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By

E. H. Lockwood

Operational Physics
Research and Engineering Operation

March, 1961

HANFORD ATOMIC PRODUCTS OPERATION
RICHLAND, WASHINGTON

Work performed under Contract No. AT(45-1)-1350 between
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CHAPTER II - TRAINING MATERIAL

1. Why was the discovery of plutonium important? Give four reasons.

Answer: 1. Will fission with fast or slow neutrons.
2. Increases potential supply of fissionable material.
3. Can be separated chemically easily - Different element.
4. Created by a slow neutron chain reaction in natural uranium.
5. Good working stability - 24,000 year half-life.

2. What are the two main types of nuclear reactions occurring in a Hanford pile?

Answer: 1. Neutrons combine with U-238 nucleus to form plutonium (production of isotope).
2. Neutrons upset U-235 nucleus and cause fission. (Simultaneously releasing more neutrons and thus maintaining a chain reaction.)

3. What type of projectile is used in a Hanford reactor?

Answer: Both types of nuclear reaction require neutrons as the projectile to collide with atoms of uranium.

4. How are the projectiles supplied?

Answer: Fission causes the release of two or more free neutrons thus giving us back at least two for the one which was absorbed in the fission reaction.

5. Will a U-238 atom fission? When?

Answer: Yes - When a high energy neutron (1 Mev or more) encounters a nucleus of U-238 it causes fission of the nucleus - a low energy neutron is subject to radiative capture leading to the formation of plutonium.

6. Does U-235 form plutonium?

Answer: No - U-238 plus a slow neutron leads to product formation.

7. Which are the most important to the Hanford process - fast or slow neutrons?

Answer: Slow - Slow neutrons are required for both fission and product formation. However, all neutrons start out fast and have to be slowed down.

8. How much time is involved in the formation of plutonium in the Hanford reactors? Explain.

Answer: ${}_{92}^{238}\text{U} + {}_0^1 \longrightarrow {}_{92}^{239}\text{U} \xrightarrow{23 \text{ Min.}} {}_{93}^{239}\text{Np} \xrightarrow{2.3 \text{ Days}} {}_{94}^{239}\text{Pu}$

In other words, the plutonium atom comes into being two or three days after the U-238 atom absorbs a neutron.

9. Do fast neutrons produce plutonium?

Answer: No - When a high energy neutron encounters the nucleus of U-238 it causes fission of the nucleus.

10. Will plutonium fission? How?

Answer: Yes - Both fast and slow neutrons will fission plutonium.

11. If plutonium is formed only from U-238, why is U-235 important to the process?

Answer: The fission of U-235 provides a source of neutrons:

- (a) A single initiating neutron causes the release of several free neutrons.
- (b) Creates a supply of neutrons for radiative capture by U-238 to form plutonium.
- (c) Creates a supply of neutrons for U-235 fission to maintain the chain reaction.
- (d) Creates a source of energy - about 200 Mev per fission.

12. When the U-235 atom fissions, does it break up into two equal parts? Explain.

Answer: Not very often; only about 0.01 per cent of the nuclei break up into approximate equal parts. Nearly all the fission products fall into two broad groups: a "light" group with mass numbers from 80 to 110, and a "heavy" group with mass numbers from 125 to 155. The most probable type of fission gives fragments with mass numbers of 95 and 150 (see chart).

13. How much energy is given to the fission fragments?

Answer: About 168 Mev. This is dissipated in the kinetic energy of the two fission fragments.

14. Where and how does this energy appear?

Answer: Since the fission occurs in the metal, the kinetic energy is absorbed in the uranium piece and appears in the almost instantaneous heating of the metal.

15. How do we know that fission actually takes place?

Answer: By the detection of elements of moderate atomic weight such as barium (atomic weight 56) when U-235 is bombarded by slow neutrons.

16. How many ways can a U-235 nucleus split?

Answer: U-235 splits up in more than 30 different ways, for more than 60 primary products of fission have been identified. Since all are radioactive, each fragment is, on the average, the parent of two others; there are over 180 radioactive species present among the fission products after the decay series starts.

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17. Name four principal by-products of the fission process.

Answer: 1. Radioactivity of certain fragments produce "delayed neutrons."
2. The negative beta emission leads also to gamma rays and neutrinos.
3. Tremendous energy release per fission.
4. Produces 180 radioactive species which complicates chemical separation.

18. How does the amount of energy released in fission compare with that released in chemical reactions? Is it equal, 100, 1000, or 100,000 times greater?

Answer: About 20,000,000 times greater for each atom or molecule reacting.

19. Can fission energy be calculated? How?

Answer: Mass is converted into energy through the fission process. Therefore, the total mass of particles after fission is less than the mass of the interacting particles before fission. The difference in mass is converted into energy of the fission process. See Table 2 of Chapter I for mass and energy equivalents.

20. At what rate is fission energy released?

Answer: About 10^{-8} or 0.00000001 seconds (one one-hundred millionth of a second).

21. At what energy are neutrons most likely to be captured by a U-238 atom?

Answer: At two different energies - one at about 25 ev where resonance capture occurs, and another at the thermal level (around .025 ev).

22. Does U-238 make any contribution to the neutron supply?

Answer: Yes. The fast fission of U-238 by neutrons having energies of 1 Mev or more makes a small contribution (0 to 5%) to the neutron supply. The contribution is small because most of the fast neutrons are quickly reduced to energies of less than one Mev by inelastic collisions within the metal itself.

23. At what energy are neutrons most likely to be captured by a U-235 atom?

Answer: The cross section of U-235 for fission is small except for the very slowest neutrons. (Thermal neutrons have around 0.025 ev energy.)

24. Why must fast neutrons be slowed down?

Answer: The free "fast neutrons" released in fission must be slowed down to thermal speeds for capture by U-238 to form product, or by U-235 to cause its fission.

25. What is meant by the "thermal status" of a neutron's speed?

Answer: Once a fast neutron is slowed down in the moderator, it's speed is the same as the speed at which the atoms of the moderator vibrate simply

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25. (Continued)

because of the temperature of the moderator. Thus, the "thermal" neutron's speed depends on the moderator temperature, or "thermal" status.

26. What is the purpose or function of the moderator?

Answer: To slow down the fast neutrons released during the fission process to thermal and resonance speeds.

27. Why was carbon selected as the moderator for the Hanford reactors?

Answer: 1. Good mechanical strength.
2. Could be machined accurately. Workability.
3. Large amounts available at reasonable cost.
4. Good moderator. Low cross section for neutron capture, and low atomic number for efficient moderation.

28. How did the name "pile" originate? Explain pile principle.

Answer: (a) Layers of graphite with alternate layers of the blocks carrying chunks of uranium were piled one on the other until a sufficiently large size - the calculated critical size - was reached. It is from this first piled structure that the name pile originated.

(b) The effect of this arrangement would be that the neutrons liberated in fission would escape from the uranium chunk into the graphite, where it would be quickly slowed down to the thermal level, safe from wasteful non-fission capture by U-238, but at the correct speed to initiate another fission of U-235.

29. Do all the neutrons produced by fission cause other fissions?

Answer: No. Some are lost in captures which do not produce fission; e.g., in coolant, moderator, structural material, and some leak from the sides of the reactor.

30. Describe a "chain reaction."

Answer: A chain reaction is one which sustains itself indefinitely because the proper balance between the fissionable and non-fissionable atoms replaces neutrons to the process at the same rate that they are lost or absorbed. Once the fission process has been initiated in a few nuclei, it should be able to continue throughout the remainder of the material without external influence.

31. What is meant by the phrase, "When the conditions are so adjusted," on page 24?

Answer: (a) Right proportion of fuel, moderator, and water.
(b) Correct lattice spacing.
(c) Correct neutron balance to produce plutonium and simultaneously maintain a chain reaction.

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32. How is a rising pile period created?

Answer: When more than one neutron becomes available to continue the fission in each neutron cycle. The reaction will accelerate at a rate which depends on how many spare neutrons are created each generation in addition to those needed to continue the chain reaction.

33. Name some of the pile materials contributing to neutron loss.

Answer: Graphite - Aluminum - Water - Gas - Shielding - Control Rods.

34. Name three ways neutron loss can occur.

- Answer:
1. A neutron can escape out of the pile while either fast or slow and thereby become lost to further fission.
 2. A neutron can be captured by materials of the moderator, fuel cladding, and heat removal systems.
 3. A neutron can be captured by U-238 while at resonance or thermal energies. Although this capture leads to product formation, the neutron is lost to the fission process.

35. What is meant by the "reactivity" of a pile?

Answer: The reactivity of a pile refers to its ability to increase the number of free neutrons within it by multiplication each generation. It is actually a comparison with a critical condition and may be negative or positive or zero (at exactly critical).

36. What is the reactivity of a pile operating steadily at 100 MW?

Answer: Zero reactivity - neither positive nor negative - but exactly critical.

37. In the initial loading of a new reactor, what is meant by "critical size?"

Answer: When the loading of a new reactor becomes large enough, a chain reaction becomes possible, and the loading is said to be of "critical size." It is the exact loading size at which the neutrons leaking out the sides will just exactly match the extra neutrons produced inside.

38. The proportion of neutrons lost by escape from a reactor can be diminished by which - increasing or decreasing the pile size?

Answer: By increasing the size of the pile. The number of neutrons lost by escape depends on the external surface area, while the number of neutrons formed is determined by the volume. To reduce the proportionate loss of neutrons, it is necessary to decrease the ratio of area to volume; this can be done by increasing the size of the reactor.

39. Does the use of a reflector have any effect on pile size?

Answer: Leakage of neutrons can be lessened by surrounding the active portion of the core with a scattering material such as graphite. This material

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39. (Continued)

acts as a mirror and bounces neutrons back into the active zone which would otherwise have been lost to fission. Thus, a reactor of given lattice design with a reflector would become critical at a lesser size than one without a reflector.

40. Does the use of a reflector change the neutron flux at the center of the pile?

Answer: Only at the edges, but when the outermost regions of the pile are used more effectively, the total power output is increased.

41. How does lattice spacing affect pile production?

Answer: By controlling the resonance capture of neutrons by U-238. *

- (a) Too small lattice spacing leads to larger loss to U-238 of neutrons of resonance energies.
- (b) Too large lattice spacing allows greater chance of capture of the neutrons by the moderator.

42. What is meant by "multiplication factor?"

Answer: The ratio of neutrons present in one generation relative to the number present in the preceding generation. For example, a chain reaction which continues indefinitely at the same rate has a multiplication factor, or k , of one ($k = 1.0000$).

43. How does a control rod affect the multiplication factor?

Answer: The control rod can change the multiplication factor through the absorption of slow neutrons. Thus, when a rod is inserted into a pile, slow neutrons are absorbed, and the k factor is reduced. When a rod is withdrawn, less neutron absorption takes place, and the k factor increases.

44. Define "excess multiplication factor."

Answer: The amount by which the multiplication factor exceeds one is called the excess multiplication factor, or excess k , and is usually expressed in terms of per cent of the multiplication factor. For example, a multiplication factor of 1.01 corresponds to an excess k of 0.01, or 1%.

45. What effect does excess k have on the multiplication factor?

Answer: Since one neutron per generation is required to maintain the chain reaction, the relative number of neutrons will increase by k excess in one generation. Therefore, if the multiplication factor " k " is greater than one (actually, $k = k_{\text{excess}} + 1$), the number of neutrons will increase exponentially with time.

46. How is the excess k controlled in an operating reactor?

Answer: If the multiplication factor is greater than one (excess k), the increase in the number of neutrons will mean an increase in the fission rate and a

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46. (Continued)

consequent increase in the power output. The neutron increase can be controlled by inserting a neutron absorber, such as a control rod. In this way, a power rise can be halted at the desired power level by reducing the multiplication factor to exactly unity. The number of neutrons present in the pile, the fission rate, and the power level will then remain constant.

47. What per cent of excess k is represented by a pile operating steadily at 100 MW.✓

Answer: Zero per cent excess k ; a pile operating steadily at 100 MW has a multiplication factor of exactly one, or $k = 1.0000$.

48. How long would it take a reactor with a multiplication factor of .9999 to increase its power level by a factor of two?

Answer: Forever. The multiplication factor " k " must be greater than one to increase the number of neutrons and thus the power level.

49. Disregarding the delayed neutron effect, what is the average neutron lifetime?

Answer: About one-thousandth of a second in a graphite moderated reactor.

50. Is the "infinite multiplication factor" useful for everyday reactor operation?

Answer: No. It refers to the multiplication constants in an infinite medium and is used only in theoretical calculations.

51. Define " k effective."

Answer: Since some neutrons escape from the surface of the reactor, the chain reaction must strike a balance between neutron-producing fissions and neutrons lost to product formation plus leakage (or escape). When this exact three-way balance is achieved by the chain reaction, the reactor has an "effective reproduction factor," or k_{eff} , of 1.0000.

52. What is the effective multiplication factor for a reactor having a k excess of 0.0002?

Answer: 1.0002.

53. What is the relationship between k effective and a critical condition?

Answer: The critical condition is that the effective multiplication factor (k_{eff}) shall be exactly unity. The chain reaction will then be maintained at a constant rate of fission and power level ($k_{eff} = 1$).

54. Is a reactor "critical" at first indication, coming up to level, at turnaround, or at equilibrium operation?

Answer: When $k_{eff} = 1.0000$. At turnaround and equilibrium. It is actually super-critical at first indication and when coming up to level.

55. When is the reactor "sub-critical" - "critical" - "super-critical" in k terms?

Answer: When k_{eff} is less than one - Sub-critical
When k_{eff} is exactly one - Critical
When k_{eff} is greater than one - Super-critical

56. Name the four main processes that determine the "neutron balance" in the Hanford Reactor.

Answer: 1. Complete loss or escape from the pile (leakage)
2. Non-fission capture by U-235 or U-238
3. Non-fission capture by the graphite, structural materials, coolant, fission products, etc. (parasitic capture).
4. Fission capture of slow neutrons by U-235, or of fast neutrons by both U-235 and U-238. ✓

57. Does fission capture of slow neutrons by U-235 increase or decrease the supply of neutrons available for fission?

Answer: Increases the supply because U-235 fission releases two or more free neutrons, whereas only one neutron is absorbed in the fission process.

58. Are the non-fission neutron captures by U-238 a complete reactivity loss? Why?

Answer: Neutron capture by U-238 leads to the formation of plutonium; plutonium will fission on its absorption of another neutron, producing more free neutrons.

59. How long would it take to complete the cycle described on page 43?

Answer: 0.001 second in a graphite reactor.

60. How does metal spacing affect the fission process?

Answer: Metal to metal spacing which is too small leads to larger loss to U-238 of neutrons of resonance energies, whereas excessively large spacing allows greater chance of capture of the neutrons by the moderator before they reach the uranium surface. ✓

61. What is meant by "dead graphite"?

Answer: Dead graphite refers to graphite which is void of process tubes.

62. Explain the functional difference between a control rod and a safety rod.

Answer: Control rod can be used to adjust the k effective of an operating reactor. The safety rods are used to shut the pile down quickly in case of an emergency and to ensure that it remains sub-critical during a reactor outage.

63. Should a control rod move fast or slow? Why?

Answer: Both - slow for minute to minute adjustment, somewhat faster for start-ups and emergency shutdowns or power cutbacks. But the control rod

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63. (Continued)

isn't depended on for such fast insertion time as a safety rod, and it may be desirable as a safety procedure backup to limit its withdrawal rate.

64. Name six aspects of reactor operation in which control rod functions are important.

Answer: (1) To control the approach to critical, (2) to adjust and control rate of rise, (3) for minute-to-minute adjustment of multiplication factor during equilibrium operation, (4) compensates for reactivity transients; that is, xenon transients, temperature effects, turnaround, etc., (5) to control heat distribution, and (6) to shut down the reactor quickly under controlled conditions.

65. What are the two most important functions of the safety rods?

Answer: 1. To shut the reactor down quickly in case of emergency.
2. To hold the pile sub-critical during reactor outages.

66. Why must we consider temperature effects when operating a reactor? Name three materials within the core which are affected by temperature change.

Answer: (a) Changes in temperature inside the reactor cause changes in the multiplication factor.
(b) Metal - Graphite - Water.

67. Name two fission products that affect the multiplication factor?

Answer: Xenon and Samarium have large absorptive cross sections for neutrons, thereby act as poisons within the reactor. ✓

68. What becomes of the neutrons absorbed by the control rods?

Answer: The neutrons react with the boron 10 in the control rods to form helium and lithium 7, both of which have very small cross sections for neutrons. ✓

69. Everything being equal - a single fully inserted control rod would absorb the most neutrons at what point?

Answer: Near the center of the rod and pile - where the neutron density is greatest.

70. Why can't we measure neutrons directly?

Answer: Because neutrons are electrically neutral. Instruments are used to measure the side effects which they produce, such as release of a charged particle following neutron capture in boron or the rate of fission heating of the coolant.

71. Is there any difference between "equilibrium" and "critical?" If so, explain.

Answer: k effective equals one describes the pile condition at equilibrium and it also defines a critical condition. An operating pile requires almost

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71. (Continued)

constant adjustment of control rods to maintain a k_{eff} of one, especially during reactivity transients. Equilibrium refers to the xenon and temperature transients arriving at a steady state; at true equilibrium, no rod movement would be required to maintain criticality.

72. How much excess k is required by a reactor operating steadily at 100 MW?

Answer: An operating pile at any level does not require any excess k ; since excess k represents a pile condition where k_{eff} is greater than one, and the level would be rising.

73. Are all fission neutrons released at the instant of fission? Explain.

Answer: All fission neutrons are not released at the instant of fission. About three-fourths of one per cent of the total number of neutrons released in the fission process are "delayed neutrons." The delayed neutrons are ejected from the fission products a few seconds after the actual fission occurs.

74. What is the range of delay times? What is the average?

Answer: There are several delay groups ranging from 0.6 to 80 seconds and averaging about 10 seconds.

75. What effect do delayed neutrons have on reactor start-up? Shutdown?

Answer: During a normal start-up, the delayed neutrons change the average time of a neutron generation from one-thousandth of a second to one-tenth of a second. ✓

When the reactor is shut down, a large number of neutrons are delayed, causing the power to drop off slowly rather than instantaneously. ✓

76. What would cause a "prompt critical" condition?

Answer: The chain reaction cycle time will fast tend to approach the average neutron lifetime of $1/1000$ second if k effective increases beyond 1.0075. This is called "prompt critical" since the pile reactivity would increase without waiting for the delayed neutron effect. A k excess of .0075 would permit an extremely hazardous rate of rise if allowed to continue for even a few seconds.

77. What is meant by the factor e ?

Answer: A super-critical reactor will double its reactivity during a specific number of seconds or minutes provided no side reactivity effects occur simultaneously. In actual practice, it is mathematically convenient to use a "magic number" called e , which is equal to 2.71828, rather than a factor of two as the multiplying factor. The factor of e (2.71828) is a "natural" number much as is π (3.14159) and can be used in all mathematical problems which resemble compound interest. ✓

78. Define a "pile period."

Answer: The time required for the neutron population to multiply itself by 2.71828. For a given excess k , there will be a given period; the greater the k excess, the faster will be the rate of rise, and, therefore, the shorter will be the pile period.

79. The power level of a reactor operating at 100 MW changes by a factor of e , e^2 , e^3 , e^4 , e^5 . What are the new power levels for each?

Answer: $e = 100 \times 2.72 = 272 \text{ MW}$ $e = 2.718$
 $e^2 = 100 \times 7.39 = 739 \text{ MW}$ $e^2 = 2.718 \times 2.718 = 7.39$
 $e^3 = 100 \times 20.1 = 2,010 \text{ MW}$ $e^3 = 2.718 \times 2.718 \times 2.718 = 20.1$
 $e^4 = 100 \times 54.6 = 5,460 \text{ MW}$ $e^4 = 2.718 \times 2.718 \times 2.718 \times 2.718 = 54.6$
 $e^5 = 100 \times 148.6 = 14,860 \text{ MW}$ $e^5 = 2.718 \times 2.718 \times 2.718 \times 2.718 \times 2.718 = 148.6$

80. Does the multiplication factor of a reactor change? How?

Answer: In many ways: Rod movement, temperature, coefficients, plutonium production, poison buildup, fuel exposure, gas composition, etc.

81. Does a large amount of k excess produce a long period?

Answer: The greater the amount of k excess, the faster the rate of rise, the faster the rise, the shorter the period.

82. Define an inhour.

Answer: The excess reactivity required to cause the neutron population to multiply itself by the factor of e (2.718) in one hour.

83. Are inhours and k excess directly related?

Answer: Since the inhour describes a unit of excess reactivity as defined above, the inhour and k excess are related.

One inhour of excess reactivity = increase by 2.718 in one hour.
 Two inhours of excess reactivity = increase by 2.718 in 30 minutes.
 Three inhours of excess reactivity = increase by 2.718 in 20 minutes.

84. A reactor operating at 15 MW starts to rise on a 15 second period. What is the level 30 seconds later? One and one-half minutes later? Two minutes later? ✓

Answer: 30 seconds = e^2 -- $15 \times 7.39 = 110.8 \text{ MW}$
 90 seconds = e^6 -- $15 \times 403.4 = 6,051 \text{ MW}$
 120 seconds = e^8 -- $15 \times 2983.5 = 44,752 \text{ MW}$

85. The factor of e is equal to the ratio of (a) two to one, (b) ten to one, (c) 2.718 to 1,000, (d) 27.18 to 10, (e) 2.718 to 1.00.

Answer: Both (d) and (e).

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86. Given that $e^2 = 7.39$ and $e^3 = 20$, what is the period when the following count data are taken at 20 second intervals: 10, 17, 27, 45, 74, 122, 200? 2

Answer: A visual inspection of the count data above shows an increase in the number of counts by a factor of 2.718 every 40 seconds.

87. How do you explain a graphite temperature several hundred degrees above outlet water temperature?

Answer: The metal surface temperature is less due to the good thermal conductivity between metal and water. The graphite heat is removed much less efficiently.

88. Does fission fragment energy heat up the graphite?

Answer: All the kinetic energy of the fission products is absorbed in the metal piece itself. However, about 50 per cent of the gamma rays emitted from these fission fragments contribute to the graphite heating. } ✓✓

89. Why does energy show up as heat? 2

Answer: Because of the disruption of the molecular structure of the absorbing materials. ✓

90. The outer pile shielding prevents the escape of two types of radiation. What are they?

Answer: Gamma rays and neutrons. ✓

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REVIEW MATERIAL ON CHAPTER III

PILE STRUCTURE

REACTOR PROCESSING FUNDAMENTALS COURSE

By

E. H. Lockwood

December 18, 1959

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REVIEW MATERIAL ON CHAPTER III
PILE STRUCTURE

REACTOR PROCESSING FUNDAMENTALS COURSE

This list is issued as a review of the material discussed during the last three months (February 24 through May 26) by the reactor specialist group attending the Reactor Processing Fundamentals Course. Each question was discussed individually and the entire list covered during this section of the training program.

The reactor specialist group is divided into two sections of approximately thirty members per section and each section scheduled on a three-month alternating basis. Each section is then sub-divided into 15-member classes which meet on alternate Tuesday evenings. Schedules are so arranged that each member on round-the-clock shift coverage can attend two training sessions per month during his free time. All classes are conducted at the 703 Building in Richland each Tuesday evening from 7:30 to 9:30 p.m.

At the beginning of each three-month period, each member receives a list of questions which serve as topics for discussion during the course. The questions pertain only to the material covered by the particular primer chapter under discussion and are compiled in a logical sequence with the information as presented in the manual. Thus, answers can be found with a minimum of effort, basic points can be brought out clearly, and informative discussions on related subjects result in a thorough understanding of all the material presented in the Primer. At the completion of each three-month period, each participating member receives a complete review of all questions and answers in this typewritten form which may be used as a training guide for shift group training meetings.

Each three-month training period is devoted to the complete discussion of a single chapter of the IPD Physics Primer series. At the present time, the specialists have completed the following:

- Chapter I - Structure of the Atom
- Chapter II - Physical Principles of the Reactor Process
- Chapter III - The Pile Structure and Instrumentation

Three additional chapters, now being processed, are scheduled for future discussion:

- Chapter IV - Variation in Pile Reactivity
- Chapter V - Control of the Pile Reaction
- Chapter VI - Operating Procedures and Standards

E. H. Lockwood

Operational Physics Sub-Section
Research and Engineering Section
IRRADIATION PROCESSING DEPARTMENT

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REACTOR FUNDAMENTALS TRAINING QUESTIONS

CHAPTER III

PILE STRUCTURE AND INSTRUMENTATION

1. In general, what are some of the characteristics required of a reactor coolant?

Answer: Should have: (1) good thermal conductivity, (2) high heat capacity, (3) small cross section for neutron capture, (4) low induced radioactivity, (5) stability to heat and radiation, (6) suitable corrosion qualities, (7) low pumping costs, (8) inexpensive, and (9) safe.

2. Why is the cooling water from the reactor held up for a period of time?

Answer: It is held up in the retention basin to allow the decay of short-lived radioactive products before it is returned to the river.

3. Is the air pressure on the rear face negative or positive? Why?

Answer: Rear face air is maintained at less than atmospheric pressure to prevent the spread of contamination to other parts of the building.

4. What are the main requirements of a production reactor?

Answer:

1. The pile components must be arranged in such a manner that the chain reaction can be started and controlled.
2. The reactor must be capable of removing heat as fast as possible, since the rate of production is directly proportional to the rate of heat generation.
3. The pile must be capable of practical and safe operation.
4. Arrangements must be made for the discharge and semi-isolation of the product.

5. What would happen if the slugs were too large in diameter?

Answer: Too many neutrons would be captured inside the slug, no additional neutrons would be formed, and the chain reaction would die off. ✓

6. Why was aluminum chosen as the metal for process tubes and fuel cladding?

Answer: Aluminum is the only common metal that has the necessary combination of good resistance to corrosion and low absorptive cross section for neutrons.

7. What is the difference between a "tube" and "filler" block?

Answer: Both are machined in the same dimensions; the tube blocks are pierced for the insertion of the process tube, the solid filler block is placed between two tube-bearing blocks to provide a square lattice pattern.

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8. What provisions were made for gas circulation?

Answer: The edges of the tube blocks and the edges of the adjacent filler blocks were beveled to provide passage for the circulation of the pile atmosphere (B-D-F Piles).

9. What provisions were made for graphite expansion?

Answer: Tube blocks at the newer reactors were undercut on the sides, and at some reactors on the top as well, to allow for graphite expansion. This arrangement also permits better circulation of the pile atmosphere.

10. What is meant by graphite "coring"?

Answer: At the C and K reactors, the tube blocks are overbored or "cored" near the edges of the tube pattern. This coring consists of varying the graphite bore inversely with expected flux density; the increased gas gap in low flux regions (or insulating layer) results in a more uniform graphite temperature distribution over the entire stack.

11. What is the relationship between the rear dummy charge and the reflector?

Answer: By placing a downstream dummy charge in the process tube, the uranium charge is properly placed in the active zone of the pile, leaving a rear reflector. The combination of aluminum dummies and water causes little enough absorption of neutrons to maintain effectiveness of the reflector at the downstream end. The water serves the same function at the upstream end of the process tube. The long downstream dummy pattern and upstream water column also provide adequate shielding against gamma rays and neutrons.

12. What are the limitations which govern maximum process tube wall thickness?

Answer: The pressure drop required to force the water through the tubes determines the pressure of the inlet to the tube, and thus sets a lower limit to the wall thickness. If the wall thickness were increased, the pressure required to force the water through a smaller annulus would be too high. Also there is a reactivity incentive to have a minimum of materials other than uranium and graphite in the reactor.

13. What per cent of activity increase is illustrated in Figures 10 and 11?

Answer: The flattened pile (Figure 11) shows the neutron activity at about 45 per cent of the maximum in the middle of the sides, indicating an increase in total neutron population approximately 20 per cent greater than the unflattened pile as illustrated in Figure 10.

14. What method other than simply poisoning the center is used to improve neutron distribution?

Answer: When the power generated in a single tube must be limited, production can be increased by loading process tubes near the top, bottom, and side fringes of the pile with material containing more than 0.712 per cent of U-235 (enrichment). The excess reactivity provided by this fringe enrichment can then be used to charge more tubes, to poison and obtain additional flattening.

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15. What the the functions of the rear dummy charge?

Answer: (1) To position the fuel elements in the active portion of the pile, (2) to permit the free flow of coolant, and (3) to provide enough scattering and absorption of gamma rays and of neutrons to provide shielding equivalent to the biological shield through which it passes.

16. How many of the reactor's sides are covered by the thermal shield? How thick is it?

Answer: A layer of iron about 10-1/2 inches thick surrounds all six sides of the reactor.

17. Why is thermal shield cooling necessary?

Answer: To remove the heat generated by gamma radiation, both that emerging from the pile and that originating in the thermal shield due to thermal neutron capture reactions. The thermal shield absorbs about 98 per cent of the energy emerging from the reflector; therefore, its cooling system is very effective in removing the bulk of the heat generated within all of the shielding.

18. Are the front and rear face thermal shields cooled? How?

Answer: The top, bottom, near and far sides are cooled by tubes imbedded in the thermal shield. The front and rear are cooled by the process tubes; front and rear cast iron blocks hang on the gun barrels which in turn are in direct contact with the tubes.

19. Does the thermal shield stop all neutrons and gamma?

Answer: The thermal shield acts as a filter which strains out the thermal neutrons and most of the pile gammas, and so prevents overheating of the biological shield. The thermal shield scatters fast neutrons, slowing them down considerably, but most of the fast and intermediate neutrons are not completely slowed down and captured until they enter the biological shield.

20. What are the functions performed by the biological shield?

Answer: (1) Slow down fast neutrons, (2) capture slow neutrons, (3) absorb any gamma radiation which emerges from the thermal shield, and (4) absorb that gamma radiation which originates in the biological shield due to slow neutron capture.

