<u>P</u>
1	0	0	0	322	661	217	--	--	0	1700
	1				644	80	-17	137	120	
	2				624	29	-37	188	151	
	3				604	11	-57	206	149	
2	0	0	0	481	562	297	--	--	0	3400
	1				567	109	5	188	193	
	2				567	40	5	357	262	
	3				563	15	1	282	283	
3	0	0	0	625	499	326	--	--	0	5100
	1				522	120	23	206	229	
	2				538	44	39	282	321	
	3				547	16	48	310	358	
5	0	0	0	872	445	341	--	--	0	8500
	1				495	125	50	216	266	
	2				534	46	89	295	384	
	3				563	17	118	324	442	
7	0	0	0	1080	447	353	--	--	0	11,980
	1				517	130	70	223	293	
	2				572	48	125	305	430	
	3				614	18	167	335	502	
10	0	0	0	1386	487	399	--	--	0	17,800
	1				583	147	96	252	348	
	2				660	54	173	345	518	
	3				719	20	232	379	611	
14	0	0	0	1776	566	457	--	--	0	26,620
	1				694	168	128	289	417	
	2				795	62	229	395	624	
	3				874	23	308	434	742	
19	0	0	0	2208	664	518	--	--	0	39,020
	1				825	191	161	327	488	
	2				954	70	290	448	738	
	3				1055	26	391	492	883	
29	0	0	0	2854	823	566	--	--	0	67,020
	1				1034	208	211	358	569	
	2				1203	76	380	490	870	
	3				1336	28	513	538	1051	

DECLASSIFIED

SCRAM RECOVERY PREDICTIONS

Critical Predictions
Calculations

Simple Non-Equilibrium Recovery Curves (Continued)

<u>t</u>	<u>Δt</u>	<u>W</u>	<u>W*</u>	<u>M</u>	<u>L</u>	<u>CgW</u>	<u>ΔL</u>	<u>ΔCgW</u>	<u>Δih</u>	<u>P</u>
00	0	0	0	3423	971	687	--	--	0	Equilibrium
	1				1225	253	354	434	688	
	2				1429	93	458	594	1048	

DECLASSIFIED

SCRAM RECOVERY PREDICTIONS

Critical Predictions Calculations

Complex Non-Equilibrium Predictions

Situations occasionally arise when a number of scrams occur during a short time interval or when a reactor scrams during a non-routine condition such as a heat distortion. In such cases, normal prediction curves will not be adequate and individual attention must be given. Instructions should be left with operating personnel to contact a Pile Physics representative under these circumstances, preferably the assigned Area Physicist, or, if he is not available, a physicist from a similar area or the Supervisor, Pile Physics.

In the event of a complex situation arising where the xenon decay rate is not known and insufficient time or information precludes a calculation, a conservative prediction may be made by assuming a value for CgW based on the average power level over the last two hours of operation. Critical at the instant of scram is equal to inhours in rods plus CmW (where CmW is the metal contribution based on the power level just before shutdown). Using the ordinary falling period with CgW , a loss rate due to graphite cooling exclusively is used for the prediction. To summarize then:

$$\text{Critical at time } t = \text{rods at } t = 0 + |CmW| \text{ at } t = 0 - Cg\bar{W} e^{-t/T},$$

Where Cm = Metal coefficient in ih/MW,
 Cg = Graphite coefficient in ih/MW,
 W = Power in MW,
 T = Graphite falling period,
 $\bar{W}$ = Average power for two hours before scram.

By omitting xenon decay, a conservative prediction is assured.

DECLASSIFIED

HW-73700
Page 120

Figure 1

105-KE Equilibrium Scram Recovery Curve
Valid From 2800 - 3200

Directions for use

Critical = Inhours in rods @ scram + 0.1 x
power level @ scram - Δih .

To pull 60 inhours supercritical, subtract
60 from above answer

DECLASSIFIED

Figure 2

105-KE Non-Equilibrium Scram Curve A(1)

Use this Curve when Turnaround Level was
Between 1600 and 1900 Non-Poison Start-up.

Refer to cold start-up prediction to determine whether
hot or cold start-up procedures apply. Do NOT
extrapolate past three hours.

Directions for Use

- (1) Calculate P since start-up.
- (2) Critical = Rods @ scram + 0.1 x power
level @ scram - Δih .