21. What type of materials should be selected for an effective biological shield?

Answer: (a) High density material for absorbing gamma radiation, for inelastic scattering of fast neutrons to slow them to the intermediate range, and for capturing slow or thermal neutrons.
(b) Low density material for efficiently "thermalizing" intermediate energy neutrons by elastic collision so that they may be captured within the shield.

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22. Name some (a) high density materials, and (b) low density materials.

Answer: (a) Steel or iron, lead, uranium.
(b) Masonite (wood), water, gases, beryllium, graphite.

23. Is biological shield cooling provided at all reactors? Explain.

Answer: Cooling of the biological shield will prolong its effectiveness by slowing down the drying of concrete in the concrete-iron ore type of shield; or the deterioration of the masonite in the iron-masonite type of shield. C and K piles have cooled biological shields, whereas the older reactors do not, therefore requiring fringe poisoning.

24. What is the approximate thickness of the biological shield?

Answer: About four feet thick.

25. How is the reactor gas confined within the reactor?

Answer: The entire biological shield is encased in a welded steel case which serves to confine the reactor atmosphere. The base of this case is a steel sealing membrane imbedded in the concrete foundation. Edges of the case are joined with a neoprene seal.

26. What are the two main functions of the reactor gas atmosphere?

Answer: (1) To provide a heat transfer medium, and (2) to keep the reactor moderator free of undesirable impurities such as water and air.

27. Is air undesirable inside a reactor? Why?

Answer: Air contains about 76% nitrogen and 21% oxygen. Nitrogen is an effective absorber of neutrons and oxygen contributes to graphite oxidation; hence, all voids inside the reactor should be filled with some other gas. ✓

28. Why were helium and carbon dioxide chosen for the reactor gas atmosphere?

Answer: Because of their chemical inertness, low neutron capture cross sections, and desirable heat transfer characteristics. Helium is completely inert chemically and is a very good conductor of heat, carbon dioxide is useful at low temperatures because it is a poor heat conductor.

29. How is the reactor gas used to detect leakage of water into the graphite?

Answer: The moisture content of the gas returning from the reactor is continuously monitored. To aid in locating the water leak, the current of gas is divided into several streams corresponding to certain sections of the reactor.

30. At what point within the reactor is the heat transfer by gas important?

Answer: The reactor gas atmosphere permits a relatively rapid transfer of the heat generated in the graphite across the spaces between graphite filler and process tube blocks and between the process tube block and the tube itself.

31. What effect does gas circulation have on the reactor?

Answer: The continued circulation of the gas atmosphere serves to maintain a uniform gas composition, thereby preventing local hot spots or local areas of contamination due to leaks in the system.

32. Can graphite temperatures be adjusted? How?

Answer: The graphite temperature at a given power level can be varied by changing the gas composition. An increase in helium concentration will cause a decrease in graphite temperature (helium is a good heat conductor). An increase in carbon dioxide will cause an increase in graphite temperature (carbon dioxide is a poor heat conductor).

33. Are any limits imposed on graphite temperature adjustments?

Answer: Yes. The graphite temperatures are so adjusted to produce just the right balance between graphite radiation damage which is annealed out at high temperatures and graphite burnout which is speeded up at high temperatures, especially in the presence of carbon dioxide or air.

34. What are the requirements for a suitable control system?

Answer: It should provide a means for: (a) starting the reactor, (b) bringing the power output to the desired level, (c) maintaining it at that level, and (d) shutting down the reactor when necessary. In addition, safety devices must be provided to prevent damage in case of an accident.

35. How is the nuclear reaction controlled?

Answer: By introducing neutron absorbing material (poison) into the reactor in sufficient amounts to compensate for excess reactivity, and by withdrawing sufficient amounts of poison to compensate for reactivity deficiencies.

36. Does the amount of poison in the reactor remain constant?

Answer: No. The amount of poison must be constantly varied in order to adjust for changes in the neutron multiplication factor caused by temperature changes, by variation in the amount of fission product poisoning (xenon), by U-235 uranium burnout, and by the conversion of U-238 into plutonium.

37. What control systems are used at Hanford?

Answer: The following methods are used to control the reactivity of each reactor: (1) Horizontal control rods (operating control), (2) vertical safety rods (fast safety control), and (3) the ball 3X system (backup safety control). A fourth method, the PCCF (poison column control facility) provides for the continuous charge and discharge of poison during reactor operation. Two additional systems, the "Poison Spline" system, and a poison column displacement system are also under development.

38. Granted that neutron production = neutron leakage + neutron absorption, how is the neutron production controlled in a Hanford reactor?

Answer: Controlling the multiplication factor by absorption is the more practical method in a Hanford pile; control rods containing cadmium, boron or other high neutron cross section materials are used to absorb excess neutrons from the reaction. In other words, it isn't practical to change the size of the pile for fine control (leakage).

39. What sort of emergency power is available for horizontal rod operation?

Answer: At B, D, F, and DR emergency oil pressure is supplied by three "hydraulic accumulators" which consists of large weights resting on pistons closing cylinders filled with oil. At the C, H, and K reactors standby electric power is supplied by batteries.

40. What is a "half-rod"?

Answer: The half-rod contains poison material in the end or "tip" half section, the near half of the rod being comparatively free of poison material. They are used to balance the equilibrium horizontal temperature distribution.

41. What are the two main functions of the vertical safety rod system?

Answer: 1. To hold the reactor sub-critical during shutdown, and
2. To stop the nuclear reaction quickly in emergency conditions.

42. Name four occasions when the vertical safety rods are vitally important.

Answer: (1) In event of a trip signal calling for a scram from normal operating conditions, the vertical rods help to offset the reactivity gain from metal cooling and quickly reduce the pile power level to effectively zero. (2) About 25 hours after shutdown the poisons have decayed sufficiently to permit the reactor to attain criticality if all the rods are withdrawn. From this point on, increasing control is necessary as poisons continue to decay and reactivity increases, especially in event of a gross loading error or unintentional withdrawal of the HCR's. (3) Sufficient control must be available to offset the large reactivity gains that would occur in case of the complete loss of water and complete poison decay. (4) Upon any indication of potential threat to coolant continuity or adequacy of control.

43. Name five ways the vertical safety rods may be tripped.

Answer: Automatic trips are provided to release the vertical safety rods in the event that (1) the power level exceeds a predetermined level, (2) two seismoscope needles swing beyond predetermined limits, (3) the cooling water in any process tube or in the front riser varies beyond operating limits, (4) electric power failure, and (5) failure of critical instrumentation. They may also be tripped manually.

44. Do the vertical safety rods require any power to enter the reactor?

Answer: No. The rods fall under the force of gravity in about 2.5 seconds.

45. Why is the ball 3X system necessary?

Answer: To provide an additional safeguard in the event that the reactor stack shifted to such an extent as to prevent the desired number of safety rods entering the pile at a critical time.

46. What are three requirements for the process cooling water?

Answer: (1) Minimum corrosive action on aluminum process tubes, (2) high in purity; must not leave scale nor other deposits on tubes or metal jackets to interfere with heat transfer, (3) low inlet temperature to minimize corrosion.

47. How does the process water affect production?

Answer: The operating capacity of the reactor is limited by the rate at which the heat generated within the pile can be removed. In order to obtain the maximum production rate the cooling water must pass through the reactor at the highest permissible rate and at the same time to obtain a maximum temperature rise allowable in the water.

48. Why not double the amount of water at all reactors and thus double power levels?

Answer: The rate of flow is directly proportional to the pressure drop across the tube, resulting in a limitation on the amount of water which can be passed through any single process tube. The maximum sustained pressure in the aluminum tubes must be limited to eliminate the possibility of slow expansion of the tube.

49. What determines the outlet temperature of the process tube?

Answer: The process tube outlet temperature must be limited to prevent unstable boiling within the tube and in the effluent piping, and to avoid harmful corrosion of the aluminum cooling tubes and the jackets of the fuel slugs.

50. Why is corrosion so important?

Answer: Corrosion of tubes would lead to tube leaks which permit water to enter the graphite block with a resultant loss in multiplication factor and with further corrosion of tubes due to an aluminum-graphite-water reaction. Slug jacket corrosion leads to ruptures which permit the highly radioactive fission products in the metal to enter the water stream. The chemical action between the metal and water would cause the slug to expand with harmful effects on tube flow rates and difficulty in removal of the swollen piece.

51. Is cooling water required after a reactor is fully shut down?

Answer: Yes. A supply of cooling water must be provided to remove the heat which continues to be generated from graphite cooling and from fission product decay after shutdown.

52. What type of emergency water storage and/or pressure is provided?

Answer: Cooling water backup is provided at each reactor by one or more of the following facilities:

1. Multiple pumping units with electrical primary power, and steam standby power.
2. Immense flywheels on the primary pumps maintain pressure while the VSR's are going in.
3. Multiple storage tanks, some of which are capable of supplying cooling water to the reactors by gravity flow (such as "high tanks").
4. Multiple pipe lines within each reactor area.
5. Pipe lines inter-connecting the reactor areas.

53. What are the primary functions of the Hanford instrumentation system?

Answer: (a) To supply the operator with the information necessary to maintain strict control over the nuclear reaction at all times.
(b) To shut down the reactor immediately upon indication of inadequate control or of insufficient flow of process water.

54. Describe a pile condition related to (a) above.

Answer: Any mishap or set of circumstances which would permit an increase in pile reactivity at a rate approaching "prompt critical" at start-up. An extremely fast rising period, if allowed to continue without control would soon exceed the rate of heat removal by the cooling water, and melting of the fuel elements might occur.

55. Cite an example for (b).

Answer: Complete and permanent loss of cooling water to the reactor while at operating levels or within hours after shutting down from operating levels would cause the fuel elements to melt, resulting in a release of radioactive material to the surrounding area. Partial loss of coolant might lead to complete loss unless the safety system were inserted immediately in order to reduce the heat load.

56. What other pile conditions are monitored by instrumentation?

Answer: Each reactor is equipped with automatic shutdown systems which stop the pile reaction in the event of certain types of abnormal behavior:

1. Any circumstance which allows excessive power levels.
2. Any condition which does not permit adequate removal of heat.
3. Any interruption in the operation of the control system.
4. Any reactor operation beyond predetermined operating limits.

57. What are the two main reasons for accurate power level measurement.

Answer: 1. To produce a maximum amount of product in a minimum of time, the operation of the reactor must be maintained constantly at the peak power. The most important reason for measuring this peak power is to keep it within safe operating limits.

57. (Continued)

2. Power level measurement is also important because the power level is directly proportional to the rate of product formation; therefore, the amount of product in the metal at any time can be calculated from the time-integrated power.

58. Can the temperature change of the coolant be used to calculate the change in power level?

Answer: Yes, but only for slow changes at high level; this method has two disadvantages:

1. The information is slow; the temperature change may lag the nuclear reactions which caused the heating by several seconds.
2. At low levels there is no appreciable temperature rise to measure.
3. Points 1 and 2 would permit an extremely fast rising period before the rate of rise could be calculated.

59. What type of instrument is suitable for maintaining control over the nuclear reaction rate?

Answer: Neutron and gamma monitoring devices have an almost instantaneous response and are particularly suitable for indicating changing power levels and for operating control and safety mechanisms. These devices include BF₃, fission, and ion chambers.

60. How can electrically neutral neutrons be measured?

Answer: Neutrons, being electrically neutral, do not signal their presence in any direct way. However, when neutrons are absorbed in boron, this reaction gives off an electrically charged particle (an alpha particle) which can be used to indicate the neutron density. If the boron is used in a chamber whose center forms one electrode and whose walls form another electrode of an external circuit, this charged particle reaction acts as a rheostat to let current flow through the exterior circuit in proportion to the rate of neutron capture.

61. What is an "ion chamber"?

Answer: An ion chamber consists of a metal cylinder (usually about ten inches long and test-hole thimble diameter for Hanford use) containing a volume of gas (generally argon) and two or more electrodes. Inside an ion chamber used for measuring neutrons, the electrode surfaces are coated with boron. Neutrons striking the boron are captured and cause alpha particles to be ejected into the gas-filled space between the electrodes. These alpha particles produce a large number of charged gas fragments, called ions, which are attracted to the electrode of opposite charge. The result is an electrical current, which when amplified, can be recorded on instruments and made to control various mechanisms. Thus, by watching a meter which indicates electrical current, the relative neutron population inside the reactor can be accurately monitored.

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62. Can an ion chamber be used to calculate a start-up period?

Answer: No. During a reactor start-up extremely low reactor power levels must be monitored continuously so that dangerously fast periods may be detected in time for corrective action to take place before high power levels are reached. Ion chambers in Hanford piles are located in relatively insensitive positions in order to be on the proper range for full-level operation; otherwise, they could conceivably be used for this purpose if the gamma background were biased out. Therefore, at low levels a method must be available whereby individual neutrons can be detected and counted in order to determine the rate of rise.

63. How does the proportional counter (PC) count individual neutrons?

Answer: (a) The PC counter consists of metal cylinder usually about eight inches long with a small diameter electrode suspended centrally within the cylinder. The cylinder is filled with boron trifluoride gas, which is in turn ionized (charged) by the alpha particle emitted in the reaction caused by radiation striking the counter tube. The ionization caused by the recoil alpha particles is accelerated toward the central electrode by the electrical field in the counter tube. The sum total of this ionization collected at the center electrode causes a voltage pulse to appear across a load resistor. Thus, the BF_3 counter is capable of emitting an electrical pulse for each neutron or gamma ray that enters it.

64. Does the PC monitor gamma rays?

Answer: The reactions are such that neutron-induced pulses are considerably larger than those resulting from gamma rays, and amplifiers are so arranged that the larger neutron pulses are accepted and passed on to a scaler, whereas the gamma rays are rejected.

65. What is the principal difference between an ion chamber and a proportional counter?

Answer: In the integrating ion chamber the total quantity of charge due to the number of ionizing particles is collected over a period of time and a steady electrical current flows which is proportional to the rate of neutron flow into the chamber.

In the non-integrating proportional counter (PC), each particle capable of causing ionization is counted separately and recorded as a pulse or count.

66. Give some control room instrumentation examples for, (a) an ion chamber, and (b) a BF_3 proportional counter.

Answer: (a) Beckman, galvanometer, and octant monitor systems.
(b) Proportional counter (PC) system.

67. What is a "fission counter"?

Answer: The fission counter is also a proportional counter, but U-235 is used as the coating material in place of boron, and the more highly-charged fission particles cause ionization which results in electrical pulses in place of alpha particles which cause the ionization in the BF_3 chamber.

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68. What is meant by an instrument's "flux range"?

Answer: From shutdown level to full power level, there are many factors of ten difference in magnitude, yet it is important that the level of neutron flux be known at all times. Since no instrument can give meaningful indications over such a wide range directly, special adaptations are used such as shunts on the electrical circuitry, movement of the chamber into or out of the high flux region, and several overlapping instruments to cover the required range.

69. Where does "background flux" come from?

Answer: Background flux is created by gamma radiation from fission products in the fuel elements. The gamma rays react with the natural deuterium in the cooling water resulting in the emission of a photoneutron; the flux chambers (Beckmans) monitor total radiation due to both neutron and gamma radiation during the reactor shutdown.

70. Why is the term "Megawatt" used?

Answer: It is convenient to refer to flux levels in terms of the rate of heat generated by the fissions taking place. The megawatt is a unit of fission heating rate equivalent to 1,000,000 watts; at Hanford power levels, this is a more convenient unit than either watts or kilowatts. The customary background level at which a Hanford pile goes supercritical is the order of a few watts, and that in the shut down reactor with the safety rods all in is of the order of a few tenths of a watt.

71. If the shutdown flux is a few tenths of a watt, what is the operating level in terms of watts?

Answer: See Figure 3-20; the operating range is given as 10^9 watts (1,000,000,000) or 1,000 MW. This means that the full power flux may be ten billion (10,000,000,000) times greater than the shutdown flux.

72. Where is normal criticality usually detected in terms of fission heating rate?

Answer: The proportional counter system is used to detect the first indication of increase in neutron flux during the approach to critical in the 10 to 100 watt range.

73. Can cooling water temperature be used to calculate low power levels?

Answer: As shown in Figure 3-20, the minimum measure of heat production occurs in the region of 10^6 watts, or one megawatt. With high cooling water flow rates, one megawatt of power is represented by a small fraction of one degree temperature rise. This minute temperature change, plus the lag in instrumentation, prohibits the use of coolant temperature rise as an accurate indicator of low power level during start-up, and makes the accuracy of high level readings questionable during rapid level changes.

74. What automatic provisions are made to guard against fast start-ups? (Also see question 132.)

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74. (Continued)

Answer: Fast operating neutron-sensitive chambers (Beckmans) are used to initiate an automatic shutdown whenever dangerously fast initial periods are encountered during start-up.

75. Is the BF_3 (PC) pulse-type chamber accurate in high flux regions?

Answer: No. For accurate pile period data, the BF_3 chamber is limited to maximum number of counts (saturates) in the region of 10^3 or 10^4 per second. When the counts reach about 10,000 per second, the neutron flux is large enough to make possible the use of an integrating ionization chamber.

76. At what power range is the integrating ionization chamber effective?

Answer: An ion chamber will operate satisfactorily when the ion current corresponds to about 10,000 pulses per second at approximately the same point where the pulse chamber ceases to be accurate prior to jamming. While the number of ionizing events in the chamber is still relatively small the accuracy and steadiness of the current will not at first be great, but both will improve with increasing neutron flux.

77. Are the integrating ion chambers used to control the rise to operating level?

Answer: Yes. After the pile period has been established and the PC range exceeded, the rise to operating level is controlled through the galvanometer system. The ion current is displayed on a galvanometer and Beckman; the power level is allowed to increase at a controlled rate, then the increase is halted and the power maintained at the desired level.

78. Why is accurate measurement at low power levels necessary?

Answer: At low levels, the importance of accurate measurement is in detecting that the level is changing and at what rate. Absolute magnitudes are not so important as warning sensitivity and speed of response sufficient to effect action before limiting conditions are reached.

79. Is the rate of rise important at high operating levels?

Answer: Of course, but the problem is handled in a different manner. At high operating levels, a slight relative change may cause limits to be exceeded, and this slight change could take place as the result of a drift in level rather than a fast compounding rate. Since limits are associated largely with heat generation rates in individual tubes, the best monitoring indication for drift is that of outlet temperature on each process tube.

80. Do we depend entirely on tube outlet temperatures?

Answer: No. Tube power limits are directly dependent upon the available flow. Therefore, the flow through each tube must be known to be sufficient at all times. Trip limits imposed on the Panellit pressure gauge for each tube will automatically trip the safety circuit upon indication of flow instability.

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81. What is the primary power level control element at the Hanford reactor?

Answer: Fast acting neutron monitors (Beckman chambers) are presently the primary automatic control element.

82. Name two ways in which neutron monitors are used at operating power levels.

Answer: (a) The octant monitoring system for operating control, and (b) the Beckman system for flux level trips.

83. Does the sensitivity and range of the individual chamber limit its effectiveness?

Answer: Yes. The ion chambers must be placed a certain distance from the active portion of the reactor so that sensitivity and range of the chambers will provide accurate data at the desired power levels. The reactor core is then considered a point source of neutrons and local neutron flux is assumed proportional to the entire core flux or power.

84. What advantage is gained through the use of the multiple PC system.

Answer: Greater sensitivity and range. By locating the PC chamber toward the reactor core, the chamber will count a greater number of pulses (greater sensitivity); placing the chamber in a low flux region will reduce the number of counts (greater range and higher power levels).

85. What might cause a "major disaster" on a Hanford plant?

Answer: Melting fuel elements would cause a large release of radioactive fission products to the surrounding atmosphere.

86. How can fuel slugs be melted?

Answer: By the permanent loss of cooling water to the reactor, either through an uncontrolled rising period during which shutdown controls were not activated as intended, or by failure of the water supply.

87. In general, what types of protection are used to prevent melting of slugs?

Answer: First: Back-up of coolant supply piping and pumps. Second, but no less important: Operational procedure and automatic shutdown instrumentation. For instance, the reactor start-up is a sensitive part of reactor operation since the chance for excessive rates of rise is greatest at this time. Rigid standards and procedures must be used to make the ensuing rise to power within the limitations of the operator's reaction time; this time in which he has to react can be increased by more sensitive and faster responding instrumentation. In case of human failure, the operational procedures are backed up with automatic shutdown instrumentation.

88. What are the two most important factors of nuclear safety in the operation of a Hanford pile?

Answer: 1. The complete control of the nuclear reaction rate at all times.
2. The constant supply of cooling water to the reactor.

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89. Which is more important to reactor safety - Operating Procedures or Automatic Safety Trips?

Answer: This is a chicken vs. egg type question, but ultimately operating procedures are more important to nuclear safety, since in many cases the ability of the safety circuit to perform its designed function is dependent on procedure.

90. Give three examples where the operation of a safety circuit is dependent on procedure.

Answer: The reliability of any safety system is dependent upon procedure in fabrication, maintenance, wiring, and testing of its components.

1. It is physically possible to operate the reactor without Panellit protection by keeping the system bypassed following a start-up. The procedure requirements must be fully understood and respected.
2. Beckman power level trip settings are set by procedure, as well as range change settings during the rise to operating level.
3. Pile period low level trips may be bypassed at start-up, a violation of the operating standard. The use of the manual trip at certain reactors is also governed by procedure.

91. From Table II, find four examples of procedural protection against a fast initial pile period.

Answer: 1. Rod withdrawal rates are made according to procedure.

2. Sub-critical monitoring as conducted and evaluated is a procedure.
3. The evaluation of loading changes and their effect on flux distribution depend upon the procedures.
4. The physicist's calculation of the reactivity status during shutdown, start-up, and turnaround are all governed by procedures.
5. Charge card accuracy, especially important with enrichment, is dependent on check sheet procedures.

92. If reactor operation is well covered by operating procedures, why are automatic shutdown systems necessary?

Answer: There are excellent reasons for having both operating procedures and safety circuits. The procedures are set up to guide the operator in accepting information from the instruments, in reaching decisions, and in taking the required action. However, the reaction time of the operator sets a limit upon the speed with which he can accept information and take action, and every human at one time or another is apt to make an error. Consequently, an automatic shutdown system should always

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92. (Continued)

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be ready for high-speed positive action. On the other hand, an automatic shutdown system is subject to mechanical failure and it can, in any event, be no better than the limited decisions built into it by the designer.

93. What safeguards are used to guard against safety circuit failure?

Answer: There are four general principles considered in the reactor control design. These are: (1) the principle of duality, (2) the fail-safe principle, (3) the sequential principle, and (4) the principle of reliability.

94. Explain the principle of duality.

Answer: The principle of duality requires that essential services should be in duplicate. For example, two independent channels of power feed, a normal feeder plus an alternative to be available in the event of emergency. Other examples, the multiple Beckman system, safety circuit inter-ties, dual relay systems, hydraulic accumulators, emergency battery banks, backup water supply, etc.

95. What is the fail-safe principle?

Answer: In the event of a serious power, instrumental, or operator failure, the safety system must act rapidly to shut down the reactor. Examples are the free-falling vertical rods, the 3-X balls, and the hydraulic accumulators. Another example is that failure of a vacuum tube in a Beckman will cause that Beckman to give a trip signal.

96. Where does the sequential principle apply?

Answer: The sequential principle in control design means that the various operations necessary for start-up and for normal or emergency shutdown must take place in a specified order. In many cases, this is accomplished through the use of interlocks in the safety system. For example, it is impossible to withdraw the horizontal rods unless the vertical rods have been raised, so that the chances for a breakdown in rod withdrawal procedures are greatly reduced. Other examples include water pressure decay trips, low and high sensitivity seismoscope trips, dual Beckman trips, etc.

97. How is the principle of reliability applied?

Answer: When sufficiently reliable equipment is not available commercially, special equipment is designed on plant. In addition, the reliability of the safety circuit system is strengthened through the use of dual relays and dual contacts at all critical points; the relay coils are arranged in parallel and the contacts in series. Examples are the DOK and DOKA, the BX and BXA, and HX and HXA dual relays.

98. From Table I, give four operating conditions which could lead to or contribute to a disaster at Hanford.

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98. (Continued)

- Answer:
1. An extremely fast initial period (fast compounding).
 2. Excessive rate of rise in MW region (fast simple rate).
 3. Excessive rate of rise in limits region.
 4. Extreme distortion or cycling.

99. What protection is used to guard against a fast initial pile period, (a) procedure, (b) automatic?

- Answer:
- (a) Accurate interpretation of all reactivity data, strict adherence to sub-critical and rod withdrawal procedures.
 - (b) Low level period trips - more sensitive the better.

100. How can an excessive rate of rise be avoided in the MW region?

Answer: Enter the MW region on a controlled slow pile period. If necessary, lengthen period by rod movement as level increases. Level off power well within operating limits.

101. What precautions are used to prevent an excessive rate of rise in limits region?

Answer: Monitor flux and temperature continuously - level out early and increase cautiously. Set Beckman trips as per operating standard.

102. What can be done to prevent flux distortion and temperature cycling?

Answer: Since the temperature cycling is usually the result of a series of local turnarounds and power changes in certain parts of the pile, the only way to prevent cycling is to maintain an even flux distribution over the various sections of the reactor. Even flux and temperature distribution can be maintained only through the correct interpretation of representative monitoring data, which includes adequate frequency and sampling. Good control techniques are then necessary to correct any detrimental flux or temperature trends before they become too hard to handle.

103. Where is the PC chamber located which is used during: (a) a "hot" start-up, and (b) a "cold" start-up?

- Answer:
- (a) The generally higher neutron and gamma flux encountered during a "hot" start-up can be accurately monitored by a chamber located in a less sensitive and more protected area than the counter used for cold start-up.
 - (b) The normal PC counter chamber is carefully positioned at the proper distance from the neutron point source so that the sensitivity and range of the chamber can be calibrated to give peak performance during the "cold" start-up.
 - (c) Such start-up chambers may be located in test holes or beneath the reactor at the various piles.

104. What is the main function of the galvanometer system?

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104. (Continued)

Answer: Because of the inherent delay in instrumentation that records power level from heat output, it is necessary to use instruments that respond directly to changes in reactor neutron density or flux. For this reason, the galvanometer system is used to control the rise to operating level and to note small deviations which require compensating rod movement when at operating level.

105. What is the principal difference between the No. 1 and No. 2 Galvanometer?

Answer: The No. 1 Galvanometer indicates the total current which is proportional to the neutron flux, or power level. Through the use of a potentiometer, the No. 2 Galvanometer becomes a differential monitor that reads small deviations about a preset or operating range.

106. What are the main advantages of the octant monitoring system?

Answer: The octant monitoring system measures and records neutron flux in each of the eight corners of the reactor; comparison of the individual readings present a picture of flux distribution throughout the reactor. For a given power level, any change of neutron flux in one region must be balanced by a corresponding change in some other region. Thus, each octant chamber provides a clue as to when to take corrective action and what method to use, and indicates the success or failure of the action taken. Because of rod shadowing effects, the octants are better for indicating local trends than for exact flux levels; therefore, octant readings should always be supplemented with tube and graphite temperature information.

107. How are neutron flux traverses obtained during (a) low level operation, and (b) at equilibrium operation?

Answer: (a) Simultaneous front-to-rear and side-to-side flux traverses may be obtained with numbered gold foils attached to wood strips which are inserted in a dry process tube (front-to-rear) and into an experimental test hole (near-to-far).

(b) Front-to-rear traverses during equilibrium operation may be obtained using number aluminum pieces or numbered fuel pieces, which are weaseled to determine relative activation following discharge.

108. Is the Beckman system important to reactor safety at Hanford?

Answer: Definitely; through the use of very detailed procedures which take advantage of the range change and trip adjustment features of these instruments, this system currently is depended upon for protection against the following events:

1. Excessively fast periods.
2. Excessively fast rates of rise at intermediate levels.
3. For power excursions above normal operating level.
4. For unplanned rod pull during an outage.
5. Accidental critical condition during an outage.

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109. Are the full power Beckman trips set close to operating level? Why?

Answer: Should the operating reactor get on a fast period, the flux trips must shut the reactor down before the hottest tube reaches its instability temperature. There is some overshoot of power above the trip level because a certain minimum amount of safety rod must be inserted before the rising power level is turned around. Therefore, it is imperative that the flux monitor trips be correctly set at all times, including reactor outages.

110. Do all process tubes receive the same amount of cooling water?

Answer: No. The removal of heat from the reactor becomes complicated for two reasons. First, the temperature of the exit water from each tube must be maintained within a definite operating limit. Secondly, the heat load varies from tube to tube, making it impractical to adjust the water flow in every tube to the same outlet temperature. Individual tube flow is determined by the size of the venturi throat or the orifice placed inside the nozzle connection to the crossheader - larger openings are used for central columns than for fringe columns.

111. Which is more important - an increase or decrease in tube water pressure?

Answer: Both are equally important - an increase in the Panellit pressure may be due to an obstruction downstream in the annular space in the tube, to "boiling vapor" lock, or to swelling of a fuel slug. A decrease in pressure may result from a plugging of the front crossheader or venturi screens, or a tube leak. Any of these conditions represents a potential hazard to the reactor.

112. Can the Panellit system ensure reactor safety?

Answer: Not entirely. All Panellit information should be closely allied with temperature data. All data, when properly interpreted can then be used to evaluate the abnormal performance of the individual tube.

113. Why are Panellit pressures recorded daily?

Answer: For two reasons. First, to provide a written history of all process tube pressures (and indirectly, flows). Second, to detect any slow-changing condition which could prove hazardous if allowed to continue.

114. What type of emergency condition would activate the seismoscope system?

Answer: An earthquake of sufficient violence could so damage the reactor that the moderator and shielding would be displaced in such a manner that it would be impossible to insert the horizontal or vertical safety rods. The process water system might be ruptured at the same time, causing a power excursion and possible melt-down of the fuel elements. For these reasons, the seismoscope contacts are set to trip the No. 1 Safety Circuit for any tremor which might cause damage to the reactor; if piping damage were great enough to cause a fast header pressure drop-off, the ball system would be automatically activated.

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115. What are the three main safety circuits of the Hanford reactors?

Answer: There are three interrelated safety circuits, the 1X, 2X, and 3X. The 1X circuit consists of relays and contacts which will release the vertical safety rods. The 2X circuit controls the horizontal rods in a like manner. The 3X circuit is a backup system which releases neutron-absorbing balls which fall into, and fill, the vertical rod channels.

116. What reactor conditions will cause the No. 1 safety circuit to operate?

Answer: The No. 1 safety circuit will cause an automatic shutdown upon receiving a signal from any of the following devices which constantly monitor pile conditions:

1. Beckman system
2. Panellit system
3. Water supply
4. Power failure
5. Seismoscope
6. Circuit interties

117. What other precautions are taken?

Answer: In addition to the automatic trip devices, other more conservative operating limits are imposed for safe operation and to prevent reactor or component damage. Whenever a critical limit is exceeded or some abnormal condition develops, it may be desirable to shut down the reactor as quickly as possible. For these reasons, manual push-button trips are provided for the No. 1, No. 2, and No. 3 safety circuits.

118. In the event of an electrical power failure, the vertical safety rods will fall because of the force of gravity. Where is the energy to insert the horizontal rods stored?

Answer: At the older reactors, the energy is provided by hydraulic accumulators; at the newer reactors, by battery banks.

119. From Figure 3-24, estimate: (a) length of time required for VSR's to drop full in after LP opens, (b) time HCR's start in to time of full in, (c) time balls are all in from pressure decay trip.

Answer: (a) about three seconds, (b) about seven seconds at C Area, a full minute at K Area, (c) about 13 seconds.

120. What is the most important feature about the annunciator panel?

Answer: Whenever the reactor is shut down automatically (scrammed) by one of the safety circuits, it is necessary that the reason for scram be determined as soon as possible so that the faulty condition can be remedied and scram recovery made. This information is provided by the annunciator; however, the operator must be instantly alert to detect the initial cause of scram before a variety of indicating lights confuses his judgement.

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121. Is the annunciator useful during reactor outages?

Answer: Yes, since the No. 1 safety circuit should be made up at all times, the annunciator should be used during reactor outage to supply information pertinent to shutdown activities. The annunciator is especially useful just prior to reactor start-up to indicate any unusual condition that may interfere with or delay start-up. An annunciator clear of all flags or lights ensures that all safety circuits are properly made up and that all major conditions relative to start-up have been satisfied.

122. What are the major requirements of an ideal neutron counter system?

Answer:

1. The information should be supplied continuously.
2. Monitors should operate on instantaneous flux.
3. There should be effectively no time delay between flux and data (immediate readout).
4. Individual monitors should cover the complete flux range, from sub-critical to full power.
5. Systems should be mechanically simple and trouble free.
6. Exposed components should be capable of withstanding intense radiation, and heat and humidity effects.

123. Does Hanford instrumentation satisfy all the above requirements?

Answer: Not entirely, particularly requirements numbered 1, 4, 5, and 6. For example, the pulse-type ion chamber used to detect initial criticality must be positioned in a relatively protected area because of the intense radiation within the reactor at high power levels. Even in the protected area, the effective range of the chamber is soon exceeded and the control of the rising period must be transferred to another system, such as the galvanometer. The range of the systems may overlap, but the sensitivity and consequently the rate of rise must be re-established at a critical point of reactor operation. The ideal neutron counter system should cover all ranges from shutdown to full power. At the present time, sub-critical monitoring is still in the prototype stage; all reactors are not equipped with low-level period trips; rate of rise trips are non-existent, and neutron level trips are not representative of the whole volume of the reactor.

124. What very low level instrumentation improvement is planned for the Hanford reactors?

Answer: The sub-critical flux monitor system, now in development, is capable of detecting and recording the neutron flux when the reactor is in the full shutdown condition. Unlike the present PC system, the proposed sub-critical monitor chamber is coated with an uranium compound enriched with U-235. The entry of a slow neutron will cause fission of the uranium compound, the resulting pulse can be used in the same manner as other counting systems. This so-called "fission chamber" can be inserted into the active portion of the reactor during shutdown to monitor the very low neutron flux. As the reactor attains critical and is brought up to operating level, the fission counter is gradually withdrawn to a protected position within the pile shielding. This withdrawing action provides the system with a high initial sensitivity and a very wide operating range, and protects the chamber from neutron radiation damage.

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125. What is the most important feature of the fission counter system?

Answer: The fission counter can detect the change in the shutdown background flux in the unlikely event of gross loading errors. It can detect the flux change as the vertical safety and horizontal control rods are withdrawn during the approach to critical. This kind of information can be used to confirm or correct the calculated critical condition before the reactor actually becomes super-critical.

126. What is the "triple PC" system?

Answer: The triple PC system is another test installation which uses three PC chambers in sequence. Three separate proportional counters are positioned in three separate flux regions within the pile shielding at a central test hole location. One chamber is placed relatively near the active portion of the pile for greater initial sensitivity. Another chamber is located in an intermediate flux region to control the rate of rise following criticality; the third chamber is positioned in a relatively low neutron flux area to monitor the rate of rise to operating level. As the effective range of each chamber is exceeded, the counter system is switched to the next less sensitive chamber, until the third and last chamber is in operation.

127. How would "zone" type temperature monitoring provide additional protection?

Answer: An approach-to-limit scan control feature would be particularly effective in monitoring heat shifts that may occur during scram recoveries and during periods of rapid rod motion required to control the reactivity transients following reactor start-up. Under equilibrium operating conditions, a flexible approach-to-limit monitor of this type would permit a safe and balanced approach to higher process tube limits.

128. What is being done about obtaining a representative indication of flux throughout the volume of the reactor?

Answer: Plans are being made to convert the present galvanometer systems at all reactors into octant-type systems wherein eight neutron chambers are installed in corner regions of the reactor block as at the C and K reactors. The older reactors will be provided with special ion chambers of small enough dimensions to be inserted into the front and rear ends of four corner process tubes. Placed in the safety circuit system, the flux level trips will be spread about the reactor block rather than beneath the pile as at present.

129. Why is rate-of-rise instrumentation important?

Answer: A doubling time of thirty seconds may be perfectly safe near background level of a few watts, but extremely dangerous at power levels in the hundreds of megawatts. At very low levels even a very fast pile period will not violate the megawatt per minute rate of rise process standard, but near full level the rate of rise limit will be exceeded with a very slow period. The pile operator has need for an instrument which will give him rate of rise information directly. In the past he has had to

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129. (Continued)

resort to "feel" - to judge his rate of rise by the speed with which the galvanometer spot traverses the scale, by the timing required in changing Beckman ranges, or by the observed approach of outlet temperatures to limiting conditions. An instrument is now being developed which will show this desired indication directly.

130. What are the major requirements of an ideal rate-of-rise meter system?

- Answer:
1. The signal used should be representative of the entire volume of the reactor.
 2. System should have sufficiently fast response that excessive rates are detected in time for remedial action.
 3. System should be selective enough so that the instrument is not so sensitive in response that sudden small changes in background flux produced by rod movement give misleading indications.

131. What procedures are presently employed to guard against fast start-ups?

- Answer:
1. All loading changes are carefully checked by the Process Physicist. Charge cards and loading check sheets are used to ensure the correct loading during discharge outages.
 2. Critical prediction curves based on existing reactivity conditions are provided by the Process Physicist for all start-ups.
 3. Slow VSR and HCR withdrawal rates are specified to ensure that, should the reactor become critical at this time, power will not rise uncontrollably.
 4. Sub-critical monitoring in operation during all rod pulls; if not available, PC in operation with specified sensitivity.
 5. Period meter trips in service during all start-ups; if not in service, manual trip of No. 1 Safety Circuit if PC jams or rising period is less than 15 seconds.
 6. Three Beckman flux monitors set to trip at full scale or less on a range that gives a reading between three and 30 per cent of full scale.
 7. Manual trip of No. 1 Safety Circuit under any set of circumstances where operator "feel" or intuition detects an unexpected fast rate of rise.

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This document classified

by HC Fuller

REVIEW MATERIAL ON CHAPTER IV
VARIATIONS IN PILE REACTIVITY
REACTOR PROCESSING FUNDAMENTALS COURSE

by

E. H. Lockwood

May 23, 1960

Series A

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REVIEW MATERIAL ON CHAPTER IV
VARIATIONS IN FUEL REACTIVITY

REACTOR PROCESSING FUNDAMENTALS COURSE

This document is the second of a series of question and answer lists issued as a review of the material discussed in the Reactor Processing Fundamentals Course. The first list, HW-59145, "Review Material on Chapter III - Fuel Structure," was issued June 8, 1959. Each list represents the material covered by the Reactor Specialists during a typical three-month training program. Each question is discussed individually and the entire list completed during the three-month period. Each three-month training period is devoted to the complete discussion of a single chapter of the IPD Physics Primer series.

Before the initial meeting of a three-month program, each member receives a list of questions which serve as topics for discussion during the class sessions. The questions pertain only to the material covered by the particular Primer chapter under discussion, and are compiled in a logical sequence with the information as presented in the manual. A specified number of questions (approximately 30) are assigned for study and review between classes; at the following session these questions are thoroughly discussed in relation to operating conditions. Basic points are stressed; the intent is, of course, that informative discussions lead to a better understanding of the material presented in the Primer. At the completion of each three-month period, the participating members receive a complete review of all questions and answers in this documentary form which may prove useful as a training guide for shift group training meetings.

A typical three-month specialist training program consists of three three-and-one-half hour (ten and one-half hours total) discussion periods on a single chapter of the IPD Physics Primer series. The meetings are held every Wednesday from 8:00 to 11:30 a.m., at the 105-KE Conference Room, with each of the four shift classes meeting monthly. At the present time the Specialists have completed the following:

- Chapter I - Structure of the Atom
- Chapter II - Physical Principles of the Reactor Process
- Chapter III - The Fuel Structure and Instrumentation
- Chapter IV - Variations in Fuel Reactivity

Similar training programs will be offered on the two remaining chapters of the Primer series:

- Chapter V - Control of the Fuel Reaction
- Chapter VI - Operating Procedures and Standards
(in preparation)

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Operational Physics Sub-Section
Research and Engineering Section
IRRADIATION PROCESSING DEPARTMENT

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REACTOR FUNDAMENTALS TRAINING QUESTIONS

CHAPTER IV

VARIATIONS IN PILE REACTIVITY

1. What term is used to denote a change in the number of neutrons from generation to generation? ✓

Answer: If the reaction rate is changing with each neutron generation, we denote this increase or decrease as a change caused by either an excess or lack of "reactivity". Thus, the reactivity of a pile refers to its ability to increase the number of "free" neutrons by multiplication each generation. It is actually a comparison with a "critical" condition and may be negative (lack of reactivity), or positive (excess reactivity), or zero (at exactly critical). Excess reactivity corresponds to compound interest, "critical" corresponds to a "constant" investment, and negative reactivity corresponds to a fall-off in investment due to service charges or taxes.

2. What is meant by "effective multiplication factor"?

Answer: The chain reaction must supply enough neutrons to maintain a balance between neutron-producing fissions and neutrons lost to product formation and other pile absorptions plus the neutrons which escape from the reactor. When this exact three-way balance is achieved, the reactor has an "effective reproduction factor," or k_{eff} of 1.0000. ✓
If the escaping neutrons were neglected, as could be done legitimately in a pile of infinite size (if it existed), the balance between absorptions and fissions would be called k_{∞} or k infinity. This concept of k_{∞} is useful in theoretical calculations in which the leakage is taken into account in other ways.

3. Why is a production reactor always made somewhat larger than the exact critical size?

Answer: If the effective multiplication factor were always exactly unity the number of neutrons would not increase or decrease. Such a pile could operate only at low level critical; it could be shut down, but its power level could not be raised. By loading more than the critical amount of fuel, so that the potential k_{eff} is greater than unity, the system can be made "supercritical." Also there is some flexibility left for control rods, poison, xenon, and temperature effects due to operation.

4. How is the neutron population controlled in a supercritical reactor?

Answer: The k_{eff} of a supercritical reactor can be reduced to a point equal to or less than unity by inserting a neutron absorber such as a control rod, thereby holding the system critical or causing it to go subcritical.

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5. How is the power level controlled in a Hanford pile?

Answer: As long as k_{eff} is less than one, the neutron density will be quite small and will remain constant at some background level (subcritical). Withdrawal of the control rods until k_{eff} becomes greater than one causes the neutron density to increase (supercritical) until the desired power level is reached (or exceeded). As the desired level is approached, the control rods can be inserted sufficiently to make k_{eff} equal to unity, the pile process becomes exactly chain reacting (critical) and the power level remains constant.

6. Are the chain-reacting properties, as described above, altered in any way in the operating pile?

Answer: Yes - during reactor operation the increase of temperature and the accumulation of product, poisons, etc., all cause "short term" and "long term" reactivity changes.

7. a. Name three principal causes for the "short term" reactivity effects.
b. Name four principal causes of "long term" reactivity effects.

Answer: a. 1. Graphite temperature
2. Metal temperature
3. Xenon poisoning
b. 1. Product formation
2. Depletion of U-235
3. Samarium production
4. Gross fission products

8. Temperatures in an operating reactor can be changed in several ways. Name six.

Answer: 1. Rate of coolant flow.
2. Power level.
3. Stored heat (shutdown and startup lags).
4. Flux distribution - flattening, skewing, etc.
5. Gas composition (affects G temperatures and shield temperatures).
6. Fuel design (I & E vs. solid, alloy vs. natural, etc.).
7. Fuel material - enrichment level, poison effect, etc.

9. Why does a change of temperature alter the k_{eff} , or reactivity, of the reactor?

Answer: For two reasons primarily: (1) the energy of the thermal neutrons is changed - affecting their capture probabilities, and (2) the energy of the U-238 atom changes, making the "apparent speed" of oncoming neutrons change.

10. How does the thermal neutron's "speed" affect pile reactivity?

Answer: A change in the thermal neutron's speed, as determined by the graphite temperature, might make the average neutron energy more subject to capture. For example, if an increase of temperature brings the neutron

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10. (Continued)

energy closer to the high capture probability range of a fissionable material, the result would be an increase of the pile reactivity; if brought closer to that of a non-fissionable material or poison the result would be a decrease in pile reactivity. In addition, as the neutron temperature changes, associated changes occur in the absorptive cross sections of the uranium metal, graphite, and water. This is especially important in our reactor where water is less apt to capture high energy neutrons - the "window" effect of the water channel causes a positive graphite coefficient in our reactor.

11. What effect do density and volume changes have on pile reactivity?

Answer: A change in density of the reactor materials could have an important influence on the pile reactivity. The uranium column expands with rising temperatures, thereby increasing the effective length of the pile, the radial expansion of the metal slugs and aluminum process tubes changes the amount of water present, the water itself expands, reducing the amount of scattering and absorptive material in the annulus. The expansion effects on reactivity are relatively minor as compared to temperature effects on capture probabilities in the Hanford reactors.

A neutron-absorbing gas such as nitrogen would, however, have considerable density effects. There is less than half as much gas in the graphite at operating level as in the cold pile.

12. When are short-term reactivity changes important to reactor control?

Answer: An understanding of the nature of short-term changes is helpful in taking a reactor through a scram, a power level change, turnaround, a reactor outage, or a temperature cycle.

13. What is meant by "coefficient"?

Answer: A coefficient is merely a number expressing the amount of some change or effect due to certain changing conditions such as temperature, length, volume, etc. For example, as graphite temperatures change, the pile reactivity changes. Since the graphite equilibrium temperature is dependent on the power level, a reactivity coefficient or number can be calculated for use as a multiplier of power level. Thus a graphite power coefficient of 0.4 ih/MW for a reactor operating at 1200 MW (0.4×1200) would represent 480 inhours.

14. What effect does graphite temperature have on pile reactivity?

Answer: The graphite coefficient is directly related to the fact that the temperature (energy) of the thermal neutron is set by the graphite temperature. As the pile power is raised, the scattering cross section of the graphite and water decreases with increasing neutron temperature; "hotter" neutrons are able to pass more freely through the water annulus, through the graphite, and into the uranium metal. This permits a greater share of thermal absorption in U-235, resulting in a gain of pile reactivity. There is, however, another effect of opposite sign. As the neutron temperature is increased, the higher speed neutrons may be captured in larger proportion by U-238, thereby creating a negative reactivity effect. However, in the case of a water-cooled Hanford pile is positive.

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- Answer: The ratio of the plutonium cross section relative to that of U-238 goes up with increasing neutron temperature as set by the graphite temperature. Since plutonium is fissionable, this results in a graphite coefficient which becomes increasingly positive as the plutonium builds up.

- Answer: No - The moderator temperature coefficient effect is time sensitive to the heating and cooling rates of the graphite itself. There is a lag time of approximately one hour to see two-thirds of the ultimate heating or cooling effect of a power change.

- Answer: Graphite heating and cooling rates or periods can be observed directly from the readings of thermocouples imbedded in the graphite, or indirectly from the electrical conductivity of the graphite.

- Answer: The graph is a plot of the temperature of the magma versus the distance from the magma chamber. The temperature of the magma is plotted on the y-axis and the distance from the magma chamber is plotted on the x-axis. The graph shows that the temperature of the magma decreases as the distance from the magma chamber increases. This is because the magma is losing heat to the surrounding rocks as it moves away from the magma chamber. The rate of heat loss is greatest near the magma chamber and decreases as the distance from the magma chamber increases. This is why the temperature of the magma decreases as the distance from the magma chamber increases.

The following information is provided to help you understand the data and to ensure that you are able to interpret the data correctly. Following a review of the data, the following information is provided according to the instructions in the data file.

- Answer: Yes - Because the thermal conductivity of carbon is about ten times greater than that of CO₂, the transfer of heat from space during operation will easily enough maintain the pile temperature at a given level and thus changes in pile resistance will be small. When the helium concentration is raised in the hot pile, the thermal conductivity decreases, the graphite block and the pressure tube temperatures, relative to the graphite to cool more rapidly, so that the temperature of the graphite block increases as a loss of pile resistance. An increase of CO₂ will also increase the cooling of graphite resulting in an increase of pile resistance. The graphite design must therefore be maintained at a constant value of 100 percent CO₂ through the use of a correction factor.

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20. What is graphite "burning"?

Answer: At C and K Reactors, the tube blocks at the front and rear ends of the pile are overbored or "bald" to progressively larger diameters in an attempt to increase fringe graphite temperatures and thereby anneal out radiation damage expansion effects. In addition, all tube blocks are overbored in the third outer rows of tubes all around the pile.

21. What is the approximate magnitude of the graphite coefficient effect on pile reactivity in going from a cold to a full level pile?

Answer: The graphite coefficient can cause gains or losses in pile reactivity on the order of 300-1000 millik, according to reactor and gas compositions. The gains will occur through the heating of the graphite; the losses through the swelling of the graphite.

22. Does the total graphite reactivity effect take place during a single heating and cooling "relaxation" period?

Answer: No - Although the heating and cooling periods are on the order of minutes (for a 1000 kw range (1000 kw and 1000 kw) respectively), the total reactivity change due to the pile graphite is effectively delayed and spread over a longer period.

23. Give the operating conditions under which the graphite coefficient is helpful in controlling the reactor.

Answer: (1) A CO₂ purge that is too slow will cause the reactor to overheat the graphite, thus extending steam recovery time.
(2) A transition to a higher level will cause the graphite to transfer heat to the primary system rapidly; thus less control rod will be required to maintain the level.

24. What is the "Doppler broadening effect"?

Answer: As the temperature of the uranium metal rises, the greater random motion of the U-238 atoms makes the absorbing nuclei appear to be traveling at faster speeds, thus increasing the "apparent" width or area of the U-238 resonance peak. The increased absorption in U-238 causes a loss in pile reactivity because fewer neutrons take part in the fission of U-235 to produce more neutrons. This negative metal coefficient is thus largely due to the effective increase in the cross section of U-238 as the motion of vibration, or temperature, is increased. This effect is known as "Doppler broadening."

25. How is the metal temperature coefficient determined?

Answer: The metal power coefficient, which is usually expressed in millik per megawatt (m/MW) is obtained from that part of the reactivity change immediately resulting from a power change which follows the metal temperature. The observed reactivity change divided by the amount of power change gives the coefficient (For example: 5 millik increase due to a sudden 40 MW jump indicates a coefficient of -0.125 m/MW). Power and metal temperatures are not strictly proportional, but the relation is close enough.

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27. Does the metal electrode of the cathode ray tube have a graphite coating?

Answer: Not if a cathode ray tube is of the parallel beam type. In a tube of this type, the power supply is connected to the cathode and the anode. This happens because the cathode is the source of electrons and the anode is the source of positive ions. The cathode is made of a material which is easily oxidized. The anode is made of a material which is not easily oxidized. The cathode is coated with a thin layer of graphite. The anode is coated with a thin layer of gold. The cathode is coated with a thin layer of graphite because it is easier to coat with graphite than with gold. The anode is coated with a thin layer of gold because it is easier to coat with gold than with graphite.

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28. Is the operating voltage of the cathode ray tube of the type of the operating voltage?

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30. Once it has been determined that the cathode ray tube is of the type of the operating voltage?

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Answer: The cathode ray tube is of the type of the operating voltage. The cathode ray tube is of the type of the operating voltage. The cathode ray tube is of the type of the operating voltage. The cathode ray tube is of the type of the operating voltage. The cathode ray tube is of the type of the operating voltage.

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Answer: No - In any particular case, the line (or solid xenon) is plotted at a rate proportional to the power output of the reactor. For example, the neutron density in a reactor at the end of a run is much lower than that in a stable reactor at the center of the pile. To find the over-all effect of the xenon, then, a weighted average is taken of the local poison effect over the entire active portion of the reaction.

Answer: The present situation in the world is governed by the power of the arms race within the western industrialized nations, in connection with rising prices and increasing of constant prices with the emission of flattening. After several years of operation of a constant power level, the amount of the arms race will be concentrated in the approach of saturation of the arms race in the world. Furthermore, the growing effect of the arms race on the environment will be the most serious threat to the future of the world.

Answer: Yes - When the engine is started, the piston rings are forced into the cylinder walls by the pressure of the combustion gases. As the piston rings move down the cylinder, they scrape excess oil from the cylinder walls and deposit it on the underside of the piston rings. In the case of the new engine, the oil is scraped off the cylinder walls and deposited on the underside of the piston rings. In this case, the amount of oil scraped off the cylinder walls is reduced by the factor of 1/2, and the amount of oil deposited on the underside of the piston rings is increased by the factor of 1/2. This 1/2-1/2 factor affects the oil consumption (helped to reduce the oil consumption) and the oil consumption and the oil consumption of the engine.

Answer: The combination of effects, the minimum resulting effect, the combined effect, and the synergistic effects are all, for a large part, the same. Building, in fact, the same.

Answer: Fortunately, the xenon poisoning (negative reactivity effect) and fuel level graphite poisoning (positive reactivity effect) are nearly equal in magnitude and opposite in sign, though the timing is different. The xenon timing is tied to the 8.8 and 9.8 hour half-lives of iodine and xenon, a smaller factor compared to the 480 day half-life of the graphite poisoning. The graphite timing is tied to the lattice temperature, and graphite temperatures rise at constant power levels and approach in about 10 minutes. For example, the graphite coefficient might increase in reactivity by 10% inherent within a few minutes after startup, and continue to contribute this amount of positive reactivity until the pile is shut down. When this happens, the pile power will approach zero.

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35. (Continued)

temperature in a period of six to eight hours. The xenon transient is much more complex and proceeds for two or three days.

36. Name the operating condition and describe each stage of the xenon transient illustrated in Figure 9 - page 32.

Answer: The xenon plot shows the growth of xenon as a function of time after a rise to power with the pile initially poison-free.

1. 0-35 hours: Xenon cannot increase until iodine is formed and decayed.
2. 35-95 hours: Constant amount of xenon - saturation value about 900 inhours.
3. Shutdown assumed at 95 hour point: Xenon increases following reactor shutdown because iodine decay continues and xenon burnout has ceased.
4. Following shutdown: Increase in amount of xenon continues until iodine concentration falls to a level where xenon production rate equals xenon decay rate. Xenon passes through maximum.
5. Maximum xenon concentration: Xenon maximum of 1400 inhours above former 900 inhour saturation value (about 110 hours on chart).
6. After maximum xenon point: The iodine backlog is reduced and xenon continues natural decay until reactor startup (about 150 hours on chart).
7. After startup: Xenon decreases because the xenon burnout has suddenly increased while the iodine concentration has not yet risen enough to produce a compensating amount of xenon (150-160 hours on chart).
8. Minimum xenon concentration: When iodine decay (xenon) equals xenon decay plus burnout, xenon concentration passes through a minimum or "turnaround" (about 135 hour point) and then increases steadily toward an equilibrium value (155-160 hours).
9. Not shown on this chart: Changes in power level produce changes in rate at which equilibrium is approached; if the power raise is great enough another transient reactivity gain involving another turnaround will result.
10. Xenon transient: Chart illustrates severe xenon buildup by a factor of two or greater, immediately following shutdown, and the partial xenon burnout following a startup. The buildup is a large factor in "scram time" and "minimum downtime" effects, whereas the xenon burnout is involved in the "turnaround" effect.

36 a. Sketch the xenon chart in Figure 9 with the vertical scale changed from "Inhours of Poison" to "Change in Pile Reactivity."

Answer: Curve would then be upside down - positive poison change is negative reactivity change.

37. Can iodine and xenon values be calculated for all reactor conditions?

Answer: Yes - the equations used to compute the values of iodine and xenon are arranged so that time and power level variables can be calculated in advance and listed in index tables. The tables are so

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arranged that any pair of iodine and xenon values calculated can become the base point for a subsequent calculation. In other words, proper allowance can be made for previous operating conditions with the calculations starting at that point.

38. What units are used to designate iodine and xenon values?

Answer: The effective concentration of iodine and xenon are stated in units of reactivity effect (not in atoms, grams, etc.). One inhour of iodine represents a potential inhour of xenon. One inhour of xenon means an amount of xenon so distributed that it actually absorbs one inhour of pile reactivity.

39. Does the discharge of irradiated metal affect the iodine and xenon values?

Answer: Yes - The discharged metal contains both iodine and xenon; therefore, the decay value of iodine and xenon must be calculated from the quantity and location of that remaining in the reactor.

40. From Figure 10, give the xenon value and/or time of occurrence for: (a) saturation value, (b) maximum concentration, (c) return to initial concentration, (d) reactivity gain or loss 50 hours after shutdown compared to time of shutdown, and (e) time of effectively zero concentration.

Answer: (a) 800 inhours at zero time, (b) 1300 inhours at eight hours after shutdown, (c) 800 inhours about 23 hours after shutdown, (d) about 650 inhour gain, (e) about 90 hours after shutdown.

41. Can the horizontal rod system compensate for the xenon decay?

Answer: After about two days the reactivity gain will exceed the capacity of the horizontal rod system in the older piles, and the reactor must be kept subcritical with the vertical safety rods and/or supplementary control or temporary poison.

42. Can a "xenon-free" reactor be re-started?

Answer: It can be re-started almost too easily. Additional control is necessary to keep the reactor subcritical during the outage and provide supplementary reactivity control so that the safety rods may be withdrawn and the pile re-started.

43. How is additional reactivity control provided?

Answer: The supplementary control is accomplished at present by charging "temporary poison" into process tubes. The reactor is operated for a few hours to build up the iodine and xenon concentrations in an amount sufficient to replace the reactivity held by the temporary poison, then the poison is discharged. In the case of temporary poison columns the reactor is shut down to replace the poison with regular metal. PCCF (Poison Column Charging Facility) systems at the older reactors permit poison charging and discharging in certain columns during operation. Poison splines used at some reactors to accomplish the same results do not require shutting down for "poison" discharge.

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44. Using Xenon Transient Table (2), or curves in Figure 11, give the following: (a) assumed reactor outage time, (b) xenon value at startup, (c) xenon value and time of "turnaround," and (d) indicated saturation value and time of equilibrium operation.

Answer: (a) 25 hours, (b) about 725 inhours, (c) about 615 inhours five hours after startup, (d) about 900 inhours approximately 50 hours after startup.

45. What is the iodine and xenon condition when the reactor is at turnaround?

Answer: About five hours after startup, the production of additional xenon from decay of the increasing iodine concentration catches up with the rate of xenon decay plus burnout, and the xenon passes through a minimum or turnaround point. The compensating control rods therefore pass through a maximum insertion point at time of turnaround.

46. Using curves shown in Figure 12, give the following data: (a) xenon value at time of scram, (b) xenon value at time of recovery, (c) time and maximum concentration if recovery is made, and (d) time and maximum value if recovery is not made.

Answer: (a) About 900 inhours, (b) about 1000 inhours, (c) about 1000 inhours two to three hours after startup, (d) about 1500 inhours eight hours from time of scram.

47. What is the "small piles" concept?

Answer: The "small piles" concept is merely a method of visualizing the entire reactor as being made up of, for example, eight blocks or cubes of equal size, each of which must be controlled to run smoothly at optimum level. Four of these "small piles" would then be to the rear of reactor center and four to the front, four above center and four below center, etc.

48. Is the xenon concentration evenly distributed in a reactor operating at equilibrium?

Answer: No, control rod movement results in the build-up or depletion of xenon in certain portions of the operating reactor in an unsymmetrical manner.

49. How does control rod movement affect the xenon transient?

Answer: Adding or subtracting an increment of poison by control rod adjustment results in absorbing more or less neutrons and a decrease or increase in the local power or flux in one of the "small pile" regions. Xenon transients resulting from an increased rate of burnout when flux is increased, or increased rate of buildup when flux is decreased, will induce further local flux changes unless the transient effect is controlled locally.