DECLASSIFIED

HW-73700
Page 122

Figure 3

105-KE Non-Equilibrium Scram Curve A(2)

Use this Curve when Turnaround Level was Between 800 and 1600
Non-Poison Startup

Refer to Cold Startup Prediction
to Determine Whether Hot or Cold
Startup Procedures Apply

For Production Greater than 18,750, Refer to Curve A.(1).

Directions for Use

- (1) Calculate P since Startup.
- (2) Critical = Rods @ Scram + $0.1 \times$ Power Level
@ Scram - ΔTh .

DECLASSIFIED

EW-73700

Page 123

Figure 4

105-KE Non-Equilibrium Scram Curve

B.

Use This Curve When Turnaround Level Was Between
2000 and 2200 Poison Start-up.

Refer to Cold Start-up Prediction to Determine Whether
Hot or Cold Start-up Procedures Apply.

Directions for Use

- (1) Calculate P Since Start-up.
- (2) Critical = Rods @ Scram + $0.1 \times \text{Power Level @ Scram} - \Delta Th$.

DECLASSIFIED

Figure 5

105-KE Non-Equilibrium Scram Curve C.

Use This Curve when Turnaround Level Was Between 2000 and 2200 after Poison-Push Outage.

Directions for Use

- (1) Calculate P Since Startup.
- (2) Critical = Rods @ Scram + 0.1 x Power Level @ Scram - ΔP .

Refer to Cold Start-up Prediction to Determine Whether Hot or Cold Start-up Procedures Apply.

For Production Greater than 25,800 Refer to Curve A.(1).

DECLASSIFIED

HW-73700
Page 125

Figure 6

Total Start-up Transient Illustrating
Scram Transients Encountered During
Various Times from Initial Start-up.

This Figure is Based on Non-Equilibrium
Curve A(1)

DECLASSIFIED

SCRAM RECOVERY PREDICTIONS

Scram Transient Tests
Purpose

The primary reason for performing Scram Transient Tests is to obtain the best prediction possible by using experimental data. Analysis of this data can also yield valuable information regarding prediction variables used for cold start-ups and transient operation as well. The most useful results obtained are metal coefficient and graphite falling period if the primary data are reasonably consistent (i.e., not too scattered). Otherwise, manipulation of the data points can result in a new rod calibration for the scram case if justified.

DECLASSIFIED

SCRAM RECOVERY PREDICTIONS

Scram Transient Tests
Description of Methods

Rising Period Technique

The first method employed to obtain scram transient data consists of:

- (1) Shutting down the reactor as quickly as feasible from equilibrium power level.
- (2) Withdrawal of HCRs to a previously calculated position that will yield a period worth 40 to 60 inhours initially.
- (3) Observing and recording period data from all available instrumentation until the period levels out and starts to fall.
- (4) Insertion of a few VSRs to kill the neutron background.
- (5) Withdrawal of VSRs a short time later and re-positioning HCRs for another period.
- (6) Repetition of steps (2) through (5) until all excess reactivity has decayed away.

The details of this method can be found in HW-34363-A, "Determination of C-Reactor Scram Transient Curves," A. P. Vinther, 12-5-55.

DECLASSIFIED

NW-73700
Page 128

SCRAM RECOVERY PREDICTIONS

Scram Transient Tests
Description of Methods

Low Power Level Critical Technique

This method has two advantages over the preceding one, in that data points suffer no interruption and a Production Test need not be issued in order to perform it since Process Standards are in no way violated. The details of the method are:

- (1) The reactor is shut down from equilibrium conditions as rapidly as feasible to a power level of from 1 - 10 MW as determined by the Number 1 Galvanometer*.
- (2) This power level is held by withdrawing HCRs in accordance with a previously determined withdrawal order. (Attention should also be paid to the insertion of rods during step (1).)
- (3) Rod positions are recorded every 30 seconds until the reactor is sub-critical with all rods out.

---

* The galvanometer is used for power level since it is indicating flux level directly. The power level recorder cannot be used because the residual graphite heat after shutdown heats the process water sufficiently to indicate a power level which is initially ~6% of the previous equilibrium power level. This "false power" decays with the same period as the graphite cools.