50. Once a local flux change is made, does the flux undergo any further changes?

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Answer: Yes, because the flux change is merely the first event of a series of changes. For example, when flux is increased the positive graphite temperature coefficient of reactivity acts in the same direction as the increased rate of xenon burnout, thus increasing or strengthening the gain in reactivity. The reverse condition acts in the same manner; when the flux is decreased, the buildup of xenon and the graphite cooling result in a decreasing reactivity trend. Furthermore, the above reactions are those seen immediately; several hours later the transient change initiates a flux change in the opposite direction.

51. Do these flux changes take place every time a control rod is moved?

Answer: Yes, when a rod tip is inserted into a "small pile" section to reduce the local flux, the following sequence of events occurs: When one rod is inserted and the other rods are pulled to compensate, the power and flux level in the problem region drops, then the decrease in the negative metal coefficient effect stops the flux from falling further. After the local flux change, local xenon buildup is greater than burnout-plus-decay, resulting in a loss of reactivity; the graphite also begins to cool to the lower temperature value and another reactivity loss results. If rod is not withdrawn from this region, the reactivity loss will continue and accelerate. If rod is withdrawn from this area to maintain the local power level, the xenon transient will reach a "turnaround" in four to eight hours where xenon decay and burnout equal, and then exceed, xenon buildup. From this point the xenon decreases to its new saturation value. While these transients occur in one "small pile" region of the reactor, opposite transients must be occurring in other regions where rods were pulled and flux increased. More rod movement is required to control the resultant turnaround of these non-symmetrical transients during the same four to eight hour interval.

52. What would occur if "small pile" xenon transients were not controlled?

Answer: A series of these local transients and changing power levels taking place in opposite sections of the reactor will cause certain sections of the pile to vary with time in both reactivity and heat generation properties. Changes in graphite temperatures start reactivity effects which cause the process tube exit temperatures to oscillate; when the tube temperatures oscillate beyond limits and force a power cut, subsequent control rod movement adds to the cycling tendencies. These flux drifts from one section of the pile to another are known as "temperature cycling" and have periods ranging from 12 to 16 hours.

53. What precautions should be taken when attempting to reduce or stop temperature cycling?

Answer: The constantly changing flux distribution during a temperature cycle makes it necessary to estimate ahead of time the magnitude of the transient which will result from any planned flux changes, and to limit such changes to the amount of control flexibility available.

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54. What are the three main processes that cause long term reactivity changes at the Hanford exposure ranges?

Answer: (1) U-235 depletion, (2) samarium buildup, and (3) plutonium buildup.

55. Do these processes occur at the same rate at all times?

Answer: No, for the following reasons: (1) Samarium buildup causes a large negative transient during the first few days with a "green" load, (2) the plutonium buildup is reduced at high exposure by increasing plutonium burnout, and (3) decay of Promethium to Samarium and Neptunium to Plutonium during outages causes quite different shutdown transients when there is no burnout of the daughter products taking place.

56. Do the net long term reactivity changes represent an increase or decrease in pile reactivity?

Answer: During an extended time of constant power operation, the net result is usually an increase in reactivity under existing fuel exposure ranges.

57. Give four long term reactivity changes resulting directly from a reactor shutdown: (a) two during the outage, and (b) two following reactor startup.

Answer: (a) 1. Reactivity increase during a shutdown from the decay of residual neptunium to plutonium.

2. Reactivity loss during shutdown from the decay of promethium to samarium poison.

(b) 1. Reactivity loss after startup due to lack of plutonium formation until equilibrium is attained between neptunium decay and formation (in the meantime the U-235 depletion continues at its usual rate).

2. Reactivity loss after startup from the establishment of an equilibrium samarium condition.

The exact magnitude of the above listed effects depends on the amount of metal discharged during the outage (for example, with no metal discharged, the samarium effect following startup would actually be a gain).

58. Are the net long term reactivity gains large at present fuel exposure ranges?

Answer: No - The net long term reactivity gains from these metal effects is positive only between about 200 and 1000 MWD/T and never by more than approximately one-half per cent k. Furthermore, the shutdown effects of neptunium decay to plutonium (gain) and promethium decay to samarium (loss) are largely self-cancelling; the net shutdown transient due to long term effects is not large compared to the short term xenon and temperature coefficient transients.

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59. How much U-235 burnup and total uranium depletion occurs during a normal exposure cycle?

Answer: A goal exposure of 500 MWD/T will consume about nine per cent of the .712 concentration of U-235. At this exposure only a little over .1 per cent of the total uranium has been used up in fission of U-235 plus transmutation to plutonium of U-238.

60. Is the rate of plutonium formation the first day in a fresh batch of new metal the same as it is several days later at the same power level?

Answer: The plutonium concentration lags behind the megawatt days of operation by an induction period of 3.3 days, which is the mean life of neptunium-239 from which it is formed (Np-239 half-life = 2.3 days).

61. What is the reactivity effect during the 3.3 day neptunium to plutonium induction period?

Answer: The pile reactivity initially decreases because U-235 is being burned up with no corresponding increase in Pu-239 until after neptunium-239 has decayed.

62. When do neptunium and plutonium rates of formation come into full equilibrium?

Answer: In about ten days of reactor operation according to tube power and exposure. After the neptunium reaches saturation, the plutonium concentration continues to increase and contributes a reactivity gain.

63. How long during an exposure cycle does the plutonium buildup contribute to the pile reactivity?

Answer: Plutonium long term gains continue until the total effects of U-235 plus plutonium burnout plus long term fission product buildup begin to exceed the plutonium buildup; beyond this point, at about 600 MWD/T, the pile loses reactivity until there is no net reactivity difference between green and ripe metal at around 1000 MWD/T.

64. Is plutonium formed after a reactor is shut down?

Answer: Yes - When a reactor is shut down after an extended operating period, the plutonium continues to be formed from decay of the neptunium-239 present in the fuel elements at the time of shutdown. At the same time, the burnout of U-235 is stopped resulting in an increase in reactivity.

65. How is samarium formed. Is it a poison?

Answer: Samarium is formed by decay of a fission product having a yield of about 0.34 per cent. Next to xenon, the stable samarium nucleus is the most potent absorber among the fission products. Promethium-149 is produced by the fission of U-235 and decays on a 2.2 day half-life to samarium-149 which has an absorption cross section of 60,000 barns.

66. What effect does samarium have on pile reactivity: (a) after reactor startup, (b) during extended operating periods, and (c) after reactor shutdown?

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Answer: (a) The buildup of samarium-149 causes an initial loss of reactivity in a freshly-charged column until it reaches its saturation value. (b) As the poison accumulates, the chance of burnout by neutron capture increases; so the reactivity absorbed reaches a maximum or saturated value of about 250 inhours under steady state operating conditions. (c) After a reactor shutdown, the promethium present at shutdown decays to samarium-149 and causes a further reactivity loss. This loss is about equal and opposite to the neptunium outage gains and is therefore not included in outage transient predictions.

67. Do all fission and transmutation products significantly affect pile reactivity?

Answer: The great majority of fission products have relatively small absorption cross sections and therefore are rather negligible in poison effects. Transmutation nuclei such as U-236, U-237, Pu-240, and Pu-241 and numerous other fission products may be formed in quantities sufficient to affect pile reactivity, but the exact quantities and cross sections of any one of these types of nuclei are not large.

68. Using Figure 15, explain the net long term reactivity changes occurring in a column of green metal during a normal operating period.

Answer: The burnup of U-235 without an increase from Pu-239 until after Np-239 has decayed plus the buildup of Sm-149 poison cause an initial loss of reactivity for the first few days of operation. At about 60 MWD/ton exposure, the samarium approaches saturation, and the rate of reactivity gain from plutonium buildup begins to exceed the rate of reactivity loss caused by the U-235 depletion and Sm-149 buildup. The reactivity continues to increase with exposure until the effects of U-235 and plutonium burnout begin to overcome the effect of plutonium buildup at about 600 MWD/ton exposure. Beyond this point the metal begins to lose reactivity until discharged.

69. Does the plutonium buildup compensate in full for the burnout of U-235?

Answer: Although the plutonium buildup does not completely replace the U-235 burnout on an atom for atom basis, it does provide an increase in reactivity because Pu-239 yields more neutrons per fission than does U-235, and Pu-239 also has a larger cross section than U-235. Above 600 MWD/ton exposure, the burnout of both U-235 and Pu-239 overcomes this effect, and the reactivity decreases with further exposure.

70. What items are included in calculation of the reactivity transient for a given outage?

Answer: Information must be available to determine the individual reactivity contribution of xenon, graphite heating and cooling, metal heating and cooling, excess at shutdown in horizontal rods, and the effects of metal and poison discharge. The sum of these separate reactivity items can be used to calculate the pile reactivity at any time.

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71. At what three times during reactor operation are accurate reactivity predictions especially important?

Answer: There are three main times when accurate reactivity predictions are essential for safe and efficient reactor operation. They are at initial critical, at reactivity turnaround, and at equilibrium conditions.

72. Could a safe reactor startup be made without an exact knowledge of the reactivity present?

Answer: If one knew when a reactor could be started, the VSR's and HCR's could be withdrawn in a slow and cautious manner, but this method would be time-consuming and inefficient. An accurate cold startup prediction informs operating personnel when the shut-down pile can be started and the type of startup most productive under the existing pile conditions.

This exact knowledge is now provided as effectively by subcritical monitoring in many cases as by advance calculations.

73. Is it important that the maximum reactivity transient (turnaround) be known before startup? If so, why?

Answer: Yes - The amount of excess reactivity present at initial startup and the extent of the reactivity transient at the turnaround point are important because the pile reactivity must be controlled within the capacity of the horizontal rods and available supplementary controls. Therefore, the choice of operating level must be consistent with the length of the outage and the amount of supplementary control available.

74. What cases are covered by reactivity predictions and how are the predictions presented?

Answer: A prediction of pile reactivity is prepared by the Area Physicist for each cold or planned secondary cold startup. These predictions are presented in the form of graphs of reactivity versus time. The graphs show the changes in reactivity with time, including critical curves for the time intervals in which the startup is expected to occur, and a sample turnaround curve for the most severe transient expected.

A critical prediction curve is also supplied for hot startups, but the turnaround in this case is not high enough to be of concern.

75. What other instructions or recommendations are supplied by the Area Physicist?

Answer: Entries in the Physicist's Log may explain how startup conditions change with time of startup and give detailed instructions concerning: (1) type of startup, (2) startup power level, (3) reactor gas composition, (4) production which must be accumulated before hot startup procedures can be used, (5) production to be accumulated during operation with temporary poison, (6) temporary poison tube numbers, and (7) descriptions of anticipated control problems.

76. What does R_{00} represent; how is it calculated?

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Answer: Reactivity infinity (R_{∞}) represents the pile reactivity that a reactor would have after a sufficient time down for complete cooling of the metal and graphite, full iodine and xenon decay, and the completion of loading changes. It is calculated by simply adding up the reactivities which are effective at time of interest.

77. What use can be made of R_{∞} , once it is established?

Answer: Since R_{∞} represents the complete decay of xenon and pile cooling, the reactivity of the pile at any time (including shutdown) can be obtained by correcting R_{∞} for xenon and temperature effects.

78. Using the assumptions listed on page 65, calculate R_{∞} for an equilibrium condition.

<u>Answer:</u> Inhours held by rods	= +316
Xenon (from xenon tables)	= +927
C_m at 0.20 ih/MW (0.20 x 1200)	= +240
C_g at 0.67 ih/MW (0.67 x 1200)	= -804
Reactivity at Infinity (R_{∞})	<u>+679</u>

The total or sum (679 inhours) represents the reactivity status of the operating pile with temperature and xenon effects at their equilibrium values; all future reactivity changes add to or subtract from this 679 inhour base.

79. Does a reactor gain or lose reactivity after a shutdown from equilibrium operation?

Answer: The reactor gains reactivity from the metal cooling which takes place almost instantaneously, and it loses reactivity as the graphite cools and xenon builds up in the absence of burnout. The graphite reactivity loss and the xenon growth quickly overcomes the momentary reactivity increase from the cooling metal and drives the reactor subcritical until 24-36 hours after a shutdown.

80. What items caused by the reactor discharge affect the reactivity status of the shut-down reactor?

Answer: The items listed below add or subtract reactivity from the shut-down reactor:

1. Reactivity loss caused by discharge of irradiated uranium metal (long term gains).
2. Iodine and xenon physically removed from the pile in the discharged metal.
3. Changes in flattening columns and special loadings.
4. Changes in graphite coefficient associated with metal discharge and reactor gas composition.

81. Are long term shutdown transients large as compared to the xenon and temperature effects.

Answer: No - As mentioned previously, long term reactivity effects tend to cancel out during a normal metal discharge (temperature effects balancing fissionable plutonium formation).

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82. How are the values of discharged iodine and xenon calculated?

Answer: The discharged metal contains iodine and xenon, so the decay of iodine (M) and xenon (L) is calculated from the remainder. Pre-shutdown saturated values for M and L are reduced through calculational methods based on pile fractions according to reactivity-weighted size of discharge.

83. How does discharged metal affect the graphite coefficient?

Answer: The metal discharge will cause the weighted exposure of the pile (the pile's plutonium inventory) to change. This will change the effect of graphite temperature on reactivity of the operating reactor following the discharge. The graphite coefficient becomes more positive with increasing plutonium.

84. Using the R_{00} established in Question 78, show the reactivity following metal discharge as follows:

$$\begin{aligned}\Delta R \text{ (long term gains discharged in metal)} &= -8 \text{ inhours} \\ \Delta F \text{ (discharge of flattening columns)} &= +48\end{aligned}$$

Answer: The sum of the assumed reactivity changes from the pre-shutdown values can be expressed as:

$$\begin{aligned}R_{00} \text{ (after loading changes)} &= R_{00} \text{ (before loading changes)} + \\ \Delta R + \Delta F \text{ or } 679 - 8 + 48 &= 719 \text{ inhours.}\end{aligned}$$

85. Assuming a metal discharge with a reactivity weighting of 9.8 per cent at time of shutdown from conditions in Question 78 and the table on page 65, show the new iodine and xenon saturated values.

Answer:

$$\begin{aligned}M_8 \text{ (before discharge)} &= 2860 - 280 = 2580 \text{ (after discharge)} \\ L_2 \text{ (before discharge)} &= 927 - 91 = 836 \text{ (after discharge)}\end{aligned}$$

86. Assuming a loss of graphite coefficient in Question 78 caused by the metal discharge as 0.04 ih/MW, what reactivity change is indicated?

Answer: The initial graphite coefficient was assumed to be 0.67 ih/MW. The metal discharge causes a change: $0.67 - 0.63 = 0.04$ ih/MW. This corresponds to a loss of $(1200)(0.04) = 48$ inhours of graphite contribution during equilibrium operation at 1200 MW following startup.

87. Can xenon and graphite transient effects be accurately calculated for the shutdown reactor in spite of loading changes?

Answer: Yes - Once the reactivity at infinity (R_{00}) is established before loading changes and then corrected for loading changes (including long term gain metal effects), the shutdown reactivity transient and critical curve can be calculated and plotted.

88. What expression, or equation, can be used to determine the reactivity status at some time (t) following a shutdown?

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88. (Continued)

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

$$R(t) = R_{00} - L(t) + C_G(t) + C_M(t)$$

where R_{00} is reactivity infinity, $(L(t))$ is the xenon poisoning, C_G is the graphite contribution, and C_M is the metal temperature reactivity loss.

89. Assuming a reactor shut down for a metal discharge as discussed in Questions 84 and 85, what is the pile reactivity at zero time down (just after shutdown)?

Answer: $R(t) = R_{00} - L(t) + C_G(t) + C_M(t) = 719 - 836 + 804 + 0 = 687$ inhours.

90. From Table I and Figure 17, pages 69 and 70, give the following:

1. Reactivity gain or loss from metal cooling.
2. Reactivity immediately following shutdown.
3. Time and amount of minimum reactivity.
4. Scram recovery time.
5. Minimum downtime.
6. R_{00} , reactivity, after infinite time down.
7. Maximum reactivity range.

Answer: (1) Gain of 240 inhours, (2) 556 inhours immediately following shutdown, (3) -771 inhours about 10 hours after shutdown, (4) about 30 minutes, (5) 29 hours from one-half down, (6) 719 inhours, (7) $771 + 719 = 1490$ inhours.

91. What is meant by "minimum outage"?

Answer: The interval between the time the pile power is half down from operating level and the reactor can first be started with all rods out following a reactivity minimum is called the minimum downtime; a shutdown of this length would be a minimum outage.

92. Explain the "turnaround" reactivity effect.

Answer: After a pile is started and its power level is held at a constant level, its potential reactivity (excess in rods) will increase for a period of several hours until the xenon formation rate from iodine decay balances, and then overrides, xenon burnout and decay plus graphite heating effects. This point of maximum reactivity is called "turnaround."

93. Does the turnaround reactivity transient impose any limit on reactor operation? Explain.

Answer: Yes - The magnitude of the reactivity transient from startup to turnaround will depend primarily on the power level, the amounts of iodine and xenon present at startup, and the over-all contribution, C_0 , which is the net sum of the metal and graphite contribution. Thus, the startup level will be limited by the amount of control available for controlling the transient.

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94. How can the turnaround point be within the operator's control?

Answer: A particular power level (W) can be found through calculational methods such that the reactivity (R_t) will barely not exceed the capacity of the control rod system, but will provide the maximum production within the limits of control and temperature.

95. Using Table II and Figure 19, pages 73 and 76, describe the reactivity transient during the seven-hour period following startup.

Answer: From the table note that the xenon (L) value of 689 inhours at startup is reduced to 567 inhours one hour after startup. Iodine (M) builds up steadily toward saturation value, but the decay to xenon lags by several hours. The graphite (C_G) heats up gradually, contributing increasing reactivity which must be compensated by control rods until turnaround. The metal (C_M) heats up almost instantaneously and causes a sudden drop in reactivity (R) for a short period of time. Iodine decay to xenon catches up with xenon burnout and decay about the same time that the graphite (C_G) attains an equilibrium condition 5.5 hours after startup. At six hours xenon poison has increased by three inhours to 406 while the graphite remains the same at 431 - the sum of all these reactivity effects (R) drops three inhours which is compensated by control rod withdrawal to maintain the power level at 785 MW. As xenon continues to build up from the iodine backlog, the power level can be gradually raised to operating limits.

96. From information in Table II, substitute the correct values into the equation for R at time of maximum reactivity.

$$R(t) = R_{00} - L(t) + C_G(t) - C_M(t). \quad (R_{00} = 719).$$

Answer: $719 - 403 + 431 - 157 = 590$ inhours at turnaround.

97. From information given in Figure 17, page 70, give (a) the reactivity change for the period of time from minimum downtime to 39 hours down, (b) amount of rod required to hold the pile just critical at that time, and (c) the amount of rod available for control of the startup transient.

Answer: (a) About 340 inhour gain in reactivity from xenon decay, (b) 340 inhours, (c) $700 - 340 = 360$ inhours for control of reactivity transient after startup.

98. What reactivity effect takes place when an outage is extended beyond minimum downtime?

Answer: When a reactor outage progresses beyond the minimum downtime, more horizontal rod is needed to hold the shut-down pile just critical as the xenon continues to decay, so less rod is available for controlling the more demanding reactivity transient following the reactor startup.

99. How is the reactivity controlled in a xenon-free pile?

Answer: By the safety rods. Additional control is sometimes necessary to keep the pile safely subcritical during the outage in event of water loss

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99. (Continued)

and to provide additional reactivity control during the transient following startup.

100. What methods are used to provide additional reactivity control?

Answer: Additional control can be provided in the form of lead-cadmium slugs which are most effective if charged into tubes located just outside the horizontal rod pattern, or by the insertion of "poison splines."

101. What effect does "temporary poison" have on the reactivity of a pile?

Answer: The use of temporary poison reduces the excess reactivity to a point where the reactivity transient at a high level can be controlled by the horizontal rod system.

102. How much temporary poison is used if POCF columns are not available? How long is the poison run?

Answer: The amount of temporary poison to be charged is determined (1) by the minimum reactivity required for startup, and (2) by the magnitude of the transient following the discharge of the temporary poison. The reactor is operated for a few hours to build up the iodine and xenon concentrations in an amount sufficient to replace the control provided by the temporary poison charges by the time the second, temporary-poison-free turnaround is reached.

103. How does temporary poison provide additional reactivity control if it is discharged?

Answer: The xenon builds up after the pile is shut down absorbing the reactivity formerly held by the temporary poison. Thus, in the operating period after poison discharge it is possible to attain turnaround at a high power level with only the horizontal rod controls, and, therefore, permit a rapid rise to the equilibrium power level.

104. From Table VI, page 82, give the following: (a) the amount of temporary poison used in the initial startup, (b) reactivity held by control rods at first turnaround, (c) xenon change during 9.5-hour shutdown for poison discharge, and (d) reactivity held by control rods at second turnaround.

Answer: (a) 250 inhours, (b) 590 inhours, (c) an increase in xenon poisoning of 205 inhours, (d) 524 inhours.

105. Which is most important in setting the time for the temporary poison run: Time operated with temporary poison, or amount of production accumulated?

Answer: If too much iodine and xenon are produced during the poison run, the pile would become subcritical four or five hours after shutdown. It would not become critical again for another 10 or 20 hours and a large production loss would occur. The reactivity curve is sensitive to total production (power level x time) accumulated during operation before shutdown. Within the probable range of operating levels it is not as sensitive to the time taken to accumulate the total production.

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106. What is the net reactivity effect of a "scram" from equilibrium conditions?

Answer: After an initial gain due to metal cooling, the pile rapidly loses reactivity as the graphite cools and xenon builds up from iodine decay.

107. Can these "scram" reactivity losses be calculated?

Answer: Yes - At equilibrium operation, the iodine and xenon saturation values are well established with known rates of creation, decay, and burnout. Since the loss from graphite cooling is a function of exposure history and pile atmosphere, evaluations can be made to calculate the scram recovery time. The greatest uncertainty is probably in the calibration of the rods withdrawn during approach to critical; these are calibrated against the scram transient from time to time.

108. Are reactivity calculations made at the time of scram?

Answer: No - Equilibrium scram critical curves for a wide range of power levels are prepared in advance to show reactivity loss versus time. The amount of inhours in control rods at time of scram will then determine the maximum available scram time.

109. Does thirty minutes scram recovery time indicate thirty minutes available for attaining criticality?

Answer: Yes, provided the rate of rise permitted by Process Standards is used from that point on. The recovery power level must be high enough to effectively halt the reactivity loss. If less than the maximum available time is used to attain this level, some excess reactivity will remain in the control rods for better temperature control.

110. Can a minimum recovery level be precisely calculated?

Answer: No, because of flux shifts during the recovery, temperature coefficient contributions are not linear with gross power level during a scram recovery. The best power level is the highest which can be attained within safe individual tube operating limits. If a high power level is attained, reactivity will be gained which will aid in control and a rapid return to equilibrium conditions.

111. From information given in Figure 22, find critical (less 60 inhours for rising period) for a pile scrambling from 2200 with 325 excess in rods: (a) 60 minutes after scram, (b) 30 minutes after scram, and (c) give rate of decay between (a) and (b).

Answer: (a) $325 + 288 (.09 \times 1200) - 60 - 250 = 303$ inhours.
(b) $325 + 288 (.09 \times 600) - 60 - 355 = 198$ inhours,
(c) About 10.5 inhours per minute.

112. Which type of scram provides the longer recovery time: the equilibrium or non-equilibrium scram?

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112. (Continued)

Answer: With a given reactor loading the non-equilibrium scram provides more time for recovery than the equilibrium case. In many cases the pile does not go subcritical and the time available for recovery is of the order of hours.

113. True or False: Since time is not important, there is less chance for trouble in making a recovery from a non-equilibrium scram than in recovering from a scram from equilibrium.

Answer: False - During a scram from equilibrium conditions, the pile reactivity is normally so low (less reactivity held in rods) that there is usually little danger of an excessively fast startup. This is not the case for the non-equilibrium scram because the pile reactivity may be increased several hundred inhours by the longer downtime, poison discharge, etc.

114. Can prediction charts be prepared to cover the variety of pile conditions and ranges of criticality encountered in the non-equilibrium scram?

Answer: Yes - The near-infinite variety of pile conditions is broken down into a series of charts according to major factors such as power level, length of previous outage, time operated, amount of temporary poison, etc. Accuracy of approximate case calculated for a given range of conditions is of the same order as the rod system calibration.

115. From Figure 22, page 88, find critical for a pile operated for a total of 10,000 MWH. Power level at time of scram 2000 MW, 400 inhours in rods: (a) one hour after scram, (b) two hours after scram, (c) three hours after scram.

Answer: (a) $400 + 120 (.06 \times 2000) - 185 = 335$ inhours.
(b) $400 + 120 (.06 \times 2000) - 280 = 240$ inhours.
(c) $400 + 120 (.06 \times 2000) - 330 = 190$ inhours.

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This document classified

by: HC Fuller

This document consists of ~~43~~ pages. A.

REVIEW MATERIAL ON CHAPTER V
CONTROL OF THE PILE REACTION
REACTOR PROCESSING FUNDAMENTALS COURSE

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November 21, 1960

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CHAPTER V - CONTROL OF THE PILE REACTION

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REVIEW MATERIAL ON CHAPTER V
CONTROL OF THE PILE REACTION

REACTOR PROCESSING FUNDAMENTALS COURSE

This document is the third of a series of question and answer lists issued as a review of the material discussed in the Reactor Processing Fundamentals Course. The first list, HW-59145, "Review Material on Chapter III - Pile Structure," was issued June 8, 1959. The second, HW-65248, "Review Material On Chapter IV - Variations in Pile Reactivity," May 23, 1960. Each document represents the material covered by the Reactor Specialists during a typical three-month training program. Each question is discussed individually and the entire list completed during the three-month session. Each three-month training period is devoted to the complete discussion of a single chapter of the IPD Physics Primer series.

The questions are compiled in a logical sequence with the material as presented in Chapter V of the Primer series. As the course progresses, a certain amount of recall of earlier chapters is essential to a thorough knowledge of the specifics of reactivity and distribution control. Therefore, the first half of this document consists of material previously presented in a slightly different manner. The second half also may contain questions of a repetitious nature - used at this point to drill home the fine points of local trend control. Basic points are stressed; the intent is, of course, that informative discussions lead to a better understanding of the material presented in the Primer. At the completion of each three-month period, each participating member receives a complete review in this documentary form which may prove useful as a training guide for shift group training meetings.

A typical three-month training program consists of three (3) three and one-half hour discussion periods on a single chapter of the IPD Physics Primer series (ten and one-half hours total). The meetings are held every Wednesday from 8:00 to 11:30 a.m., at the 105 KE Conference Room, with each of the four shift classes meeting monthly. At the time Specialist classes have covered the following:

- Chapter I - Structure of the Atom
- Chapter II - Physical Principles of the Reactor Process
- Chapter III - The Pile Structure and Instrumentation
- Chapter IV - Variations in Pile Reactivity

Similar training programs will be offered on the two remaining chapters of the Primer series:

- Chapter V - Control of the Pile Reaction
- Chapter VI - Operating Procedures and Standards (in preparation)

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REACTOR FUNDAMENTALS TRAINING QUESTIONS

CHAPTER V

CONTROL OF THE PILE REACTION

1. Are all neutrons produced in fission available to cause other fission reactions? Explain.

Answer: Only a fraction (about 4 of every 10) of the fission neutrons are available to produce another fission; some are lost in captures which do not produce fission, in coolant, moderator and structural material, and some leak from the edges of the pile.

2. Name four neutron processes that affect the value of the "multiplication factor" in the Hanford (or any) reactor.

Answer: 1. Complete loss of fast or slow neutrons by escaping from the pile.

2. Non-fission capture by U^{238} .

3. Non-fission capture by coolant, moderator, fission products, etc.

4. Fission capture of slow neutrons by U^{235} , or of fast neutrons by both U^{235} and U^{238} .

3. What is the fast fission effect?

Answer: Before the velocity of the newly-created fast neutrons is decreased to any great extent, they will cause a few fast fissions in the more abundant U^{238} nuclei, and also a negligible number in the relatively scarce U^{235} nuclei. This effect is called the "fast fission" factor and it multiplies the number of neutrons created by thermal fissions each generation by a value slightly in excess of unity (about 1.03). In other words three per cent additional neutrons are produced in this way.

4. When newly created fast neutrons enter the graphite: (a) what is the initial speed of the fast neutron, (b) about how many collisions are required to reduce the speed to "slow" or "thermal" values, (c) how long is the neutron life cycle, or generation time, (d) what is the approximate rate of travel of a slow (thermal) neutron?

Answer: (a) An energy of about 2 Mev is equivalent to a speed of 18,000 miles/second, about 10% the speed of light. (b) About 115 collisions, (c) about 0.001 second, and (d) more than 3000 miles per hour.

5. Assuming optimistically that three neutrons are produced in each fission reaction, describe a possible three-term neutron balance for a multiplication of exactly unity, or $k_{eff} = 1.0000$.

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5. (Continued)

Answer: One of the three fission neutrons carries on the fission chain with U^{235} , another is captured by a U^{238} nucleus to form plutonium, while the third is lost, either in other forms of non-fission capture or by escape from the pile.

6. What is the primary method of controlling the neutron population in a Hanford reactor?

Answer: The primary method of controlling the neutron population, and thus the power output of the reactor, is to control the parasitic capture reactions. This is accomplished by inserting into or withdrawing from the reactor a rod of neutron absorbing material that readily absorbs neutrons, but does not in turn liberate new neutrons.

7. What is meant by the statement: Production = absorption plus leakage?

Answer: The statement describes the neutron balance for a steady state condition where the number of neutrons produced is equal to the total number lost by absorption and leakage. When the chain reaction is steady and exactly self-sustaining, such a system is said to be "critical." This means that the system is perfectly balanced in rate of neutron replacement relative to losses.

8. What is the relationship between the multiplication factor and an increase in power output?

Answer: Since the power level of a given reactor is directly proportional to the neutron density or flux, the only practical way to increase this density is to make use of a rising fission chain reaction, for which k_{eff} must be greater than one: this means that the reactor must be built with enough potential reactivity so that k_{eff} can potentially exceed unity. However, once the power increase is attained, the k_{eff} must be returned to and maintained at exactly 1.0000.

9. What term is used to describe the amount by which a multiplication factor is greater than unity?

Answer: The amount by which the multiplication exceeds one is called the "excess multiplication factor," or excess k , and is usually expressed in terms of per cent of the multiplication factor. For example, a multiplication factor of 1.01 corresponds to an excess k of 0.01, or one per cent. Since $k_{eff} = 1$ for a just critical reactor, k_{ex} is a measure of departure from this condition. Numerically then:
 $k_{ex} = k_{eff} - 1.$

10. Are there any neutrons in the shutdown reactor?

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10. (Continued)

Answer: Even when shut down, every Hanford reactor has a residual neutron density. These may come from the spontaneous fission of uranium, from fission caused by cosmic rays, or from other sources such as the fission decay gamma reaction with the deuterium in the cooling water. As long as the system is subcritical ($k_{eff} < 1$) the neutron flux will be quite small and will remain constant at a level depending on the degree of subcriticality.

11. How is the neutron density of the shutdown reactor changed during startup and the following rise to operating level?

Answer: By withdrawing the neutron-absorbing control rods, the parasitic capture of neutrons is reduced so that k_{eff} becomes greater than one and the rising chain reaction causes the neutron density to increase until the desired power level is attained. The control rods are then partially inserted to absorb enough neutrons to make k_{eff} equal to unity; the chain reaction now becomes steady and the power level remains constant.

12. Are all fission neutrons released at the instant of fission? Explain.

Answer: All neutrons produced by fission are not released at the instant of fission. Over 99 per cent of the neutrons are released within an extremely short interval of time; these are referred to as "prompt neutrons." The remainder, about $3/4$ of one per cent of the neutrons, are "delayed neutrons" which are ejected from the fission products a few seconds after the actual fission occurs.

13. Are delayed neutrons ejected from a single fission product? What are the delay times?

Answer: The delayed neutrons accompanying the fission of uranium-235 and plutonium-239 fall into five major groups, each of which is detected by a definite rate of decay. The rates of decay range from 0.6 to 80 seconds and average about 10 seconds.

14. What effect do delayed neutrons have on reactor startup? Shutdown?

Answer: Since the prompt fission neutrons are released almost instantaneously, the generation time as far as these neutrons are concerned, is one-thousandth of a second. However, when the delayed neutron time of roughly one per cent of the neutrons is averaged with the lifetime of the 99 per cent prompt neutrons, the effective generation time is changed from one-thousandth of a second to one-tenth of a second. When the reactor is shut down, the large number of delayed neutrons cause the power to drop off slowly rather than instantaneously. If there were no such thing as the delayed neutron effect, the neutron generation time in the graphite reactor would be about one-thousandth of a second, and there would be a constant danger of the reaction being too fast for human control.

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15. How can a "prompt critical" condition be avoided?

Answer: If the delayed neutron effect sets the effective neutron lifetime as 0.1 seconds, it follows that for a reaction that is just barely critical ($k_{eff} = 1.000$), the rate of neutron population increase or decrease will be determined by the average neutron emission time of 0.1 second. Since the delayed neutron effect is 0.75 per cent, or a fraction 0.0075 of the total, prompt critical can be avoided provided the multiplication factor is kept between 1.0000 and 1.0075. In other words, the control rods should be withdrawn in steps so that at criticality, the k_{eff} is less than 1.0075, but greater than 1.0000. If criticality can be attained with k_{eff} slightly in excess of 1.0000, the neutron population can increase only through the additional contribution from the delayed neutrons.

16. What would occur if criticality were attained with a k_{eff} of 1.0075?

Answer: The reactor would be critical on prompt neutrons alone and would increase without waiting for any delayed neutron effect. The combination of k_{eff} 1.0075 and the 1/1000 second generation time would cause the chain reaction to increase at a tremendous rate. At the defined point of "prompt critical," the reactor period would be of the order of one second.

17. From Figure 4, give the rate of increase for: (a) k excess of 0.001, (b) k excess of 0.0075, and (c) k excess of 0.015.

Answer: (a) 46 seconds for the neutron flux to increase by a factor of $e(2.718)$, (b) 0.7 seconds (prompt critical), and (c) 0.2 second.

18. What is the relationship between the length of the pile period, the per cent of excess k , and the inhour (or c-mk)?

Answer: A given amount of excess reactivity will cause the neutron flux to increase at a given rate. The rate of this increase can be measured with time and converted to either inhours or units of k (such as c-mk). The theoretical relation between inhours and excess k indicates that one per cent of excess corresponds to approximately 400 inhours. Thus prompt critical or 0.75 per cent excess k is equivalent to almost 300 inhours. Using this assumption, we can convert k excess to inhours thus:

$$\text{Inhours} = 40000 \times \frac{K_{ex}}{K_{eff}}$$

The table below shows the relative values of k effective, k excess in per cent and in inhours, and the corresponding pile periods in seconds.

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18. (Continued)

Answer: (Continued)

<u>Reactivity and Pile Period</u>				<u>Rising Period</u> <u>(seconds)</u>
<u>k_{eff}</u>	<u>k_{ex}</u>	<u>c-mk</u>	<u>k_{ex} (inhours)</u>	
1.0000				
1.0001	0.0001	10	4	900
1.0003	0.0003	30	12	300
1.0006	0.0006	60	24	120
1.0012	0.0012	120	48	45
1.0024	0.0024	240	96	14 Period Trip
1.0050	0.0050	500	200	2.5
1.0075	0.0075	750	300	0.7 Prompt Critical
1.0100	0.0100	1000	400	0.2
1.0150	0.0150	1500	600	0.1

19. Should the k_{eff} of a reactor operating at a steady 100 MW ($k_{eff} = 1$) be suddenly increased by a rod pull representing 240 c-mk of k excess, the power level would increase by a factor of e in 14 seconds. If allowed to continue, what would the level be in 14 seconds, in 28 seconds, in 42 seconds, and in 56 seconds?

Answer: 14 seconds after rod pull the power would be $100 \times 2.718 = 271.8$ MW, at 28 seconds $271.8 \times 2.718 = 739$ MW, at 42 seconds 2,010 MW, and 56 seconds 5,465 MW.

20. How can fast rising periods be avoided during reactor startup?

Answer: During reactor startup the exponential rate of increase can cause the level to rise to dangerous proportions if allowed to continue unchecked for even a few minutes. The inherent danger of fast rising periods must be considered carefully in the approach to criticality. By correct regulation of the rod withdrawal rate, in accordance with procedure alone or including subcritical monitoring, the amount of excess k can be controlled so that after criticality the rising period will be sufficiently long to provide time for accurate measurement of the supercritical rate of rise. In other words, the reactor should enter the supercritical stage with only that amount of excess k necessary to generate a reasonable and safe pile period.

21. From Figure 5, give the rate of increase for the following amounts of k excess: (a) 0.0023, (b) 63 inhours, (c) 120 c-mk, (d) 40 inhours, (e) 0.0007, (f) 24 inhours.

Answer: (a) 15 second period, (b) 30 second period, (c) 45 second period, (d) 60 second period, (e) 90 seconds, (f) 120 seconds.

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22. What are the requirements of an "ideal" horizontal control rod system?

- Answer:
1. An ideal horizontal control rod system would be perfectly calibrated for total control capacity and incremental rod strength, and would provide adequate control for safe and steady operation of the reactor under all possible reactivity conditions.
 2. It would be able to completely control any reactivity transient or flux distortion arising from startups, turnaround, power level changes, or changes in gas composition.
 3. It should provide fast-moving controls for the adjustment of extremely short pile periods, for scram recoveries and emergency shutdowns, and yet it should be capable of fine adjustment control during equilibrium operation.
 4. It should be flexible enough to obtain maximum flattening and flux distribution adjustment ability from the amount of excess reactivity available.

23. Do the Hanford reactor control systems satisfy these requirements?

Answer: No, the horizontal rod systems alone at any of the reactors falls far short of an ideal system. Certain provisions are made that provide adequate control, but they fail to meet the requirements for ease of control.

24. What provisions were made to supplement the present horizontal control rod systems?

Answer: To improve the flexibility of the horizontal rod systems for uniform flattening and to increase the total control capacity, the five older reactors (B, D, DR, F, H) are equipped with the Poison Column Control Facility (PCCF) which permits adjusting the strengths of poison columns during operation. This facility also provides additional transient and flux distribution control, permitting more efficient startups and better flattening at equilibrium operation. Other supplemental controls such as the Poison Spline Facility and the Displacement Column Facility are used to provide a complete and flexible control system for the Hanford reactors. Fringe enrichment is used to increase pile flattening while providing enough excess reactivity to maintain sufficient control rods in the reactor for adequate control.

25. Does the multiplication factor of a reactor change?

Answer: When a reactor operates at high level, its temperature rises because of the tremendous amount of fission energy released. From earlier discussions, we know that the higher temperatures inside the operating reactor will cause changes in the relationship among the fission, absorption, and scattering cross-sections for thermal neutrons of fuel and moderator. In addition, gas

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25. (Continued)

Answer: (Continued)

composition, fuel depletion, fission products, etc., will also cause changes in the reactivity status of the operating or shutdown pile.

26. Do all of these reactivity changes take place at the same rate? How are they controlled?

Answer: Some of the activities which cause these reactivity changes in the operating pile take place very slowly, and their effects are noticeable only over long periods of operation (long term variables). Others take place more or less rapidly (short term variables). In order to keep the neutron activity at a constant level during these changes in pile reactivity, the pile operator must insert or withdraw control rod at such a rate that instrumentation trends indicating decreases or increases in neutron level are halted and the neutron level is held effectively constant at $k_{eff} = 1.0000$.

27. What is meant by the term "transient"?

Answer: "Transient" is a term used to describe the potential behavior of the reactivity in a pile under changing conditions such as fuel depletion, fission product poisoning, and temperature effects. Thus a "reactivity transient" implies that the pile reactivity is not settled or established, but is shifting and changing continuously according to the pile conditions at any particular time. This variation in pile potential reactivity must be continually balanced by rod insertion or withdrawal.

28. What effect does fuel exposure have on pile reactivity?

Answer: As the reactor operates at high power levels, U^{235} atoms are consumed, causing a reduction in pile reactivity which proceeds at a rate proportional to the accumulated megawatt days of exposure. The amount of depletion or burnout which a reactor can tolerate depends on such things as the pile size, structure, slug concentration, and power level. If the maximum burnout of a high-power reactor is of the order of five to ten per cent, five to ten per cent more fissionable material must be loaded into the reactor to allow for fuel burnout. If a reactor were used to produce power only with no isotope production, it is easy to see how the fuel would deplete with time and lose reactivity. In our reactor it becomes a little more complicated because the plutonium atoms formed during operation are also subject to fission; the net result is that the reactor does not lose reactivity nearly so fast and under some operating conditions may gain in reactivity.

29. What effect does the formation of plutonium have on pile reactivity?

Answer: Because plutonium- 239 is highly fissionable by slow and resonance energy neutrons, the pile will gain reactivity from the formation of Pu^{239} in the operating pile. When fresh metal is loaded into a reactor,

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29. (Continued)

Answer: (Continued)

neptunium builds up to its steady state concentration and decays into plutonium with an effective 3.3 day lag. The neptunium and plutonium come into full equilibrium in a week or so according to tube power and pile exposure. The pile reactivity will then increase with time until the total effects of U^{235} and plutonium burnout and fission product poison buildup begin to exceed that of plutonium formation; beyond this point the reactor loses reactivity.

30. Does the formation of plutonium atoms replace the U^{235} burnout?

Answer: Not completely; although the plutonium buildup does not replace the U^{235} burnout atom for atom, it does provide an increase in reactivity because Pu^{239} yields more neutrons per fission than does U^{235} (about 2.89 to 2.43). Pu^{239} also has a larger fission cross-section than U^{235} (about 742 to 582). Above 600 MWD/ton exposure, the burnout of both U^{235} and Pu^{239} overcomes this effect, and the reactivity decreases with further exposure.

31. Does the presence of samarium create any control problems in the Hanford reactor?

Answer: Although a potent absorber of neutrons, samarium is a minor problem compared with that of xenon poisoning. Promethium-149 is one of the fission products of U^{235} and decays on a two-day half-life to samarium-149 which is a stable nuclide with a large absorption cross-section (66,000 barns) for thermal neutrons. As the samarium poison accumulates, the chance for burnout by neutron capture increases, so the pile reactivity absorbed by samarium reaches a maximum or saturated value of around 600 c-mk under steady operating conditions.

32. Which of the fission products is most important from the operating viewpoint?

Answer: The most important fission product to reactor operation is xenon-135 because of its large absorption cross-section - about 3.2×10^6 barns - for thermal neutrons. The effects of the xenon poison transients influence reactor operation in many ways. For example, although the saturated poison effect at equilibrium operation may cause a reactivity loss of 2 to 2-1/2% k (2000-2500 c-mk) in the usual power ranges, the decay of this amount of poison in the shutdown pile will represent a total swing of 4000 to 5000 c-mk from the initial xenon-free pile at startup. This delayed action effect in xenon formation and decay is the major cause for the scram transient, minimum downtime, and turnaround problems encountered in the operation of a high power reactor. A detailed discussion on the effects of xenon poisoning on pile reactivity may be found in Chapter IV of this series.

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33. Does the metal effect cause a gain or loss in pile reactivity?

Answer: The metal temperature effect can cause gains or losses in pile reactivity of the order of 500 to 750 c-mk, according to temperature change. The reactivity losses will occur through the heating of the uranium metal, the "gains" (actually cancellation of the losses) through the cooling of the metal. As the temperature of the metal rises, the increased absorption of neutrons by U^{238} causes a loss in pile reactivity and produces a negative coefficient. Because the thermal conductivity of the metal is high and the thermal contact between the metal and water is good, the metal temperature follows the power output of the reactor with very little time lag.

34. Is there any connection between cooling water temperature and reactor power level?

Answer: The water temperature can directly affect the power level only through its inlet temperature which may fluctuate between 0° - 5°C during the winter to 20° - 25°C during the summer. Thus, the inlet water temperature determines the delta temperature of a pile operating on set process or bulk outlet temperature limits.

35. Would a change in cooling water temperature have any effect on the pile reactivity?

Answer: The cooling water temperature has a two-way directional effect on both the graphite and metal temperatures. This occurs because an increase of water temperature must be accompanied by corresponding though somewhat smaller increases in the graphite and metal since it acts as a cooling agent for both materials. An increasing temperature will cause radial expansion of process tubes and slugs, changing the size of the water annulus and hence the amount of water present; the water itself expands and reduces the amount of neutron scattering and absorbing material in the annulus. Actually, increasing water temperature produces a "window" effect in the water annulus which tends to let "hotter" neutrons pass more freely between the metal and graphite and vice versa. Altogether, however, the temperature of the water itself is relatively unimportant in the reactivity status of Hanford reactors.

36. How does the water itself affect pile reactivity? Where is it accounted for?

Answer: The amount of cooling water and the power level will largely determine the temperature of the fuel elements, water, and graphite. The effect of the water itself and its temperature are included in the reactivity calculations of the metal and graphite temperature coefficients.

37. Explain the connection between power level, graphite temperature, neutron energy, and graphite coefficient effect.

37. (Continued)

Answer: The power level determines the temperature of the graphite, and the graphite coefficient is directly related to the fact that the temperature or energy of the thermal neutron is set by the graphite temperature.

38. Using Figure 7, explain the relationship between graphite temperatures and pile reactivity.

Answer: As shown in Figure 7, the graphite temperature has a direct relationship with pile power and pile reactivity. In addition, the graphite temperature indirectly affects every other component or product contributing to the pile reactivity status. The main characteristics of graphite temperature changes are listed below:

- (a) Graphite temperatures (assuming constant gas atmosphere) are directly related to power level.
- (b) The temperature or energy of the thermal neutron is set by the graphite temperature.
- (c) Higher graphite temperatures tend to increase the chance of plutonium fission; increased local plutonium fission results in a local increase in graphite temperature.
- (d) The production of plutonium, samarium, and xenon are directly dependent on power level, but the graphite temperature also exerts a secondary effect on the production of each.
- (e) Because the graphite temperature does not approach a steady state until an hour or more after a power change (or several hours after cold startup), the moderator temperature effect on pile reactivity is time sensitive to the heating and cooling rates of the graphite.
- (f) Because of the thermal conductivity of the graphite and the gas composition, any change in gas atmosphere during operation will cause changes in the pile reactivity.
- (g) As the graphite temperature changes, the various positive and negative effects cause associated changes in pile reactivity. The graphite temperature can cause gains or losses of two or three per cent in the neutron multiplication rate as the graphite temperature changes over a period of several hours.

39. What is meant by the term "reactivity transient" of a Hanford reactor? How are they controlled?

Answer: One might say that the "reactivity transient" is the net potential reactivity effect of a complicated combination of different components, isotopes and fission products, and temperature effects

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39. (Continued)

Answer: (Continued)

present in the reactor at any given time. Each reactivity variable has unique characteristics under varying pile conditions such as startups, turnaround, and steady state operation. Coolant flow, gas composition, rates of decay and burnout, fuel exposure and product formation are continuously changing in the operating pile. In order to control these reactivity transients, the reactor must be operated in such a way that the net reactivity effects can be handled within the capacity of the horizontal rod system plus supplementary control while operating, and by the addition of the safety rod system during shutdown outages.

40. Are reactivity transients considered a hazard to nuclear safety?

Answer: Only under certain non-standard operating conditions. For example, an operating transient of five or more c-mk per minute is relatively fast, yet the operator can compensate 150 or more c-mk per minute if necessary. Thus nuclear safety is critical during full power operation only in the case of an accident such as flow stoppage or a gross operational error such as the sudden withdrawal of control rods. However, nuclear safety does depend on operational procedures and adequate instrumentation. For instance, it is very important that rod withdrawal rates (set by procedures) be conservative so that large excesses of reactivity cannot develop before a supercritical rate-of-rise can be measured by accurate instrumentation.

41. Does the pile reactivity ever reach a true equilibrium condition?

Answer: Not a true equilibrium; actually this is only an average condition over the pile as a whole. Small temperature and xenon changes are going on at all times, helped along by the frequent rod movements and by self-induced reactivity effects of these transients themselves. As each minor change occurs in various sections of the pile, control rod is inserted or withdrawn to maintain a constant reactivity ($k_{eff} = 1.0000$) and thus a constant power level.

42. Could a reactivity event in the "controlled" pile proceed to an extent as to cause a lapse of control, or a power excursion?

Answer: There are three common occasions in which this could occur: (1) lack of sufficient control at turnaround, (2) lapse of control while operating, especially during poison discharge or spline work, and (3) excessive and continued rates of rise during reactor startup. Excursion possibilities due to loss of cooling water would also be potentially serious, but cooling water supply is not under the direct control of the reactor operator.

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43. What determines the size or magnitude of the reactivity transient after a cold startup?

Answer: The magnitude of the reactivity transient from startup to turnaround will depend primarily on the power level, the amounts of iodine and xenon present, and the metal and graphite coefficients. Thus, the startup level and operating efficiency will be limited by the amount of rod available for controlling the reactivity transient following startup. A particular power level is determined through calculational methods such that the resulting transient will barely not exceed the capacity of the control rod system.

44. From information shown in Figure 9, give the following: (a) inhours (and c-mk) in rod at time of scram, (b) reactivity gain or loss immediately following scram, (c) inhours (and c-mk) in rods at time of scram recovery, (d) time from scram to equilibrium condition in the recovery case, (e) time and amount of minimum reactivity, (f) minimum downtime, (g) inhours (and c-mk) in rod at turnaround, and (h) time from cold startup to equilibrium conditions.

Answer: (a) 400 inhours, 1000 c-mk; (b) about 200 inhours, 500 c-mk, reactivity gain from metal cooling; (c) about 175 inhours, 438 c-mk; (d) near-equilibrium conditions in about 6 hours; (e) reactivity loss of more than 1000 inhours (2500 c-mk) about 10 hours after scram; (f) about 28 hours; (g) about 800 inhours, 2000 c-mk; (h) about 48 hours.

45. Would running out of rod at turnaround be considered a nuclear safety hazard at Hanford?

Answer: The possibility of a power excursion resulting from lack of control at turnaround is considered as an operating problem rather than a safety problem. In normal reactor operation it is extremely unlikely that a transient as fast as one inhour per minute (2.5 c-mk/min) would occur at turnaround after running out of control rod. Such fast rod movement just prior to turnaround would surely be noticed and remedial action taken before actually running out of rod. However, assuming that the reactor would gain reactivity at the rate of 2.5 c-mk per minute, the power level would increase two per cent in the first five minutes. Under these circumstances, plenty of time would be available for operator action (manual scram of the VSR's) some time before emergency trips would take place.

46. Would the accidental discharge of a full column of poison during reactor operation cause a power excursion? What precautions are taken?

Answer: The discharging of poison columns during reactor operation is normally covered by procedures requiring prior insertion of control rod and reduction of power level. Should this procedure break down and a poison column be flushed rather than displaced piece by piece, a total power rise of approximately six per cent would occur within about 30 seconds. At this time the power rise would be limited by the negative metal coefficient which had taken place. The slow rate of power rise would afford plenty of opportunity for an automatic trip should any

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46. (Continued)

Answer: (Continued)

tubes approach instability limits before the operator had taken compensating control action. However, local tube limits based on rupture considerations could be exceeded, especially because of the sudden increase in local flux. Protection against such excursions and sudden hot spots which could lead to rupture rashes may be provided by procedure - by cutting power level and local tube limits during poison column discharge, and by zone temperature monitoring with careful attention to light and alarm indications.

47. Why are rod withdrawal rates restricted during a cold startup?

Answer: The phase of operation most pertinent to reactor safety is the startup, where extremely fast rod withdrawal rates could cause an excessive rate of rise. Large changes in reactivity can take place during a minimum or extended outage, especially in case of gross loading errors, so there is always a chance for error in the calculations for critical. For this reason a conservative rate of rod withdrawal is the only safe method of approaching critical, and controlling the rate of rise is the only safe method of reaching the desired operating levels. Of course, as one's knowledge of level and period is improved through better instrumentation, a faster withdrawal rate may be as conservative as the slower rate was without good instrumentation.

48. Are rod withdrawal rates equally restrictive for "hot" startups?

Answer: No, during a hot startup more liberal withdrawal rates are allowed. In this case, the pile reactivity is rapidly falling away in a "failsafe" direction. It is falling so fast that allowances must be made for its rate if the scram recovery is to be accomplished. Here the pile conditions are safer; the falling transient values are better known and there is no reasonable chance of unknown loading or poison changes to take place. Therefore, a somewhat faster rate of approach to critical is permitted in the hot startup case.

49. Should a reactor operator depend on automatic safety controls?

Answer: No, the operator's main task is to keep the reactor under complete manual control at all times. He should consider the automatic safety trip backup in the same manner as an automobile driver considers emergency brakes, seat belts, and dashboard padding.

50. What are the four main functions of a reactor operator with regard to reactor control?

Answer: The flexibility and variety of responses required to adequately control the pile under varying conditions makes it difficult to describe the exact duties of the pile operator. In general, the main functions

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50. (Continued)

Answer: (Continued)

may be defined as: (1) to accept and analyze instrument data, (2) to correlate pertinent information, (3) to make prompt decisions, and (4) to exert the appropriate control action.

51. Explain the relationship between operator reaction time and automatic safety devices.

Answer: During emergency operating conditions the reaction time of the operator sets a definite limit upon the speed with which he can accept information, formulate a decision, and take corrective action. For example, if an instrument indicates that the neutron flux is rising at a dangerously fast rate (10-second period or less), an operator may not be able to act quickly enough to decrease the reactivity in time to avoid an accident. In circumstances of this kind, it is far better to automatically insert control rods than to rely entirely on human control. In order to ensure safe reactor operation, operating standards and procedures are set for operator guidance and enforcement which, if followed exactly, should always keep conditions within the reaction time of the operator; automatic devices are then provided as a second backup to cover the possibility of procedural breakdown or operational error.

52. Why is a production reactor always made somewhat larger than the exact critical size?

Answer: When a production reactor is started with a fresh loading of "green" metal the poisoning of the chain reaction by fission products formed, and other short term and long term reactivity contributions and losses, must be compensated for in order that the reactor can continue to operate at a constant rate as these changes take place. For this reason it is necessary that the reactor be made larger than critical size and use some neutron absorbing material which can be introduced into the reactor in controllable amounts. This excess reactivity allows leeway against the self-poisoning tendency of the chain reaction and against any temperature effects on the multiplication factor.

53. What is the approximate amount of excess reactivity built into a Hanford reactor?

Answer: The size of the reactor is so much larger in excess of that actually required for the chain reaction process that a considerable amount of absorbent material must be used to bring the reactor to the point of steady operation. The amount of excess may be of the order of 2-1/2% k (2500 c-mk), most of which can be compensated by the horizontal rod system.

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54. If the amount of excess reactivity built into the pile is greater than the capacity of the horizontal rod system, how then can it be controlled?

Answer: During reactor shutdown the vertical safety rod system is added to the horizontal rods to hold the pile subcritical. During reactor operation small changes in temperature, coolant flow, and reactivity variables cause positive or negative reactivity effects to take place from minute to minute. These small reactivity changes are compensated by moving a small amount of the horizontal rod system in or out of the reactor as these changes take place.

55. What is the principal difference between operating control and safety control?

Answer: Operating control would include the use of sufficient poison to control the reaction during startup, normal transients, and equilibrium operation. In case something unexpected should occur during operation which resulted in a sudden large increase in the multiplication factor, a loss in coolant supply, or some other threat to the reactor, it would be necessary to insert quickly a large additional amount of poison material into the pile. The fast insertion of large amounts of poison material is known as "safety control." The operating control system must be flexible enough to allow adjustment of neutron flux during all conditions of operation; the safety control system must provide a "fail safe" component which is automatically activated under emergency conditions.

56. How many control systems are used at Hanford? What is the function of each?

Answer: Control requirements at Hanford consist of a combination of three independent systems: (1) the horizontal control rods (HCR's), (2) the vertical safety rods (VSR's), and (3) the Ball 3X system. The HCR's, supplemented by PCCF columns, splines or other operating control devices, provide sufficient poisoning effect to control the reaction under normal transient and equilibrium operation. The VSR's have sufficient strength to hold the "wet" pile subcritical even after complete xenon decay and provide the rapid shutdown capability required. The Ball 3X system is designed to independently hold the dry, xenon-free pile subcritical.

57. What is most likely to limit the total output of a production reactor?

Answer: A production reactor's "weakest link" will probably be the heat generation rate of some particular component at only one part of the reactor. If most of the volume of the reactor can operate at heat generation rates approaching this limiting rate, the total output will be much greater than if temperatures fall off sharply in all directions from the limiting component. Because it is not always possible to have everything symmetrical within the reactor it is necessary to develop techniques for maintaining a balanced heat distribution in spite of non-symmetric loading and control rod patterns.

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58. What is the "flattening" concept?

Answer: In order to achieve a critical size pile, it is necessary to have a lattice design with a k infinity greater than one. This means that each small increment of volume inside the pile is producing neutrons faster than it absorbs them and these excess neutrons leak toward the sides of the pile where they escape. Since the lattice cells near the edges of the pile can send their excess neutrons in any direction, toward the center as well as toward the edges, the neutrons will tend to peak or pile up in the middle of the pile. In a supercritical pile, enough neutrons could not leak out the sides to prevent a continuous buildup of excess neutrons in the middle of the pile - an uncontrolled reaction. By placing the right amount of control rods or other poison material at just the right spacing in the middle, the central leakage to this poison will just balance the excess neutron production. The effect of this arrangement is the same as having a central region with a k infinity of one, and the side region with a k infinity sufficiently greater than one to make up the neutron leakage out the sides. By this method, the pile neutron distribution can be made "flat" to some degree.

59. What is meant by "temperature moment"?

Answer: There is a direct relationship between heat generation and neutron production rate. Although we measure temperature effects, we are actually getting an indication of local fission rates, or more basically, local neutron population. If the neutron population per unit volume is greater in one portion of the pile than in another portion symmetric to the first, it means that this second region has greater chain-reacting tendencies than the first. This difference in chain-reacting properties, or local reactivity effects, can be caused by the local presence or absence of a control rod tip, by local temperature or fission product poison effects, or by local differences in loading patterns. The trick to getting heat generation rates symmetrical over the pile is therefore that of balancing the reactivity properties of symmetrical regions about the pile. If control rods are only partially inserted on the near side of the pile, an equal amount of rod or some other poison material should be added to the far side of the pile to balance the reactivity effects. Or if the pile has been operated for a considerable length of time with a skewed distribution so that fission poisons have built up more strongly in the top half, an unbalance in the control rod pattern toward the bottom half of the pile must be made to achieve symmetrical regions of equivalent reactivity properties.

The unbalance of reactivity properties in symmetrical regions about the pile is proportional to the amount of reactivity and to the spacing of the unbalanced regions. The effect is quite similar to a teeter-totter; the unbalance is proportional both to the weight of the

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59. (Continued)

Answer: (Continued)

individual and to his distance from the center of the board. The product of the weight and "lever arm" in the teeter-totter case is known as a moment of force in mechanics; the concept is useful to us in thinking of measuring temperature unbalance as a "temperature moment." Thus, the farther a control rod is from the center of the reactor, the greater "temperature moment" or unbalance it will cause. And the greater the size of the increment of poison, the greater will be its "temperature moment."

60. Assuming an ideal neutron distribution throughout the reactor core, describe a "temperature moment" created by control rod movement.