DECLASSIFIED

SCRAM RECOVERY PREDICTIONS

Scram Transient Tests Analysis of Data

Rising Period Method

Period data taken during the test is plotted in the usual manner on semi-logarithmic paper. Tangents are then drawn to the curve at points about one minute apart and represent the period at that point, so that for each set of period data, about five individual points are obtained representing the rate of reactivity decay during the period measurement. These points, which correspond to reactivity increments above a base point (in hours in rods at the particular configuration during the measurement), are added to the base point and plotted on a linear graph of reactivity versus time. When this has been done for all sets of period measurements, the result is sections of an actual transient and the spaces between the sections can be drawn in.

In some cases, it will appear that the sections do not fit a smooth curve. This is an indication that the base points are inconsistent and that the rod calibration used is in error. By modifying the rod calibration on a trial and error basis, the sections can be made to fit and a new rod calibration will result.

The plotted transient may then be extrapolated back to one-half-down time and the difference between this extrapolated value and in hours held in rods prior to shutdown is the metal contribution. Assuming calculated xenon values to be correct, this decay can be subtracted from the transient and the remaining curve is loss of reactivity from graphite cooling versus time. From this it is possible to obtain a value for the graphite falling period by using overall coefficient data obtained from a collection of past shutdowns and cold start-ups, adding metal contribution to find graphite contribution, and then fitting the observed transient by trial and error.

It is not possible to obtain an actual graphite coefficient from these data since graphite decay can only be observed over approximately one-fifth of its actual range and many possible combinations of coefficients and falling periods can be made to fit.

DECLASSIFIED

SCRAM RECOVERY PREDICTIONS

Scram Transient Tests
Analysis of Data

Low Level Critical Method

From the rod position data taken during the test, a plot of reactivity versus time is constructed, and analysis of the data is accomplished the same way as in the previous section. Discontinuities in the plot will indicate effects of flux distribution on the rod calibration used and usually a "best-fit" line is drawn to minimize errors which might occur in using the raw data. Of course, if the discontinuities are extreme, a modification can again be made to the rod calibration, but such a case would probably be incentive for performing actual rod calibration tests or repeating the scram transient test.

DECLASSIFIED

Figure 7

Rising Period Method

Scram Transient Test
of October 31, 1956,
C Reactor

Low Level Critical Method

Scram Transient Test of
11-25-57
KW Reactor
(From 3080 MW)

Figure 8.

DECLASSIFIED

DECLASSIFIED

XENON CALCULATIONS*

SECTION I

CONTENTS

PAGE NO.

The Xenon Problem	
Historical Aspects	1
The Xenon Effect on Operation	2
Meanings of Terms	5
Xenon and Iodine Calculations	
Formation and Decay	6
Equations Based on Flattening in Inhours	7
Equations Based on Known Flux Distribution	10
Discharge Effects	16
Effects of Flux Distribution Changes	18
The Xenon Tables	
Development of the Tables	28
Use of the Xenon Tables	31
Routine Applications of the Tables	
Example 1 - Shutdown	33
Example 2 - Simple Start-up	36
Example 3 - Complex Start-up	38
Example 4 - Scram Recovery	40
Useful and Descriptive Curves	
General Use of Curves	
Figure 1 - Saturated Iodine and Xenon Values with Zero Flattening vs. Power Level (L_g vs. W) 2004 Tube Pile	12 & 44
Figure 2 - Saturated Iodine and Xenon Values with Zero Flattening vs. Power Level (L_g vs. W) 3220 Tube Pile	13 & 46
Figure 3 - $d(L_g)/dW$ vs. Power - 2004 Tube Pile	14 & 48
Figure 4 - $d(L_g)/dW$ vs. Power - 3220 Tube Pile	15 & 50
Figure 5 - Xenon vs. Time from Shutdown from Various Powers for 2004 Tube Pile	52
Figure 6 - Xenon vs. Time from Shutdown from Various Powers for 3220 Tube Pile	54
Figure 7 - Pile Fractions Values: A_1/A_0 vs. $\Sigma F^3/\Sigma F^2$ - 2004 Tube Pile; A_1/A_0 vs. $\Sigma F^3/\Sigma F^2$ - 3220 Tube Pile	56
Figure 8 - Pile Fractions Values: $\Sigma F^3/\Sigma F^2$ vs. Flattening - All Hanford Piles	58

* This section replaces HW-25076.

**DATE
FILMED**

9/23/94

END

_____

_____