Answer: If a certain amount of control rod is inserted at one point in the reactor and the total power level is held constant by the uniform withdrawal of all other rods, the neutron flux or local power will tend to decrease at the point of rod insertion and increase in all other regions of the cube. However, the poison effect of the inserted control rod is not strictly localized, but rather exerts an over-all effect which diminishes as the distance from point of insertion increases. Thus, the least poisoning effect would be experienced in the region farthest from the point of insertion, and the flux would have the greatest tendency to increase in that particular area. The region of maximum increase can be expected to occur diametrically across the center of the cube at a point which is approximately the same distance from the center of the pile as the point of rod insertion. An analogy which may be useful to obtain a mental picture of this situation is to consider the total flux or tube power distribution as an inflated membrane attached to the edges of the tube temperature map. As you insert control rod in one region; that is, press down on the membrane at one point, it tends to bulge upward in a region across the center point from the depressed region.

61. Which type of control is important - heat distribution or total power?

Answer: Both are equally important; we know that control rod movement is required during operation to control temperature and fission poison effects, and that this rod movement causes changes to occur in different regions of the reactor which may make these regions unbalanced in reactivity properties. If we control solely to maintain the over-all reactivity constant (constant power level) we may initiate distortions in the temperature distribution about the pile. Actually, we must control both for constant over-all pile power level and for balanced temperature distribution.

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62. How can an operator know what is happening to the reactivity properties of each little increment of pile volume at any given time?

Answer: This approach would be much too complicated. We can get a better idea and a better feel for what's going on simply by watching the instruments which tell us temperatures and neutron population at different points about the pile and how they vary with time. Going back to the teeter-totter idea, we need to be able to add weight to either side if it starts to get out of balance in order to get it back in balance again. We can keep the total weights (constant power level) by lightening one side slightly by the same amount which is added to the other. In case of temperature distribution problems, we need to be able to insert some control rod into the region which is getting too hot and simultaneously be able to withdraw some from the region which is getting too cold. The best approach to solving the temperature distribution situation is to divide the problem into two parts:

- (a) General degree of flattening - this is generally taken care of in advance by recommended rod configurations and loading changes.
- (b) "Moment" control - by thinking in terms of trends in the three dimensions of space (vertical, sideways, and lengthways) instead of point by point throughout the reactor.

In reactor terms, the trends in the three dimensions of space become near-to-far, top-to-bottom, front-to-rear. The operator can control the temperature better through directional trends than he can by following point to point indications. So long as he can keep the temperature "moments" in good balance and the hottest spot in the reactor within limits, he doesn't have to worry about so many detailed data points.

63. What is the "small piles" control concept?

Answer: The "small piles" concept is a method of visualizing the entire reactor as being made up of, say, eight blocks or cubes of equal size, each of which must be controlled to operate smoothly at optimum power level. Four of these small piles would then be to the rear of reactor center and four to the front, four above center and four below center, etc. This is merely a method which may help us to think in three dimensions when selecting control rods for even flux distribution over the entire reactor.

64. Can each of these eight small piles be controlled separately?

Answer: Not entirely; in order to establish control over each of these small piles, one or more rod tips must be placed in each region so that movement of the rods will affect the flux density and tube temperatures in that region. Although each small pile may be considered separately, one must remember also that a change of flux and the

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64. (Continued)

Answer: (Continued)

resulting transient is not confined to each small region, but will in turn induce similar changes in adjacent regions. This effect gradually diminishes as the distance from the first region increases.

65. What type of operating transients can be expected in each of these small piles?

Answer: The primary transients created by rod manipulations are metal heating or cooling, graphite heating or cooling, and xenon buildup or burnout.

66. What effect does metal heating and cooling have on flux and power?

Answer: Adding or subtracting an increment of poison by control rod adjustment results in absorbing more or less neutrons from the region of interest, and causes an increase or decrease in the local flux and power in that particular region. Because the metal coefficient has a negative effect on pile reactivity it will tend to counteract any change in the local power or reactivity caused by the rod movement. Therefore, any change in the small pile region is stopped almost instantaneously by the metal coefficient. The net result is that the local power level changes from just critical at one level to just critical at a different power level. However, this is just the metal effect; two other time-dependent temperature transients quickly begin to change this simple just-critical condition.

67. Once a flux or power change is made in a given region of the pile, does the flux remain constant until another rod adjustment is made?

Answer: No, because the flux change is merely the first event of a series of reactivity changes. For example, when flux is increased the positive graphite temperature coefficient acts in the same direction as the increased rate of xenon burnout, thus increasing or strengthening the gain in reactivity. This tendency must be counteracted by rod insertion in order to maintain the desired flux distribution. The reverse condition acts in the same manner; when the flux is decreased, the buildup of xenon and the graphite cooling result in a decreasing reactivity trend. This tendency must also be compensated by control rod withdrawal from the region to maintain constant power. Furthermore, the above reactions are those seen immediately after a flux change; several hours later the transient effect initiates a flux change in the opposite direction.

68. If a certain amount of control rod is inserted into one of the small pile regions to reduce the flux, will the withdrawal of an equal amount of rod during the resulting transient compensate fully for the reactivity change?

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68. (Continued)

Answer: Not fully, only in part. Because the combined reactivity effects of changes in graphite temperatures and xenon buildup are usually much larger than the reactivity gain from the metal temperature effects, much more rod must be withdrawn temporarily than was originally inserted to cause the reduction in flux. The reverse condition (withdrawal of rod) also will act in the same manner.

69. Do these reactivity transients take place every time a small control rod adjustment is made?

Answer: Yes, when a small amount of control rod (rod tip) is inserted into a "small pile" section to reduce the local flux, the following sequence of events occurs: When one rod is inserted and other rods are pulled to compensate, the power and flux level in the problem region drops, then the decrease in the negative metal coefficient effect temporarily stops the flux from falling farther. After the local flux change, local xenon buildup is greater than burnout-plus-decay, resulting in a loss of reactivity; the graphite also begins to cool to a lower temperature value and another reactivity loss results. If rod is not withdrawn from this region, the reactivity loss will continue and pick up speed. If rod is withdrawn from this area to maintain the local power level, the xenon transient will reach a "turnaround" in four to eight hours where xenon decay and burnout equal, and then exceed xenon buildup. From this point the xenon decreases to its new saturation value. While these transients occur in one "small pile" region of the reactor, opposite transients must be occurring in other regions where rods were pulled and flux increased. More rod movement is required to control the resultant turnaround of these non-symmetrical transients during the same four to eight hour interval.

70. What would occur if these "small pile" reactivity transients were not controlled?

Answer: A series of these local transients and changing power levels taking place in opposite sections of the reactor will cause certain sections of the pile to vary with time in both reactivity and heat generation properties. Changes in graphite temperatures start reactivity effects which cause the process tube outlet temperatures to oscillate; when the tube temperatures oscillate beyond limits and force a power cut, subsequent control rod movement adds to the cycling tendencies. These flux drifts from one section of the pile to another are known as "temperature cycling" and have periods ranging from 12 to 36 hours.

71. How important is the selection of the proper rod for control during equilibrium conditions?

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71. (Continued)

Answer: Very important - The effects of loss of control vary in seriousness depending on the strength of the transient (which varies with time) and the size and location of the region in which control is lost. For example, assume that the reactor is at equilibrium and that the near-top-rear "small pile" section is high in flux and tube power. If an error were made and the wrong control rod used, a front top near rod might be inserted into a relatively balanced flux region which would instantly create an additional problem area. Thus the selection of the wrong control rod can strengthen existing transients and create new ones; the continuing reactivity transients then cause further changes in local power and flux. Should these transients be permitted to proceed until all available control rods are withdrawn from regions which are still decreasing in reactivity, the process then "snowballs" unless other means are found to reverse the reactivity trend.

72. If control flexibility is lost in one region of the pile because of rod withdrawal, what other means of control are available?

Answer: Referring to the small pile concept, if the control is lost in one of these small pile sections, it is sometimes possible to increase the over-all pile reactivity by increasing graphite temperatures with CO₂ additions. By inserting control rods in the other seven small pile regions, the relative flux should increase in the problem area, thus reversing the reactivity trend.

In addition to gas composition changes, PCCF tubes and poison splines are used to reduce the magnitude of flux cycling in one or more regions of the reactor, thereby making available more control rod for more flexible control. A new supplementary control system; the Displacement Column, is expected to provide adequate front-to-rear control over flux cycling tendencies. This system consists of a fuel column with poison pieces replacing fuel elements at each end of the column. By means of a remotely controlled winch and cable arrangement the entire metal column may be moved upstream or downstream within the process tube, thereby inserting poison at one end of the tube and simultaneously withdrawing it at the other end. Correctly positioned about the reactor, ten or twelve displacement columns should provide direct control over front-to-rear cycling conditions.

73. What happens if undesirable reactivity trends cannot be reversed?

Answer: Any change in flux will "snowball" if permitted to proceed, and the longer it is left uncorrected the more rod is required to correct it. If allowed to continue the loss of control will become more general, as when it is lost on the entire near side of the reactor under a condition of falling reactivity. When all near side rods are withdrawn,

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73. (Continued)

Answer: (Continued)

the flux usually continues to decrease on the near side and increase on the far side. Under these conditions, withdrawal of rod from the far side will force a cut in power because of far side rising tube outlet temperatures.

74. If near side control were lost (all near side rods withdrawn), would a cut in power level solve the problem?

Answer: When an unbalanced flux distribution reaches this stage, rising process tube temperatures force a cut in power level in order to remain within specified temperature limits. The power cut does not relieve the temperature or distribution problems since a cut in power causes even faster xenon buildup and graphite cooling, requiring further rod withdrawal. Since the only remaining rods are long rods inserted to the far side, pulling these rods may only accentuate the flux distortion and lead to further cuts in power until the reactor is shut down.

75. Can the speed or direction of required control rod movement be altered in any way during reactor operation?

Answer: Yes, the speed or direction can be changed through the graphite temperature contribution by varying the gas atmosphere composition. Increasing the helium concentration of the gas allows the graphite to cool, the reactivity contribution decreases, and rods must be withdrawn to compensate. Increasing the CO₂ concentration slows or hampers the graphite cooling, the reactivity contribution increases, and rods must be inserted to maintain constant power. This procedure must remain within the graphite temperature limits as specified by Process Standards.

Supplementary control systems such as PCCF columns or splines may also be used to augment HCR control flexibility.

76. Name three pile conditions where gas composition control might prove useful.

Answer: Control by variable gas composition could be useful under the following conditions:

- (a) Many times during reactor operation it may be desirable to insert rod tips into a high flux region or withdraw rod tips from a low flux region without compensating by rod movement in other regions of the reactor. When controlling by this method, the flux distribution change can be accomplished in a smooth and gradual manner through the selection of the correct rod for minute-to-minute

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76. (Continued)

Answer: (Continued)
(a) (Continued)

control, thus avoiding the many small transients which occur when a number of rods are adjusted to correct the flux distribution.

- (b) When the reactor is experiencing long term reactivity gains due to plutonium buildup, this gain in reactivity must be compensated by rod insertion to maintain the desired level. In many cases, the amount of rod in the reactor increases to the point where further rod insertion may result in loss of a flexible configuration, and flux distribution and temperature control would become troublesome. This condition can be avoided by adding helium to the gas atmosphere at a controlled rate so that the reactivity held in the HCR's remains the same or is allowed to increase at a slower and more controllable rate for optimum flattening.
- (c) When a high helium concentration is maintained during equilibrium operation, a CO₂ purge when the reactor scrams is sometimes used to reduce the rate of graphite cooling while the reactor is down to provide extra reactivity for a recovery attempt.

77. Are the Hanford reactors equipped with instrumentation specifically designed to provide operational control information?

Answer: Unfortunately, most of the control instrumentation was originally designed before the techniques for flux distribution control were developed. Consequently they were designed primarily as a means of observing operating limits, or as a protective system, rather than to provide control information. Consequently, the readings from such instruments as the tube outlet temperature monitors, Beckman flux monitors, octant monitors, graphite temperature thermocouples, and power level recorders must be adapted to provide the information necessary for adequate control. Readings from all informative instrumentation must be combined mentally into a three-dimensional picture of flux distribution, and control rods manipulated in such a manner as to counteract any changes in order to maintain or improve the flux distribution.

78. Once established, does the relationship between the various instruments remain constant?

Answer: Yes, for a given operating period only. For maximum control benefit, all instrumentation should be checked for sensitivity and calibration for each new equilibrium operating period. Since the previous flux distribution may be distorted by discharge of poison, enrichment, or high exposure metal, instrument settings may not coincide with the

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78. (Continued)

Answer: (Continued)

new pile condition. After the reactor reaches an equilibrium condition following a discharge outage, every effort should be made to determine whether any instrument requires adjustment to improve and maintain an even flux distribution. In other words, good pile control does not depend on a single indication from any one instrument. Any reading which appears out of line should be carefully checked against all other available information before any control decisions are made.

79. What is the connection between startup power level and the magnitude of the following reactivity transient?

Answer: The three major startup transients, the negative metal reactivity effect, positive graphite reactivity contribution, and the xenon buildup and burnout changes are all dependent on the startup power level. At the higher operating levels, the large xenon burnout following a minimum outage limits the startup power level to a point where it becomes uneconomical to start up unless temporary poison, poison splines, or some form of additional poison is used to supplement the HCR system. When all the HCR's are inserted to override the startup transients, the region within the rod pattern is overpoisoned, and the regions outside the pattern become the areas of high flux and high tube temperatures. Since an operating limit is placed on the maximum tube power or outlet temperature, the amount of this flux and temperature distortion partially determines the startup power level.

80. How important is flux flattening just prior to or immediately after "turnaround"?

Answer: During the approach to turnaround individual rods are selected for insertion so as to maintain the best possible flux distribution in order to avoid local high flux regions and limiting tube temperatures. When a low flux level is allowed to persist in any particular region of the reactor, other sections of the pile are essentially operating at a higher power level. This equivalent power level may be high enough so that the local transients eventually exceed the local poison effect, and a loss of control is experienced in this section of the pile. If this occurs, further flux distortion may take place, again strengthening the existing transient, and the process may "snowball" until power cut, and possibly eventually a shutdown, is required to avoid exceeding the operating limits.

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81. Why is a knowledge of previous operating conditions important?

Answer: Some of the reactivity changes occurring in an operating pile have fairly long time constants. For example, the typical cycling problem is associated with the half-lives of xenon and iodine (9 and 6 hours, respectively) and with the graphite heating and cooling periods. Consequently, the transients build up and die down over a period of about one day. To damp out and control such a cycle it is necessary to know what the trends are at a given time and what the operating history has been so that one can anticipate and counter future flux changes. For these reasons, an accurate history of reactor operation for the preceding 24 hours should be available at all times during operation.

82. How should control rods be withdrawn after turnaround? Explain.

Answer: After turnaround the reactivity starts to decrease due to xenon building up faster than it is burned out and decays. As the reactivity decreases, power level is raised and this causes the reactivity to decrease at a slower rate because of the higher xenon burnout and increased contribution from the graphite heating.

As the pile reactivity decreases, the sequence with which the control rods are withdrawn will determine the flux distribution about the reactor. In other words, the sequence is set up so that the remaining inserted rods will balance the flux distribution in all sections of the pile. A pattern should be set up and followed such that there is always an available rod tip in each of the "small pile" control regions of the reactor. This flexible rod pattern should be obtained as soon as possible after turnaround so that the transients set up in various parts of the pile by the power raises will tend to further maintain an even flux distribution. Elimination of the need for large distribution corrections after turnaround tends to make a smoother, more efficient approach to an equilibrium operating level.

83. Does the amount of reactivity held in the rods impose any limitations on the approach to final operating level?

Answer: Yes, the approach to maximum operating level must be made cautiously because xenon poisoning will continue to increase as a result of the final raise in power level. This will require rod withdrawal to compensate for the xenon increase; if the power level is too high, extensive rod withdrawal may cause tube outlet or graphite temperatures to be exceeded. By slowing the power raises as limits are approached, the equilibrium power level is reached at approximately the same time as the equilibrium reactivity. Final adjustment of control rods, power level, flux and temperature distribution can then be made to approach a maximum power level without forced changes in rod configuration.

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84. If flux changes take place every time a control rod is moved, how can temperature cycling be prevented?

Answer: Since temperature distortion is usually the result of a series of local power changes in certain parts of the pile, the only way to prevent severe temperature cycling is to maintain a steady flux distribution over all sections of the reactor. Even flux and temperature distribution can be maintained only through the correct interpretation of representative monitoring data taken at frequent time intervals. Good control rod techniques are then necessary to correct any detrimental flux or temperature trends before they become too difficult to handle. Assuming a basic understanding of the "temperature moment" and "small pile control" concepts, the problem becomes that of selecting the proper control rod for given local trends.

85. Can multiple-point recorders, such as tube temperature deviation and graphite temperature, be relied upon completely?

Answer: No, temperature maps and individual tube outlet temperature read-out are considered as the final authority and what the absolute flux distribution is and what the tube temperatures are. Supplemental instruments such as the corn popper, zone temperature monitor, and tube temperature deviation recorders are designed to provide crude data on temperature stability or trends. Since most supplemental instrumentation can be adjusted or biased to fit a particular operating period, this type of equipment cannot be relied upon until adjustment is made for existing pile conditions. In other words, strict adherence to a single false or biased indication from any one instrument can lead to severe control difficulties.

Because of the relatively slow graphite heating and cooling periods, one or more couples on the graphite temperature recorder may increase or decrease over a period of time before emerging from the stripchart "field" as a potential threat to flux stability. This occurs on all multiple type recorders and results in a tendency to ignore small changes until the transient becomes more or less firmly established.

86. Can a true picture of temperature and flux distribution be obtained so that misleading or false indications can be recognized?

Answer: Yes, the first step is to obtain a picture of existing tube outlet temperatures in representative sections of the pile. A fast and simple procedure for tube temperature sampling such as the following can be set up to obtain comparative readings in a minimum of time. Nine tubes, carefully selected, can be monitored quickly for tube outlet temperature through the use of the skip-switch or hand jack. Tube location should be carefully chosen so that individual tubes are evenly spaced about the flattened zone and are not unduly influenced by venturi size (flow), adjacent enrichment, poison, etc. Four tubes, each located the same distance from the edges and/or the center of the reactor, will monitor the temperature of each of the four main sections of the pile.

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86. (Continued)

Answer: (Continued)

With an even flux distribution, each of the corner tubes should operate at approximately the same tube temperature. The temperature of each quadrant can then be compared with the temperature of all other quadrants. In addition to the four quadrant tubes, three tubes can be selected across the center of the pile to monitor this area. For overall top and bottom control, one tube is placed at top center above the rod pattern, and another at center bottom below the rod pattern. Repeated readings of these tubes recorded on a work sheet over a period of hours will show definite trends resulting from previous operation as well as existing conditions. In this way a clear picture of the rate and extent of the flux and temperature trends will provide accurate data for comparison with instrument performance. After an even temperature balance is obtained by the temperature sampling method, outlet tube temperature points can be accurately adjusted on the deviation recorder to maintain or improve the flux distribution.

87. Does the outlet tube temperature map present a clear picture of flux and temperature distribution?

Answer: The temperature map (or any tube temperature monitor) will quickly identify the regions of high and low temperatures in the four main sections of the pile, but (1) it cannot supply information on front-to-rear flux distribution or temperature, and (2) a single map does not show changes, and it is difficult to define specific trends from the mass of data on a number of maps. Thus, the tube outlet temperature map represents only the first step in determining the flux distribution; further information is necessary before any control action can be made.

88. What information is necessary in order to take any control action?

Answer: Before an intelligent decision can be made, consideration must be given to the "small pile" control concept. Recalling the mental image of the entire reactor as being composed of eight small piles of equal size, and knowing that control rod movement will initiate reactivity and temperature changes according to the previous operating history of that particular region, further information is required to justify the use of any particular control rod. In other words, each of the eight small piles is primarily controlled by one rod tip only; the selection of the wrong rod will create a transient in its own locale, and have little or no effect on the region of interest. For an even flux distribution each of the eight small piles should contribute equal amounts of flux density or power; therefore, a comparison of temperature indicating flux density, must be made to determine the control action to be taken in each of the eight sections. A comparative picture of the flux distribution in each of these eight small piles, especially in the front-to-rear direction, can be obtained from a graphite temperature survey.

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89. What type of instrumentation will give front-to-rear flux information?

Answer: At the present time, graphite thermocouples are the only reliable source of front-to-rear flux density information in the older reactors which can be used to determine whether a front or rear control rod should be used. Thermocouple locations should be selected to coincide with the outlet tube temperature sampling pattern and arranged on a work sheet for quick analysis of front-to-rear temperature distribution. For example, the tube outlet temperature may indicate that rod withdrawal might be made in the top-near section of the pile. This area includes two of the small piles, front and rear. From which small pile should the rod be withdrawn? Careful analysis of the graphite temperature pattern reveals that the top-near-front temperature is considerably less than other comparable front thermocouples about the reactor, whereas the temperature of the top-near-rear is among the highest in the entire reactor. Obviously, any rod removal from this region should be from the front small pile. Removal of rod from the rear small pile would increase temperatures in a high flux area, eventually resulting in a so-called "temperature cycle."

90. Why should tube outlet and graphite temperature be taken on work sheets when graphite temperatures are chart recorded and tube temperatures are given on a multiple-point recorder?

Answer: First of all, tube outlet and graphite temperature sampling patterns used over a period of hours will show definite temperature trends as well as existing conditions. Continual analysis of this type of information will quickly develop a three-dimensional picture of the entire control problem. Pile conditions can change from outage to outage thereby changing the value of certain instrument readings. Instruments can be biased or adjusted to fit the preceding operating period and should not be relied upon until double-checked against existing pile conditions. Because most instrumentation provides only crude information, there is a tendency to ignore small changes until the transient becomes firmly established. These small changes can be easily followed on temperature sampling patterns; the results of rod adjustment can be monitored to one-tenth of one degree of tube temperature and to one degree of the slower-changing graphite temperature. Repeated sampling in the same pattern of these two all-important control factors, taken at regular time intervals, soon presents a mental image of all reactivity changes occurring in the pile and provides a complete history of past performance and flux distribution.

91. Some reactors are equipped with octant monitoring systems. When is this system useful?

Answer: The usefulness of the octant system or any other monitoring device can only be measured by the experience and resourcefulness of the people using the data. The octant system measures and records the neutron flux at each of the eight corners of the reactor; although it was

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91. (Continued)

Answer: (Continued)

installed primarily as a safety device, comparison of the individual readings can be used for high level distribution control in many ways. For a given power level, any change of neutron flux in one of the eight regions (small piles) must be balanced by a corresponding change in some other region (mechanical moment analogy). When used in conjunction with tube and graphite temperature data, each octant meter reading can be used as additional confirmation of a suspected flux situation and/or to provide a clue as to whether the desired results are being obtained from previous rod adjustments made to improve the flux or temperature distribution. The octant chambers are useful during a cold startup to pinpoint the correct "small pile" region for rod insertion at a time when all other pile data is at a minimum. At operating levels each octant provides a clue as to when to take corrective action and what method to use, and will then record the success or failure of the action taken. Octant data can be verified with tube outlet and graphite information, thereby providing a means of double-checking the temperature trends as they develop in various regions of the reactor.

92. Can Beckman readings be used for control purposes?

Answer: Although primarily designed for flux level monitoring, the chambers can be used to detect slight flux changes in the lower portions of the pile. In addition to top-to-bottom control, a knowledge of individual chamber location provides another means of detecting flux and temperature trends in the lower sections of the pile. This information, coupled with octant monitoring, tube outlet, and graphite data provides an additional method of double-checking the flux and temperature trends in the entire reactor.

On the other hand, Beckman readings can be very misleading if not used in conjunction with other indications. For example, a falling Beckman reading might be interpreted as "safe," whereas an undetected distortion to the top might be its real significance.

93. Can perfect equilibrium conditions be maintained in the Hanford reactor?

Answer: The control of a Hanford reactor is a never-ending task in the sense that perfect flux and temperature balance will ever be attained. One of the easiest mistakes to make in reactor control is to assume that once good temperature balance is established it will remain constant. In each of the "small pile" sections of the reactor there is a tendency for the neutron flux density to vary with time according to its previous operating history. This causes the flux to rock or cycle from region to region, and unless constant corrections are made

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93. (Continued)

Answer: (Continued)

these temperature cycles soon become large and difficult to control. Perhaps the most prevalent error made is to hesitate in applying control to a flux situation because of indecision. During this period of indecision the reactor is essentially being allowed to drift out of distribution control, the flux change is allowed to "snowball" and the longer it is left uncorrected the more difficult it is to correct.

94. If the neutron flux is constantly moving from region to region in the pile and each movement varies with time, how can the correct control rod be selected at the right time for any given pile condition?

Answer: The possibility of selecting the wrong control for any pile condition can be considerably reduced through the proposed temperature sampling work sheets (see answer to questions 86 thru 90). The work sheets are not intended as a substitute for any monitoring or operating procedure, but rather as a method of developing a better understanding of the two basic principles of reactor control-maximum tube outlet temperature and flux (temperature) distribution. The method can be briefly summarized in four basic steps:

- (a) Set up tube outlet temperature work sheets as illustrated in Figure 24 of Chapter V, IPD Physics Primer.
- (b) Set up graphite temperature work sheets as illustrated in Figure 25.
- (c) Record sampling data at twenty-minute time intervals to establish temperature trends.
- (d) Cross-check validity of all tube and graphite temperature data with octant monitor and Beckman readings.

The work sheet sampling data should be used in conjunction with all other monitoring instrumentation. It is imperative that information from all sources be observed and correlated before, during, and after all control rod movement. When used in this manner, every rod selection is based on control data from a variety of sources, results and performance can be evaluated, and a "feel" for reactor control can be developed.

95. Which is more important, accurate instrumentation or good control techniques?

Answer: Both are equally important; the information gained from the instruments must be converted into good control techniques in order to operate the reactor in a safe and efficient manner. Both of these responsibilities rest squarely in the hands of the people operating

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95. (Continued)

Answer: (Continued)

the reactor. An enormous amount of excellent data, taken at the most advantageous time by the most accurate of instruments, are generally useless unless appropriate control action is taken. Data must be taken, understood, and interpreted in the form of action. Understanding of these data can at times be difficult and deciding on the correct action at the proper time even more so. Plans must be made to detect and follow small temperature shifts and flux tendencies, and the proper action initiated to correct them as soon as possible.

96. What type of knowledge is required to operate a reactor safely and efficiently?

Answer: Operating "know-how" involves a thorough understanding of the nuclear process and monitoring instrumentation; knowing at all times what is going on, and then exercising judgement and discretion. In order to plan intelligently, an operator must keep in mind at all times the changes which have occurred, the changes taking place, the expected results of these changes, and the correct action to take to maintain or improve the flux distribution. To operate safely, he must have adequate control data on which to base his judgement and he must know the operating limits at all times. To operate efficiently, he must approach these limits in a wise and safe manner, guiding the reactor through the various operating conditions to an optimum level of safety and efficiency.

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NOTES ON REACTIVITY

The subject of this talk is "Reactivity." You all hear your physicists talking about reactivity, and you have to work with it each day - you talk about "c-mk's," and "in-hours," and all sorts of strange things. To understand what is meant by reactivity, and why you see some of these things that you see, we need to introduce two basic concepts: multiplication and reactivity.

Multiplication

Multiplication deals with the neutrons in the reactor, and how fast they grow. Neutrons, however, are kind of hard to see, so I think I should talk about money, instead. Let's say that you got \$100,000 from somewhere. Now, if you wanted to, you could lend this money to someone - perhaps at 5% interest, compounded semi-annually. This means that every six months you would get 2.5% interest. At the end of the first six months you would have \$102,500 (\$100,000 plus the \$2,500 for the interest). At the end of the second six months (in other words at the end of a year) you would have \$105,062.50. Note that every six months you get 102.5% of what you had at the beginning of that six months. In this case, your multiplication would be 1.025, for to find what you would have in six months, you just multiply what you have now by 1.025.

On the other hand you might be borrowing this money yourself, and paying 5% interest, compounded semi-annually. Only, the fellow you borrowed the money from really only wants you to pay the money back at that rate, with no interest. This means that at the end of six months you would have to pay him 2.5% of what you had, or \$2,500, and then you would have \$97,500. At the end of a year you would pay 2.5% of that, or \$2,4937.50, and you would have \$95,062.50. In this case your multiplication is 0.975, and six months from now, you will only have 97.5% of what you have now.

Then, one question you might ask is "How much money will I have 20 years from now?" We can figure it out like this for the case where the multiplication was 1.025:

Start	\$100,000
End of six months	\$100,000 x 1.025
End of year	\$100,000 x 1.025 x 1.025, or \$100,000 x (1.025) ²
End of 18 months	\$100,000 x (1.025) ² x 1.025 or \$100,000 x (1.025) ³

Notice that the number of times we use 1.025 is just twice the number of years - and this figures because we collect interest twice per year. So it should be evident that at the end of twenty years, we will have \$100,000 x (1.025)⁴⁰. Now to write a mathematical formula: the 1.025 was the multiplication, and we will call that "k"; the time was 20 years, and we will call that "t"; we compounded the interest every half of a year, and we will call that the "lifetime," or "l". We will call the number of dollars you start with N₀, and we have

$$N = N_0 k^{t/l} \quad (\text{in our case, } N = \$100,000 \times 1.025^{t/0.5})$$

At this rate, in about 20 years you would have \$271,828.18, or you would have increased your money by a factor of "e".

Now let's suppose that you lend your money to a real cheapskate, who is only willing to pay 0.00278% interest, so that your multiplication will be only 1.0000278. However, being naturally sharp fellows, you realize the way to really soak this guy is to make the "lifetime" very short, so that he must pay interest quite often. In fact, you make this only 0.1 second. With this very handy arrangement, you will increase your

money by a factor of "e" in just an hour. This is, needless to say, a good arrangement.

What if k , the multiplication were 1.0000000000? No matter how many times you multiply something by 1.0, you always get the same thing, so you would always have the same amount of money.

So what has all this got to do with a reactor? Well, the power level is directly proportional to the number of neutrons, and neutrons multiply, so if the multiplication is greater than 1.00, we are raising power, just as we were making more money - so the reactor is supercritical. On the other hand, if the multiplication is less than 1.00, as was the case when we were losing money, the reactor would be subcritical, and the power level would go down. When the multiplication is exactly 1.00, the power level does not change, so the reactor is exactly critical.

Also, you may recall that the length of time it takes for the power level to increase by a factor of "e" is called the period. So when we had a k of 1.025, and a lifetime of half a year, we had a 20 year period. But when k was 1.0000278, and the lifetime was only 0.1 second, the period was 1 hour.

In order for the reactor to operate, k must be at least 1.0. If it is 1.025 there is an "excess" of 0.025, or 2.5%. This means that 2.5% of the neutrons are free to do something other than maintain the chain reaction. They can be used as the interest was used, to increase the power level. Or they can be absorbed in a control rod. If they are absorbed in a control rod they do not multiply, and so can't be counted in the multiplication - and the multiplication will again be 1.0, and the reactor will be critical. In the case where we were dealing with the cheapskate, we had a k of 1.0000278, or an excess k of 0.0000278. One c-mk is a thousandth of a percent, and since 0.0000278 excess k is the same as 0.00278%, this must be 2.78 c-mk. You probably recall that the inhour is defined as that amount of excess reactivity which will produce a stable rising period of one hour. When the multiplication was 1.0000278, we had a period of one hour, and we had 2.78 c-mk of excess reactivity. So 2.78 c-mk must be the same as one inhour.

Now let's go back to the 2.5% case. If the lifetime there were 0.1 second instead of 6 months, the period would be 4 seconds. However, you probably recall that we have what we call "delayed neutrons" that come off shortly after fission. Some of these come off about 20 seconds after fission. If the period were 4 seconds, the multiplication for that lifetime would be over before these neutrons got a chance to help, so the average lifetime would be shorter than 0.1 second since these neutrons could not be counted. As a result of this delayed neutron effect, the period would probably be a lot closer to 0.4 seconds instead of 4 seconds. This is because the average lifetime of the "prompt" neutrons is only 0.001 second. About $\frac{3}{4}$ of 1% of all the neutrons are delayed. This is 0.75% or 750 c-mk. If the multiplication were 1.0075, that is, we had 750 c-mk of excess reactivity, we could take away all the delayed neutrons and still be critical. Now the reactor would be critical on prompt neutrons alone - it would be "prompt critical."

Buckling

Now that you are experts on multiplication, let's talk about buckling. And since buckling is even harder to see than neutrons, I think we should talk about production and leakage of neutrons.

Let's start with a reactor that is in the shape of a cube that is A feet on each side. The volume of the cube is A^3 cubic feet, and the surface area is $6A^2$ square feet,

since it has six faces of area A^2 square feet each. The number of neutrons produced is proportional to the volume:

$$\text{production} = K_1 A^3; \quad K_1 \text{ is a proportionality constant.}$$

The number that leak out the sides is proportional to the surface area:

$$\text{leakage} = K_2 6A^2; \quad K_2 \text{ is another proportionality constant.}$$

So the fraction of neutrons that leak out is the leakage divided by the production:

$$\text{fraction leaking} = 6K_2 A^2 / K_1 A^3 = K/A; \text{ and } K \text{ is just } 6K_2/K_1, \text{ or just another constant.}$$

The first thing that you will notice is that as the reactor gets bigger and bigger (A gets larger and larger), the fraction that leak out gets smaller and smaller. Let's look at some numbers: If K is 5 feet, then:

<u>A</u>	<u>Leakage</u>
1	500%
2	250
3	167
4	125
5	100
6	83
7	71
10	50
15	33
20	25
30	17
50	10

You will notice from this that when A is only 1 foot, the leakage is greater than the production - so the reactor will not work. When we get to A - 5 feet, the leakage is exactly equal to the production. At this point, let me explain that the absorption of neutrons by U-235 is also proportional to the volume, so that when I say production, I really mean production after all the losses to Uranium. So when the leakage is 100%, the reactor is just critical, because the leakage is just equal to the excess production. However, we just might want to make Plutonium in this reactor by absorbing the neutrons in U-238. In our reactors, this takes up so many neutrons that we would have to cut down the leakage until it were closer to 33%. Note that to do this we must increase the side by a factor of 3, or the volume by a factor of 27. Also, it would probably be nice to have a few control rods and such, so that we can probably only stand about 10 to 15% leakage. Suppose that we had a reactor, but it did not have enough reactivity. We could increase the reactivity by cutting down on the leakage; and this can be done by making the reactor bigger. This effect is described by what we call the geometric buckling. It depends only on the size of the reactor, and as the geometric buckling increases, the leakage increases.

However, there is another way to increase the reactivity - as you all know, this is to charge enrichment. In this case, we increase the production, so that we can stand greater leakage. This has nothing to do with the size of the reactor, but it depends entirely on the material in the reactor (really the entire lattice, including graphite, coolant, etc. is the determining factor), and so the effect is described by what we call the lattice material buckling. Increasing the material buckling is just like

charging enrichment - it causes the production to increase, and therefore increases the reactivity.

If the geometric buckling and the material buckling are the same, then the excess neutrons from the nuclear processes (absorption, fission, etc.) are exactly the number that will leak out, and the reactor will be critical. In fact, in a real reactor, the material buckling will be reduced by the amount necessary to support the leakage, and what is left over will be the excess reactivity. In other words:

$$B_m \text{ (material buckling)} - B_g \text{ (geometric buckling)} = \text{excess reactivity} \\ = k - 1$$

So here we are back to multiplication again. And you can see that for the reactor to be critical, k must be 1.00, $k - 1$ will be 0, and the material buckling must equal the geometric buckling.

The Four-Factor Formula

Now that we are all experts on both multiplication and buckling, we can go on to talk about reactivity. Somewhere you have probably seen diagrams about what happens to a neutron as it winds its way through the reactor. Let's look at one of these and see what happens:

N thermal neutrons are absorbed in Uranium

of these, about 35% are absorbed by U-238, which then decays to Plutonium. The other 65% are absorbed in U-235, but only about 85% of these, or 55% of the total cause fission. The other 10% just make U-236.

You know that for every fission there are about 2.5 neutrons given off. Since 55% of the neutrons absorbed in Uranium cause fission, after fission we will have 55% x 2.5 or 139% neutrons. This number, 139% or 1.39 is called η , pronounced eta. It is a Greek letter (which may explain why nuclear physics is "Greek" to so many people) - By the time nuclear physics came along, all the other sciences had pretty well used up the English alphabet. Anyway, now we have

ηN fission neutrons from thermal fission.

Although U-238 is not fissionable to slow neutrons, it will fission with a fast neutron, such as we get from fission. This is much like hitting the nucleus harder - so hard, in fact, that it splits. This is a fairly small effect, adding only about 3% to our neutrons, so now we have 103% of 139, or about 143% of what we started with. This number, 1.03 or 103% is called the fast fission factor, and is denoted by the Greek letter epsilon, ϵ . So now we have

$\epsilon \eta N$ fission neutrons from all fission.

As the neutrons slow down in the graphite, some are absorbed by the U-238. As a matter of fact, about 12% of the neutrons vanish this way. This is called resonance absorption, because the cross section of U-238 has a bunch of peaks in this energy range (between fast and slow, or thermal) which are called resonances. In case

you didn't know, a cross-section is merely the odds that a particular thing is going to happen - in this case absorption of a neutron by the U-238. At any rate, the neutrons which manage to escape this resonance capture are free to become thermal neutrons. The fraction of neutrons that escape resonance absorption is given by p , the resonance escape probability, and we now have

$\eta \epsilon p N$ thermal neutrons.

Some of the thermal neutrons are going to be absorbed in Xenon, others in water, and still others in control rods. What we are really interested in is the fraction of these thermal neutrons that are absorbed in Uranium, for they will be utilized by the reactor to maintain the chain reaction. This fraction is called the thermal utilization, f , and we have

$\eta \epsilon p f N$ thermal neutrons absorbed in Uranium. We started with N thermal neutrons absorbed in Uranium, so we are back to where we started, and we have gone through one lifetime. You recall from the section on multiplication that the number of neutrons at the end of one lifetime was the number at the start multiplied by the multiplication. So since we know what we have at the start and the end, we can divide and find the multiplication. It is:

$$k = \frac{N \eta \epsilon p f}{N} = \eta \epsilon p f$$

This, for obvious reasons, is called the four factor formula.

Since we have yet to say anything about leakage, we must be talking about a reactor that has no leakage. Going back to the buckling concept, we recall that

$$B_m - B_g = k - 1$$

If there is no leakage, B_g must be zero, and to make B_g zero, the reactor must be infinitely large. So this multiplication refers to an infinite reactor, and for this reason, we call it "k-infinity," k_{∞} . Since B_g is zero,

$$B_m = k_{\infty} - 1$$

However, it's pretty hard to come by an infinite reactor - finite reactors, where we do have to worry about leakage, are about the only kind we have. Therefore we will have to throw a leakage term into our four factor formula. If L is the fraction of neutrons that do not leak out, then we can write the following:

$$k_{\infty} = \eta \epsilon p f$$

$$B_m = k_{\infty} - 1$$

$$k_{eff} = \eta \epsilon p f L$$

$$B_m - B_g = k_{eff} - 1$$

Since η is 1.39 (for a natural Uranium reactor), and ϵ is 1.03 (for a natural Uranium reactor), and p is somewhere near 0.88, and f is close to 0.85, k_{∞} is about 1.07. So we must not lose more than 7% of the neutrons by leakage. In fact, we had better lose less than 7%, for we will probably want some extra reactivity for those control rods.

Conversion Ratio

Notice that we caused fission with 55% of the neutrons and at the same time we lost 35% to the U-238. A little later on, we absorbed about 12% of 143% of the neutrons in the U-238 resonances - this corresponds to about 17%. Since almost all of the U-238 that absorbs neutrons becomes plutonium, we must make 52% plutonium. In other words, we could set up a balance like this, starting with 100 thermal neutrons:

55 neutrons cause fission, so
55 atoms of U-235 split, releasing energy and neutrons.

35 thermal neutrons, and 17 resonance neutrons are absorbed in U-238, so
52 atoms of plutonium-239 are made.

This means that we make only 52/55 or about 95% as much plutonium as we fission Uranium. Since the fissioning of one gram of U-235 will release about 1 MWD of heat, every MWD is about one gram of plutonium. ✓

However, don't forget that we actually destroy 65 atoms of U-235, because there was that other 10% that did not cause fission, but went to make U-236. So in reality we only replace 52/65, or about 80% of the U-235 atoms with plutonium. This number, the number of Pu atoms formed per U-235 atom destroyed, is called the conversion ratio. Here at Hanford the term conversion ratio often means the grams of Pu per MWD.

Individual Reactivity Effects

Things that Affect the Resonance Escape Probability

Metal Heating

The physics behind this is pretty hairy, so we won't bother to discuss it much, except to say that as the temperature of the Uranium increases, more neutrons are absorbed in the U-238 resonances. This means that there are fewer neutrons for other purposes, such as fission, and so this is a reactivity loss. Since the metal heats up instantaneously, this reactivity effect appears immediately after a power level change.

Xenon

Xenon is one of the fission products that is formed when the U-235 atom splits. Since there are lots of ways the atom can split (think of how many different ways you can split a ball with an axe), Xenon is not formed in every fission, only in about 6.5% of them. As you probably know, Xenon comes from Iodine, which is the real fission product, and which decays to Xenon, which then decays to Cesium. If we vary the power level, the equilibrium values of Iodine and Xenon look like this:

At the power levels where we operate, the Xenon is out in the flat part of the curve, so that if we raise power, there will be only a small change in the amount of Xenon poisoning. On the other hand, the Iodine is directly proportional to the power level, so that if we double the power level, we will double the amount of "potential" Xenon, existing as Iodine. Since the Xenon absorbs neutrons, it decreases the thermal utilization. Consequently, fewer neutrons are available for absorption in Uranium, and we have a reactivity loss.

Samarium

Samarium is another fission product that is a strong poison. It is very much like Xenon, except that it does not decay, and what you have at shutdown does not decrease as the outage goes on. Samarium comes from Promethium, just as Xenon comes from Iodine. During an

Samarium
(Cont'd)

outage, the Promethium decays to Samarium, and since the Samarium does not decay, there is an increase in the amount of Samarium poisoning during the outage. Samarium, like Xenon reduces the thermal utilization, and therefore causes a reactivity loss.

"Graphite" Effect (Part 1)

The physics behind the graphite heating effect is very complex and involved. It deals mainly with two things: water and plutonium. For now, we will worry only about the water. The first thing to realize is that just heating graphite will not necessarily cause a reactivity increase. Many other things have to be true first. However, we can talk about what happens without worrying too much about all these other things.

The neutrons that we play with in the reactor are primarily "thermal" neutrons. This does not mean that they have a specific energy or speed, but that they are in equilibrium with their surroundings. You know that the atoms in the graphite crystal are moving back and forth - they are not perfectly still. If the temperature of the crystal is increased, the atoms will move faster. Now when the neutron is a fast neutron, it is moving a lot faster than the carbon atom, so every time it hits a carbon atom, it slows down (think of pool balls hitting each other - the cue ball slows down every time it hits another ball). But if the neutron gets slowed down so far that it is going slower than the carbon atom, it will speed up on the next collision. So the thermal neutrons will, on the average, be going at the same speed as the carbon atoms. Then, if we increase the temperature of the graphite, the carbon atoms will be moving faster, and so will the neutrons. Now the chances of absorbing a neutron in water decreases as the speed of the neutron increases, and so as the temperature of the graphite goes up, fewer neutrons are absorbed in the water. This means more neutrons are available for absorption in Uranium, and the thermal utilization will increase, causing an increase in reactivity. One very important thing to remember - this is a positive reactivity effect only under certain circumstances.

Control Systems

All reactors have control systems of some sort. At Hanford we use rods, splines, and PCCF quite frequently. Each of these systems introduces a "poison" into the reactor. A poison is merely a material which absorbs neutrons, but does not emit neutrons. As a matter of fact, U-238 is a poison, because it absorbs neutrons, but does not fission (at least with slow neutrons). Obviously, it cannot be used for rod material because it makes plutonium which does fission, and this would make a pretty poor poison. Materials such as Boron and Cadmium are good poisons, and are used in our control rods (and splines and poison pieces). Since the poisons absorb thermal neutrons, they reduce the number of neutrons available for fission, and thereby cause a decrease in the thermal utilization, and in reactivity.

Things That Affect ETA (Fission Neutrons from Thermal Fission per Neutron Absorbed in Uranium)

Cold Long-Term Gains

By expanding our definition of eta to include neutrons absorbed in plutonium, we can consider what happens when we get plutonium in our reactor. Plutonium absorbs neutrons more readily than Uranium, and so a given amount of plutonium is worth more (in terms of reactivity) than an equal amount of U-235. For a while, the extra reactivity gained from having plutonium instead of U-235 more than offsets the loss in reactivity because of the

Cold Long-Term Gains (Cont'd.)

decrease in the total amount of fissionable material (remember that we replace only about 80% of the U-235 atoms with Pu). This is called Cold Long-Term Gains, because it includes no temperature effects. Do not confuse this with what your physicist normally calls "long-term gains." Cold long-term gains is only a part of it. Obviously, since the cold long-term gains are dependent on the amount of plutonium and U-235 in the pile, they are dependent upon exposure. So as the pile exposure increases, there will be a reactivity increase from the increase in η due to these long-term gains. If the reactor is operated to a high enough exposure, so much U-235 will have been burnt out (along with some of the plutonium we worked so hard to make) without being replaced by more plutonium, that the extra reactivity from the plutonium will no longer be sufficient to compensate for the burnout, and the cold long-term gains will turn into long-term losses.

Graphite Effect (Part 2)

Now is the time to worry about what effect the plutonium has on the graphite heating effect. Recall that as we heat the graphite we increase the neutron energy. As the neutron energy increases, the cross sections, in general, decrease. If all of them decrease at the same rate, there will still be the same number of neutrons absorbed in U-235 per neutron absorbed in Uranium (you may recall that this was about 65% of the neutrons). Although it is true that the number of neutrons absorbed in uranium will decrease, it is unimportant (it shows up in the thermal utilization, f), and we are only concerned about the relative absorption in U-235, U-238, and, in this case, plutonium. Plutonium is different from the other materials, in that its cross section has a bump in it. In the figure, the curve marked "A" is the way the cross sections of U-238 and U-235 decrease with increasing neutron speed (or energy), while the same curve for plutonium is marked "B". Notice that a neutron with speed indicated at "x" would think that the plutonium had a much larger cross section than one at "y", even though the cross section is actually smaller. The way this influences the graphite coefficient is this: as we get some plutonium in our fuel, we reduce the number of thermal neutrons that get absorbed in the U-238 and increase the number that cause fission. This was the cold long-term gains effect. Now if we increase the graphite temperature, and thereby increase the neutron speed, we will accentuate this effect, because we will have increased the relative cross section of the plutonium - in other words we have made it a more powerful reactivity addition. Since this depends on both the graphite temperature and exposure (amount of plutonium) of the metal, we can offset a gain in reactivity from increased exposure by cooling off the graphite.

Neptunium

Neptunium is a rather strange thing to throw into a reactivity lecture, because it is not "worth" any reactivity. If we took a reactor and added a batch of neptunium, there would be no reactivity change. However, Neptunium acts like a poison, because it "holds up" the formation of plutonium. For the first few days of operation, U-235 is being burnt out,

but no plutonium is being made yet because it must first decay from Neptunium, which has a 2.3 day half life. So the whole time we operate, we are "behind" on plutonium production. Of course, when the reactor is shut down, the Neptunium decays to plutonium, and we finally catch up. Since the Neptunium prevents us from having as much plutonium as we should have, it represents a decrease in η , and therefore acts somewhat like a poison, in that it decreases reactivity. It is a rather interesting fact that the increase in reactivity due to the decay of Neptunium to Plutonium during an outage is almost exactly compensated by the poisoning effect of Promethium decaying to Samarium.

Enrichment

Since enrichment has more U-235 than natural uranium, it increases η and causes a reactivity increase. You remember that for natural uranium, about 35% of the neutrons were absorbed by U-238, 10% went to make U-236 from non-fission capture by U-235, and 55% caused fission. And at 2.5 neutrons per fission, we calculated η to be 0.55×2.5 , or 1.39. In enrichment, only about 29% of the neutrons are absorbed in U-238, while about 11% go to make U-236, and 60% cause fission. Then η for enrichment must be 0.60×2.5 , or 1.50.

The Reactivity Balance

Every time the area physicist makes a prediction, he makes a reactivity balance. In order to be just critical, all the reactivity effects must add up to zero. Since the effects are really just parts of k_{excess} , or $k_{\text{effective}} - 1$, if they all add up to zero, $k_{\text{effective}} - 1$ must be zero, so that we will have a $k_{\text{effective}}$ of 1.0, which is, of course, critical. In an operating reactor, the balance might look like this:

Since the change in Samarium during an outage is almost exactly offset by the change in Neptunium, and since both of these effects together are about the same as the cold long-term gains, and more or less compensate for that, we will neglect them for a moment, and just say that they are part of the "inherent" reactivity. When this is done we call the result R_{infinity} , and it is the reactivity of the reactor after an infinite outage (in other words, no Xenon and no temperature effects). Then, since all the positive terms must equal all the negative terms, we can add like this:

$$\text{Rods} + \text{Splines} + \text{Xenon} + \text{Metal} - \text{Graphite} = R_{\text{infinity}}$$

Now to make a prediction: Since the reactor is shut down, there are no temperature effects, so the reactivity balance looks like this:

At Minimum Time, we are critical with no rod in the pile, and so the Xenon must be exactly equal to R-infinity. Then as the Xenon decays away, the difference between R-infinity and Xenon must be made up by rod (or splines). Eventually, when there is no more Xenon, all of R-infinity must be made up by control, and since R-infinity is larger than the total worth of the rod system, some poison or splines must be used to prevent having a period before completing the VSR pulls.

Of course, during the outage, some of the Xenon will be discharged with the Uranium. You might think that if 20% of the tubes were discharged, 20% of the Xenon would be discharged. A little more thought would show that this is not true, for if this 20% came from the center, there would be more Xenon discharged than if it came from the fringe. Also, you may have heard that the reactivity effect is proportional to the square of the flux. This means that if a certain amount of poison is next to a tube with a certain tube power, a similar amount of poison next to a tube with twice the tube power would have four times the effect. So this is another correction that must be made to the Xenon calculation. Already you can see that making a prediction involves a lot of this type of correction.

And don't forget, that the exposure of the reactor will decrease, so the graphite effect will decrease, and the physicist may want to increase R-infinity by changing enrichment. To do this he must predict what the next equilibrium will look like, so the problems start becoming complex in a hurry.

The physicist cannot calculate critical exactly (that's one reason why he "predicts" critical instead of "calculating" it). To show how bad this could get, let's say that the physicist makes a 1% error on everything he calculates, except the rods, and that he is unfortunate enough to have the errors add up in exactly the wrong way. Now some things the "physiker" can calculate to better than 1%, but other things present a little more of a problem. Anyway, let's look at a prediction:

	<u>Actual Number</u>	<u>Error</u>	<u>Calculated Number</u>	
	700 (c-mk)	0	700	Rods
	300	3	303	Splines
Add:	2700	27	2727	Xenon
	575	6	581	Metal
	425	4	429	Neptunium
	<u>575</u>	<u>6</u>	<u>581</u>	Samarium
	5300	46	5346	

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	<u>Actual Number</u>	<u>Error</u>	<u>Calculated Number</u>	
Subtract:	1900	19	1881	Graphite
	<u>900</u>	<u>9</u>	<u>891</u>	Cold Long-Term Gains
	2500	64	2564	Inherent Reactivity
At Startup:				
Add:	750	8	758	Cold Long-Term Gains
	<u>3250</u>	<u>72</u>	<u>3322</u>	
Subtract:	600	6	594	Samarium
	<u>100</u>	<u>1</u>	<u>99</u>	Neptunium
	2550	79	2629	Predicted Rods + Splines with no Xenon
Subtract:	2655	26	2629	Xenon (at Minimum Time)
	<u>-105</u>	<u>105</u>	<u>0</u>	Excess Reactivity

A 105 c-mk error at minimum time is about a fifty-minute wait. Since you have to wait 15 to 30 minutes after critical to get enough reactivity for a period, if you wait less than about an hour and 15 minutes for first indication on a minimum outage, your physicist has made a darn good prediction.

If you do not include the Neptunium, Samarium, and Cold Long-Term Gains in the calculation, you will find the R-infinity is 2600, and the error will be 71 c-mk. Note that we would calculate the Xenon to be 2645, a difference of only 16 c-mk from the more complicated way.

Now to predict the equilibrium conditions:

Inherent Reactivity	2500	
Cold Long-Term Gains	750	Add
Graphite	<u>1550</u>	
	4800	

Neptunium	425	
Samarium	575	
Metal	575	Subtract
Xenon	<u>2700</u>	
	525	

left for rods - No doubt the physicist will want to add some enrichment. If you normally operate with 650 c-mk in rod, he will want to add 125 c-mk of enrichment, at least!

If you ever wonder at the ability of your physicist, remember that a 100 c-mk prediction error at first indication is unimportant, but 100 c-mk at equilibrium could be the difference between smooth operation and inadequate control. Not only that, but 100 c-mk is only 0.1% of all the neutrons. So he is already calculating to within a gnat's eyebrow (most of the time)!

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UNCLASSIFIEDGLOSSARY OF TERMS USED CONCERNING REACTORS
AND THEIR OPERATION

By

D. E. Clark

INTRODUCTION

This glossary was prepared originally by D. E. Clark of the Pile Physics Operation for HW-46100 (The Pile Physics Manual of Standard Practices). This unclassified version was prepared at the request of E. H. Lockwood for use throughout HAPO as an aid for many training and information activities. It was not written for such a large and varied audience and will probably be found to be incomplete. We would appreciate any comments concerning improvement of this glossary for its new use, and we plan to revise it using your suggestions. Please send your ideas to E. H. Lockwood, D. E. Clark, or R. O. Brugge.

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GLOSSARY

Active Tube - A reactor (or pile) process tube which contains a charge of fissionable material. The term is applied almost exclusively to reactor process tubes containing uranium fuel.

Air Tube - A reactor process tube channel which is disconnected from the coolant water supply and which may or may not contain an empty or unloaded process tube. (Also referred to as an air channel or blank channel if the tube has been removed.)

Active Zone or Region - The volume of the pile bounded by the ends of the uranium columns (front and rear) and by planes one-half lattice unit beyond the row and column center-lines (top, bottom, near, and far).

Augmentation Distance - A distance beyond the active zone of a reactor at which the neutron flux extrapolates to zero. The extrapolation is made by fitting a cosine or bessel function to data taken in the active zone.

Back-seat - Any means by which the material (charge) in a reactor process tube is moved toward the upstream (or front-face) end of the tube.

Ball 3X - A third safety system that when activated will drop a hopperful of boron-steel and/or steel balls into each vertical channel from a hopper mounted at, or near, the top of each channel. The channels used are the VSR channels except for additional ball channels at the K piles. This system would be used only if the other two systems failed.

Barn - The unit of area used in expressing a nuclear cross section. $1 \text{ barn} = 10^{-24} \text{ cm}^2$.

Beckman - A micro-microammeter made by Beckman Instruments, Inc. These are used with an ionization chamber to monitor neutron flux level and/or other types of radiation in various parts of the reactor.

BGST - Biological, Graphite, and Steel Temperatures as determined from thermocouples located in these three components.

Blackness - The probability that an incident thermal neutron will be absorbed.

B-Shield - A biological shield, which is generally made of concrete or iron and masonite laminations, built around the reactor for the specific purpose of reducing the radiation level to one that is tolerable to personnel as they perform necessary duties near the reactor.

Burnup - Destruction of atoms by neutrons in reactor operation; the term may be applied to fuel or other materials.

Cadmium Ratio - The ratio of the neutron-induced saturated activity in an unshielded foil (thermal + fast neutrons) to the saturated activity of the same foil when it is covered with cadmium (fast neutrons).

Charge - The fissionable material or fuel placed in a reactor (or process tube) to produce a chain reaction. To assemble the charge in the reactor.

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GLOSSARY (Continued)

Chain Reaction - A reaction in which one of the agents necessary to the reaction is itself produced by the reaction so as to cause like reactions. In the neutron fission chain reaction, a neutron plus a fissionable atom causes a fission resulting in a number of neutrons which in turn cause other fissions.

Cold Clean Reactivity - (Which may also be noted as: CCR or RCC) The excess reactivity that a cold, xenon-free pile would have if there were no control or safety rods inserted, no poison columns, and no flattening material. The value, as commonly used, includes the enrichment in the pile at the time and assumes that all other columns are charged with (irradiated) natural uranium. The initial cold clean reactivity is the excess available when the pile was first completely loaded with every tube containing natural uranium. It is the difference between the material and geometrical bucklings.

Cold Start-Up - (a) Initial cold start-up is any attempted start-up while the pile reactivity is increasing. (b) Secondary cold start-up is any attempted start-up while pile reactivity is decreasing, and if the outage continued, the excess reactivity would eventually fall to not less than 40 inhours. An example of (a) is any start-up after the minimum downtime; an example of (b) is a start-up after a scram before the pile has operated very long.

Cored Slug - A uranium slug with a central core removed and which is canned so that the hole is covered by the cap and bottom of the aluminum can.

Corn-Popper - An electronic temperature monitoring system which provides a rapid scan of the temperatures of the outlet water from a small selected group of process tubes.

Counting Rate Meter - A device which gives a continuous indication of the average rate of ionizing events. Frequently the log of the counting rate is provided (LCRM). When plotted, the slope can be interpreted as period. The log of the counting rate may be differentiated to provide a direct indication of period.

Critical - The condition existing when the effective multiplication constant for a reactor is unity (or 1) so that a self-supporting fission chain reaction can be maintained is said to be "critical." As commonly used, this means "delayed critical" and the reaction is dependent upon both prompt and delayed neutrons. Prompt critical is capable of sustaining a chain reaction without the aid of delayed neutrons. This means a reactivity excess of $\sim 0.006 \frac{\Delta k}{k}$; this is exposure - dependent in the Hanford Piles - see delayed neutrons.

Cycling - A continuous periodic shifting of heat concentration or power density within the reactor.

Danger Coefficient - The danger coefficient of a material for a particular reactor is the change in reactivity caused by inserting that material into the reactor. The danger coefficient depends on the amount and distribution of the material inserted and is usually quoted as reactivity change/column for the central position in the reactor. These are called "nominal" reactivity values.

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Delayed Neutrons - Those neutrons with an emission time after the fission process that is delayed by the half-life of certain fission products (precursors). An arbitrary time limit exists (10^{-14} sec.) to distinguish between prompt and delayed neutrons. The delayed neutron fractions and half-lives are different for the various fissionable isotopes. This means that the delayed neutron characteristics of a pile are exposure-dependent.

Depleted Uranium - Uranium fuel with less than 0.712% U-235. The depletion may result from burnup of U-235 while under irradiation or from removal of some of the U-235 in a diffusion process.

Diffusion Length - The square of the diffusion length (called the diffusion area) is equal to one-sixth the mean square distance traveled by a particle of a given type or class from appearance to disappearance within an infinite homogeneous medium. Under certain conditions it is the distance required for the neutron density to diminish by a factor of e.

Dollar and Cents Units - Units (proposed by L. Slotin) which are sometimes used to express reactivity of a pile. The "dollar" is the reactivity that will make a reactor prompt critical. A "cent" represents 1/100 of the dollar reactivity (see The Elements of Nuclear Reactor Theory, Glasstone and Edlund, page 310). A reactor is "prompt critical" when it is critical on prompt neutrons alone.

Doppler Broadening - The spreading of frequencies of radiation which is potentially all of the same frequency with a consequent broadening of the corresponding spectral line, which results when the radiating atoms, molecules, or nuclei do not all have the same velocity relative to the observer, so that each radiating particle may give rise to a different Doppler shift. For example, since the molecules of a luminous gas have a Maxwellian distribution of velocity that increases with temperature, each spectral line of the gas comprises a range of observed frequencies symmetrically distributed about the frequency for the atom at rest, this range increasing with increasing temperature; and there is a distribution of intensities throughout the broadened line that is determined by the Maxwellian distribution of velocities. In absorption spectra, a similar broadening of the lines can result from the motions relative to the observer of the absorbing atoms or molecules. In nuclear physics, thermal motions of the nuclei in the material under examination can contribute appreciably to the widths of resonance lines, many of which (for instance, in slow neutron absorption) have natural widths of about 1 ev. It is this phenomenon that contributes to the negative metal temperature coefficient of reactivity of a Hanford pile. (See Principles of Nuclear Reactor Engineering, Glasstone - page 257.)

Downcomer - A large conduit (or pipe) at the rear of the reactor through which the outlet water flows downward and on toward the retention basins.

Drip-Leg - The small basin(s) or tank(s) (according to the Hanford reactor design) in the lowest portion of the gas line for collecting water that drains from the graphite stack. Periodic checking of the drip-legs for water content is an added means for detecting water leaks within the reactor.

Dummy - An inexact term applied to solid aluminum, tubular, perforated tubular, and even poison and steel pieces occasionally. It is used most commonly for solid aluminum (S.A.) pieces and for the downstream seating charge (dummy pattern). See below.

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GLOSSARY (Continued)

Dummy Pattern - The predetermined order in which solid aluminum slugs, perfs, and/or other types of materials are charged into the process tube ahead (i.e., downstream) of the uranium slugs.

ECT - Effective Central Tubes - The ratio of total pile power output to the average power output of the ten most productive tubes.

Effective Reactivity - (Re) - The effect upon pile reactivity that a material has for a given configuration of the material in the pile in a particular location.

EFT - Effective Flow Tubes - The ratio of total process-tube water flow to average flow/tube for the central zone.

Enrichment - A material which adds more reactivity to the pile than natural uranium when placed in the active zone of the pile; e.g., enriched uranium or uranium aluminum alloy.

Equilibrium - The operation of a reactor in steady state; that is, a reactor which is operating so that the rate of production of xenon, its burnout, and decay are constant. The effective multiplication factor is unity and changes only very slowly with time.

E-Slug - (Eisenhower or Ike Slug) - Slugs made from uranium enriched in the 235 isotope. Various degrees of enrichment have been made for various purposes.

E-Column - A process tube in the active zone of a reactor that is charged with E slugs. The charge may be entirely E slugs or may be a short charge centered with other material.

Excess Reactivity - (Sometimes called in-in-rods) - The excess reactivity that the pile would have above the poison, flattening, xenon, etc., if the HCR's were withdrawn. The inhours in horizontal control rods that are necessary to keep the effective multiplication factor at unity during pile operation.

Factors - F , F^2 , and F^3 ; f_1 is the ratio of the 1th tube power to the average tube power; F^2 and F^3 are the second and third powers respectively of F . f , f^2 , and f^3 are the pile fractions usually associated with discharges of uranium

$$f = \frac{\sum_{i=1}^n F_i}{\sum_{i=1}^n F_i} \quad f^2 = \frac{\sum_{i=1}^n F_i^2}{\sum_{i=1}^n F_i^2} \quad f^3 = \frac{\sum_{i=1}^n F_i^3}{\sum_{i=1}^n F_i^3}$$

Far-Side - The side of the reactor opposite from that into which the HCR's are inserted.

Filler Block - The solid blocks in the graphite stack of a reactor between the tube-bearing blocks are called filler blocks.

First Indication Time - The time when the most sensitive instrumentation shows the first evidence that the reactor is super-critical during a start-up.

Fission Heat - See Heat of Fission.

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GLOSSARY (Continued)

Flattening - Any material, which when placed in a process tube in the active zone of the reactor, will reduce the volume average neutron flux in that lattice relative to the value in the same lattice when natural uranium is charged in order to give a better (or flatter) distribution of flux so that near-optimum power levels may be attained; also the act of charging material to improve the flux distribution.

Flattening Tube - A process tube which is charged with flattening material.

Flexowriter - An instrumentation system that produces a typed record of process tube outlet temperatures. The typed form is called a temperature map. The whole system consists of thousands of thermocouples, many stepping switches, a potentiometer, a device that converts the signal to digital information, and an electric typewriter and relay assembly; the typewriter is built by Flexowriter.

Flux - (Neutron Flux) - The product nv where n is the number of neutrons per cm^3 and v is their mean velocity in cm/sec .

Flux Cycle - A periodic change or shift in the concentration of neutron flux within the reactor.

Flux Traverse - A means of determining the distribution of flux along a line through the reactor. The most frequently used method consists of placing units of some material at regularly spaced intervals in a process tube for the F-to-R direction and in a test-hole for the S-to-S direction and then irradiating them for a short period of time. After the material is discharged, it is measured for radioactivity. The flux value along the line is directly proportional to the saturated activity of the irradiated material.

Front or Front Face - The face of a reactor through which the cooling water enters the process tubes.

Fuel - A fissionable material of reasonably long life used or usable in producing energy in a nuclear reactor. The term frequently is applied to a mixture, such as natural uranium in which only part of the atoms are fissionable, if it can maintain a self-sustaining chain reaction under the proper conditions.

Galvanometer - An instrument for measuring small electric currents by the movement of a coil in a magnetic field. Ion chambers placed in the active zone of a reactor and connected to the No. 1 and No. 2 Galvanometers indicate the approximate power level at which the reactor is operating. No. 1 Galvanometer deflects in direct proportion to neutron flux, while No. 2 Galvanometer shows the deviation of the flux from an arbitrary level. (A potentiometer provides the reference voltage.)

Gamma Monitor - An instrumentation system that monitors a band of gamma energy of the effluent water. Each end of each rear crossheader is monitored to detect fission product gamma activity if a slug ruptures and contaminates the effluent stream with fission products.

Gamma Background - The result of a photonuclear reaction (multiplied many times) in which a gamma-ray photon is the incident particle and results in neutron expulsion. A Hanford reactor produces several fission products which emit gamma rays of sufficient energy (2.21 Mev) to produce photo-neutrons from the deuterium in the cooling water. Two important isotopes are I-135 and La-140; thus, the background neutron activity in the shut down pile varies with time after shutdown.

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GLOSSARY (Continued)

Graphite Coefficient - The moderator temperature coefficient of reactivity; however, for convenience sake it is normally expressed as a power coefficient of reactivity (C_g) in lh/MW .

Graphite Contribution (Commonly written C_g or WC_g) - The pile reactivity effect obtained by multiplying C_g by the pile power level.

Graphite Heat - The heat that is transferred to the graphite stack by gamma rays and neutrons as a result of the fission process.

Graphite Stringer and Thermocouples - A means of measuring graphite temperatures installed because in the older piles the built-in graphite-temperature-monitoring thermocouples have failed. To provide a means of monitoring the graphite temperature a few selected process tubes have been removed and replaced by a train of graphite cylinders which contain thermocouples. (See HW-46000 - Process Standards)

Gun-Barrel - A steel sleeve (pipe) extending through the shields into the graphite reflector and through which the process tube passes. A gun-barrel at each end of a process tube acts as a sleeve bearing for the tube and supports the nozzles.

Half Rod - A horizontal control rod with poison material (Boron Carbide) only on the innermost "half" of the rod. The fraction which contains absorber varies in the different piles.

HCR - Horizontal Control Rod (sometimes called HSR or Horizontal Safety Rod) - An element of control consisting of a long cylindrical or rectangular aluminum shell containing boron or cadmium and cooling passages for carrying water into and out of the rod. Each reactor type is designed with a particular number which may be inserted into and/or withdrawn from the reactor to control pile reactivity.

Heat of Fission - The energy released by the fission process and which can be converted to heat. This specifically excludes the neutrino energy. The value given in Glasstone and Edlund is 191 Mev/fission. This means that about 3×10^{10} fissions/sec. will produce a pile power of one watt.

Heavy Metal - (Hanfordese) - A term loosely applied to the solid cylindrical natural uranium fuel elements.

Heise - The name of the firm which manufactures the pressure gauges used to measure the water pressure in crossheaders at Hanford reactors. When speaking of a "Heise" the speaker is usually referring to the gauge for measuring water pressure at the reactor or to the actual monitoring procedure.

Hot Start-Up - 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 lh. (See Process Standard C-060, HW-46000.)

I & E Slug - A cored slug which has been canned so that when a column of these slugs is charged into a process tube cooling water will flow both through the core and the annulus for internal as well as external cooling.

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GLOSSARY (Continued)

In-Hour - (ih or IH) - A measure of reactivity. If zero reactivity is defined as that reactivity which causes the reactor to operate with constant power (infinite period); a reactivity of one inhour will result in a stable period of one hour. For a reactor which is very nearly critical (long period), the reactivity in inhours is the reciprocal of the period in hours. For wider departures from critical (shorter periods) the inverse period does not hold because of the delayed neutron groups. Since the delayed neutron makeup of a production reactor is exposure dependent, the "inhour" is a somewhat elastic unit.

Inlet - See T_1 .

Insertion Order - See Withdrawal Order.

Iodine - (Also noted as M) - Iodine-135 is formed from the fission process in a reactor and decays with a 6.68 hour half-life to xenon-135. Since the Xe has a considerable poison effect due to its large capture cross section, the I-135 is significant as a source for Xe-135 and must, therefore, be considered in all reactivity calculations, particularly during start-up.

Lattice or Lattice Unit - The distance from the center of a column of metal to the center of an adjacent column of metal taken vertically or horizontally along the front or rear face. The B, D, DR, F, H, and C piles have 8.375" lattice spacing, and the K pile value is classified.

LCRM - (Log Count Rate Meter) - See Counting Rate Meter.

Long Term Gains - The net increase or gain in reactivity shown over a long operating period by a reactor charged with "green" uranium fuel due to the following four factors: (1) U-235 burnout, (2) Pu-239 production and burnout, (3) Sm-149 buildup, and (4) burnout of impurities in the graphite stack.

Metal Coefficient - (C_m) - The metal temperature coefficient of reactivity; however, for convenience sake, it is expressed as a power coefficient of reactivity (C_m) in ih/mw. It is caused primarily by the Doppler broadening phenomena - see Doppler Broadening.

Metal Contribution - (CM or WC_m) - The pile reactivity effect obtained by multiplying the metal coefficient by the pile power level.

Migration Area - The migration area of a medium is one-sixth the mean square distance that a neutron travels from its birth in fission until its absorption. The medium is assumed to be of infinite extent. In Fermi age theory of thermal reactors, the migration area is the sum of the age and the square of the thermal diffusion length. In multigroup theories of thermal reactors, the migration area is the sum of the squares of the diffusion lengths for the various groups.

Minimum Downtime - The time in hours required for the pile reactivity to pass through a minimum and increase to the extent that the pile would become critical if the rods were withdrawn.

mr - Milliroentgen - 1/1000 roentgen. One roentgen is the quantity of gamma radiation which will produce by ionization one electrostatic unit of electricity of either sign in 1 cc of dry air measured at standard conditions of temperature and pressure. A flux of about 10^6 1-Mev or 2-Mev gammas equals 1r/hr. or 1000 mr/hr.

GLOSSARY (Continued)

mrem - Milli-rem - 1/1000 rem - The rem (roentgen equivalent man) is an index of the damage effects produced in the human body by the various types of radiation. Biological effects of the various types of radiation are frequently correlated by a coefficient called the relative biological effectiveness (RBE). RBE is the ratio of the body damage from a given type of radiation to that caused by the same dose of gammas. The rem is the dosage in rep (see below) multiplied by RBE for the type of radiation involved.

mrep - Milli-rep - 1/1000 rep - The rep is that radiation dosage which produces energy absorption in human tissue equal to 93 ergs per gram of tissue. Rep stands for roentgen equivalent physical.

Moderator - A material of low atomic weight and low absorption cross section used for slowing down neutrons. Graphite is used as the moderator in the Hanford reactors.

Multiplication Factor - The ratio of the number of neutrons present in a reactor at a given time to the number present one finite lifetime earlier. Sometimes called the effective multiplication constant (K_{eff}). For a homogeneous medium the infinite multiplication constant (k_{∞}) refers to the multiplication constants in an infinite medium. The multiplication constant minus one is called the excess multiplication constant (k_{ex}). (See Reactivity.)

MWD - Megawatt-Day - Unit of production or exposure equivalent to 1,000,000 watts for a 24-hour period.

MWD/AT - Unit of exposure called Megawatt-Day per Adjacent Ton. This term applies when the exposure of the material (in MWD/T) is calculated and is used to designate the exposure of the adjacent material which does not generate appreciable heat itself.

MWD/T - Unit of exposure per ton of fuel material.

MWD/Tube - Unit of exposure called Megawatt-Day per Tube and indicates the average exposure of the material in a process tube.

Natural Uranium - Uranium with the following isotopic composition:

U-234	0.006%
U-235	0.712%
U-238	99.282%

Near-Side - The side of the pile (reactor) through which the HCR's are inserted.

Neptunium - A man-made element with 93 protons in the nucleus. Np is formed when the U-238 captures a slow neutron and the U-239 decays by beta emission (23 minutes half-life) to Neptunium-239. The neptunium then decays by beta emission to Pu-239 with a 2.3 day half-life.

Nominal Reactivity - A measured value for the effect on pile reactivity that a known amount of a given material would have if charged into the central tube of the unflattened reactor.

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Nozzle - An adapter or fixture at each end of a reactor process tube through which the cooling water and slugs enter into and exit from the process tubes.

Octant Monitor - A flux monitoring system of eight ion chambers located near the corners of the reactor and connected to meters in the control room.

Orifice - A metal disk with an opening of specific diameter which is inserted in the inlet nozzle or pigtail assembly so that the flow of inlet cooling water is at a controlled rate which is determined by the diameter of the orifice; the flow can be determined by measuring the pressure on both sides of the orifice.

Orifice Pattern - The pattern of venturies and/or orifices used to establish flow rate zones in the pile. The pattern is usually represented by zones on a temperature map form, and consists of a large central area of maximum flow/tube surrounded by one or more concentric zones of less flow per tube.

Outlet - See T_o .

Overall Coefficient - (Also noted as C_o) - The algebraic sum of metal coefficient (C_m) and graphite coefficient (C_g).

Overall Contribution - (Also noted as C_o or WC_o) - The algebraic sum of metal contribution (C_m) and graphite contribution (C_g).

Overbore - The relative size of annular gap between the process tube and the graphite blocks through which it passes. This gap controls the heat flow from the graphite to the process tube; thus, the graphite temperature distribution is controlled by the overbore pattern (if any) and the composition of pile atmosphere.

Panellit - A water-pressure gauge or a system of water pressure gauges (Panellit Gauges) mounted on a panel board (Panellit Board) so that each gauge monitors the inlet or venturi throat pressure of a specific tube. A Panellit gauge is a calibrated pressure meter equipped with adjustable high and low trips which activate the No. 1 Safety System when the pressure deviates outside of some prescribed range.

PC-BF₃ Counter - A Proportional Counter tube filled with Boron-Trifluoride gas so that when a neutron enters the tube an n- α reaction emits enough energy to form a pulse which will then activate a scaler. By combining amplification and a discriminator into the system a controlled portion of radiation can be counted.

PCCF - Poison Column Control Facility - A facility for increasing flexible control of a reactor which consists of a limited number of selected process tubes to which ball-valves are attached so that poison material may be charged and/or discharged during operation of the reactor.

Perf - A piece of tubular aluminum with dimensions approximately those of a canned uranium slug and having one-half inch perforations in the walls. These are placed downstream in the dummy charge so that the cooling water may flow through the center of the tubular pieces; that is, the perms permit mixing of the cooling water as it comes off the uranium slugs and also reduce the flow resistance of the dummy train.

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Period - The time (usually in seconds) required for the neutron flux in a reactor to change by a factor of e is called the pile period or reactor period and is represented by T or t.

Period Meter - A device from which an operator may read the reactor period in seconds. It may operate interlocks and scram the reactor if the period is dangerous; that is, a few seconds or less. The device actually measures $d(\log \text{neutron flux})/dt$, which is the reciprocal of the period. (See Counting Rate.)

Pigtail - A connector between the crossheader and nozzle through which the coolant water flows from the crossheader into the process tube on the front face and from the process tube to the crossheader on the rear face of the reactor. It provides the flexibility necessary for expansion and contraction as the process tube heats or cools.

Plutonium - (Pu) - An element artificially produced, atomic number 94, discovered in 1940 by G. T. Seaborg, E. M. McMillan, A. C. Wahl, and J. W. Kennedy. They first prepared 90 year Pu-238 by the reaction:

The 2.41×10^4 year Pu-239, which is fissionable with slow neutrons, is the one prepared in nuclear reactors by the following series of reactions:

Poison - (Also noted as "P") - Any material which produces a reactivity loss relative to natural uranium.

Power Density - Power generation per unit volume of reactor core. In Hanford reactors the units would be kw/ft. of lattice cell for example.

Power Traverse - A plot of the powers of the tubes in a single plane, side-to-side or top-to-bottom, through a reactor.

"P" Push - ("Hanfordese") - The term refers to the discharge of temporary poison that has been charged into a reactor to gain more control of reactivity during a start-up from an extended outage.

Precursor - One that precedes - In nuclear physics a precursor is a radioactive nuclide that decays to the one of immediate interest; that is, U-239 is the precursor of Np-239 which in turn is the precursor of Pu-239. The most common use of the word is with reference to delayed neutrons where the half-life of the precursor determines the apparent half-life of the delayed neutron which is actually emitted promptly from the daughter of the precursor. An example is Br-87 which decays with a 55.6 second half-life to Kr-87 which in turn promptly emits a neutron. The apparent half-life of this delayed neutron is the 55.6 second half-life of the Br-87 precursor.

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GLOSSARY (Continued)

Prediction Error - The difference between the observed pile reactivity and calculated pile reactivity at the time when a reactor first begins to operate or indicate excess reactivity during a start-up.

"P" Run - (or Poison Run) - A short period (few hours) of operation of a reactor after a start-up with temporary poison charged in the active zone. After the reactivity has reached a maximum and is decreasing the reactor is shut down so the temporary poison can be discharged.

Promethium - The mother (precursor) element or isotope from which samarium is produced by beta emission.

This occurs in about 1.4% of fissions.

Prompt Critical - The condition of a nuclear reactor that is critical because of prompt neutrons alone without requiring the contribution of delayed neutrons. If a reactor is super-critical on prompt neutrons the reaction rate will rise rapidly because the time required for the average neutron cycle is extremely short. A reactor in this condition is very difficult to control.

Push - ("Hanfordese") - A "push" is an act of discharging material from a reactor or may mean the discharged material itself.

Quickie - A brief shutdown (for rapid removal of a ruptured slug from a process tube) with start-up of the reactor before the pile reactivity decreases so much that a start-up cannot be accomplished.

Reactivity - A measure of the departure of a reactor from critical such that positive values of reactivity correspond to reactors above critical and negative values to reactors below critical. Often represented by (a) the multiplication constant minus one (K_{ex}), (b) a quantity proportional to the inverse asymptotic period (ih). Sometimes used interchangeably with the term multiplication constant.

Reactivity Transient - The variation of "available excess reactivity" with time. Since the reactor is normally operated with a nearly constant power level (that is, K_{ex} equal to 1.000) the reactivity transient is the variation with time of the amount of control rod, plus any supplementary control in the reactor.

Rear-Face - The face of the reactor through which the material is discharged from the process tubes and through which the cooling water exits.

Reflector - The "extra" moderator around the active zone of a reactor which reduces the leakage of neutrons from the reactor by reflecting some of them back into the active zone. In a Hanford pile this is a layer of graphite ~24" thick.

Regular Metal - ("Hanfordese") - A term applied to the natural uranium slugs that are used for reactor fuel elements. See comments under "Heavy Metal."

GLOSSARY (Continued)

Rem - See m-rem.

Rep - See m-rep.

R_{oo} - The reactivity that a reactor would have after a sufficient time of non-operation for complete cooling of the metal and graphite in the pile and for complete decay of iodine and xenon.

Riser - (1) Water risers are the large conduits which carry the inlet water to the front crossheaders and the exit water from the rear crossheaders. (2) Instrument risers are vertical piles through the bottom shield, covered with a gas-seal at the top, so that monitoring of the flux can be done by placing instruments in reduced flux levels in or under the risers. They are usually partially filled with lead to reduce the gamma to neutron ratio.

Rod Configuration - The physical position of the horizontal control rods at a particular time. At the B, C, D, DR, F, and H Reactors the positions are given in "inches out;" that is, a rod at 50" is one that is within 50" of being all-in. At the K piles the positions are given in "per cent of the rod out of the pile;" that is, a rod at 25% is within 25% of being all-in or there is 25% of the rod out of the pile.

Rod-Swap - The act of inserting one Horizontal Control Rod while simultaneously withdrawing another, generally during operation of the reactor in order to gain an improved flux distribution.

Roentgen - See mr.

Samarium - A stable isotope (Sm-149) or nuclide resulting from the decay of Promethium-149. Its absorption cross section for thermal neutrons is ~53,000 barns and, therefore, it must be accounted for in reactivity calculations.

Scaler - A device that produces an output pulse whenever a prescribed number of input pulses have been received. The number of input pulses per output pulse of a scaling circuit is termed the scaling factor. A binary scaler is a scaler whose scaling factor is two. A decade scaler is a scaler whose scaling factor is ten.

Scram - An almost instantaneous shutdown of a reactor. A No. 1 scram is the insertion of both HCR's and VSR's simultaneously as rapidly as possible. A No. 2 scram is accomplished by inserting the HCR's only as rapidly as possible.

Scram Recovery Level - The minimum power level that the reactor must attain during the recovery from a scram to stop the loss of reactivity.

Scram Recovery Time - The maximum time within which a reactor will start up and continue to operate after a scram has occurred. This time is dependent upon the level of operation and time operated before the scram and reaches its minimum value as the reactor reaches equilibrium. For reporting purposes the time is measured from scram to the latest time at which the pile must go critical (and follow specified hot start-up procedures) to attain the scram recovery level.

Sensitivity - (As used in Pile Physics) - The pile power level in watts or kilowatts at which a particular neutron-sensing instrument first shows an indication of super-criticality during the start-up procedure.

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Shadowing - A term commonly applied to the effect noted from the following condition: when a non-fissionable strong neutron absorber is placed in a reactor there is a reduction in the neutron flux in the region; if a second absorber is inserted in the region it will produce a smaller reactivity effect than if the first absorber were not present.

Shutdown - A term applied to a pile when it is sub-critical and with a neutron induced power of less than one megawatt. Operations considers shutdown time as extending from the time rods are in to first indication. For Pile Physics purposes it is necessary to consider the effective time of shutdown as the time when the pile power level was reduced to 50% during the shutdown procedure.

Shutdown Data Sheets - (SDS) - Prepared forms on which the Area Physicist records the data concerning a shutdown of longer than scram duration.

Slug - A lump of nuclear fuel commonly in the form of a short round bar or cylinder to be inserted into holes or channels in the active lattice of a reactor. Slugs commonly are encased in jackets. At Hanford the jackets are aluminum and the term slug is applied even to non-fuel pieces which are loaded into process tubes.

Specific Power - Power produced per unit mass of fuel present in a reactor. Common Hanford units are kw/ft. of slug, kw/slug and MW/ton.

Start-Up - The act of withdrawing the Vertical Safety Rods and Horizontal Control Rods from a reactor in such a manner that the chain reaction fission process will begin in the reactor at a controllable level. This starting-up period is the most crucial portion of operating time because of the increased possibility for personnel errors and greater number of uncertainties in reactivity factors.

Sub-Critical - The state of a pile having an effective multiplication constant less than one so that a self-supporting chain reaction cannot be maintained.

Sub-Critical Monitor - An electronic system for monitoring the neutron flux level while the K_{eff} is less than unity. The system consists of a fission chamber in the active zone of the reactor connected to an amplifier-scaler, etc.

Super-Critical - The state of a pile having an effective multiplication constant greater than one so that the rate of reaction increases.

TAI - (Trip After Instability) - A temperature limit for process tube effluent that takes into account the empirically determined dynamic characteristics of the flow system and the Panellit protection. It is based on the requirement that the pile be shut down before melting damage occurs to the charge following upstream or downstream plugging of the flow passage. It is less conservative than the TBI limit.

TBI - (Trip Before Instability) - A temperature limit for process tube effluent which is based on the requirement that the pile be shut down before unstable boiling occurs in the tube following upstream or downstream plugging of the flow passage. This limit has been superseded by the TAI concept.

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Temperature Map - A printed form on which the exit temperatures of the reactor cooling water are recorded automatically by a Flexowriter.

T_f and T_r - The graphite temperature falling and rising periods respectively; that is, T_f is the time it will take for the graphite reactivity contribution to fall by a factor of e when the reactor is shut down, and T_r is the period associated with the exponential increase in the graphite reactivity contribution when the reactor is starting up.

Thermal Shield - Essentially a layer of water-cooled cast iron around the graphite stack of a reactor, which absorbs most of the gamma energy escaping from the reflector. It is constructed of over-lapping blocks of iron.

Thermal Neutrons - Neutrons in thermal equilibrium with the substance in which they exist; most commonly, neutrons of kinetic energy about 0.025 ev, which is the mean kinetic energy of a molecule at 15°C.

Thermal Utilization - The probability that a thermal neutron which is absorbed is absorbed usefully; usually used to describe the probability that a neutron is absorbed in a fissionable material.

Thermocouple - T/C - The classical thermocouple is used to measure a wide variety of temperatures at inaccessible points in and around the reactor. The most common couples are iron-constantan and chromel-alumel; platinum and platinum-rhodium are used on special occasions. The emf is almost invariably measured by an electronic potentiometer and directly in °C.

Thermom - A registered trademark (Leeds & Northrup) for a resistance thermometer loosely used at Hanford for any resistance thermometer. RTD - (resistance temperature device) is another commonly used term.

Thorium - An element from which Uranium-233 is produced by (n, γ) reaction and beta emission =

T_i - (May also be noted as I_T) - The temperature of the cooling water as measured just before it enters the reactor process tubes.

T_o - (May also be noted as O_T) - The temperature of the cooling water as measured just as it exits from the reactor process tubes. May also refer to the reactor bulk outlet temperature.

T.O.E. - Time Operated Efficiency - A value which is calculated as the total hours operated during a month divided by the total number of hours in the month x 100.

Re-Forming Blocks - The graphite blocks in a reactor which have been bored longitudinally and aligned so that a process tube passes through from end to end. These blocks bear the weight of the process tube (also called bore blocks).

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Tubular - A piece of aluminum tubing with over-all dimensions approximately the same as those for a uranium slug that is used as a spacer in the downstream dummy charge.

Turnaround - (Or T.A.) - A term referring to the maximum and minimum points in the curve of pile reactivity vs. time. The term is most commonly used in referring to the maximum pile reactivity which occurs a few hours after a start-up due to the effects of xenon burnout and buildup and heating the graphite.

Vanstone - A method of flanging the process tube (or the flange itself) in order to make a water-tight seal between the gun barrel, process tube, and nozzle.

Venturi - A short tube with an internal surface consisting of two truncated cones connected at the small ends by a very short cylinder. This is inserted into the front-face nozzle or pigtail connector so that the inlet cooling water must flow through the venturi which controls and permits measurement of the rate of flow of the cooling water through (into) the process tube.

VSR - Vertical Safety Rod - Boron-containing rods suspended over open channels in the pile during operation, so arranged that when the safety circuit is tripped the rods will fall into the pile by gravity. The structure and number of rods varies considerably from pile to pile. The VSR system is the fastest reactivity control system and absorbs almost as much reactivity as the Ball 3X system.

Weasel - The instrument used for measuring the radioactivity of a slug (or slugs), or the act of measuring with a weasel. This may be done under water or in air, if the activity is not too great, or under water, but through an air-column with special equipment.

Weep Hole - A small hole drilled across a tube-bearing block and extending diagonally from the bore of the block to a lower corner so that water from a leaking process tube will drain into the gas channels between the blocks.

Withdrawal Order - A term referring to the sequence of movement of the HCR's during a start-up. After a reactor has started up or during the process of starting up, the HCR's are withdrawn in a definite sequence or "withdrawal order." Then as the reactivity increases due to Xe burnout, buildup, and heating of the graphite, the HCR's must be inserted to control the reactivity. This is called the insertion order and is the reverse order until such time as temperature effects dictate otherwise.

Xenon - (Also noted as L) - A nuclide formed mostly by the two-stage decay of the direct fission product Tellurium-135. Te-135 has a half-life of two minutes, and the decay product, I-135, has a half-life of 6.7 hours. Because of its large neutron capture cross section, xenon is poisonous to pile reactivity and must be accounted for in calculating pile reactivity.

Zone Temperature Monitor - An instrumentation system, which will provide a fast scan of selected process tube outlet temperatures. This device will provide near-instantaneous tube-power distribution information by monitoring a well-distributed fraction of the active tubes in the pile.

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23 - A code number for ${}_{92}\text{U}^{233}$, the first digit of the code referring to the second digit of the Atomic Number of ${}_{92}\text{U}^{233}$, and the second digit of the code referring to the last digit of the Mass Number of ${}_{92}\text{U}^{233}$.

25 - A code number for ${}_{92}\text{U}^{235}$ formed in the same manner as the preceding code number for ${}_{92}\text{U}^{233}$.

28 - A code number for ${}_{92}\text{U}^{238}$ formed in the same manner as the code number for ${}_{92}\text{U}^{233}$.

49 - A code number for ${}_{94}\text{Pu}^{239}$ formed in the same manner as the code number for ${}_{92}\text{U}^{233}$.

240 - The code number indicating ${}_{94}\text{Pu}^{240}$.

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