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U.S. ATOMIC ENERGY COMMISSION

ORNL-TM-2034, Vol. III

REACTOR OPERATOR STUDY HANDBOOK
(Programmed Instruction Version)

VOLUME III - REACTOR PHYSICS

R. A. Costner, Jr.
E. N. Cramer
R. L. Scott, Jr.

Editors

C. D. Cagle
S. D. Sheppard

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OPERATIONS DIVISION

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OAK RIDGE NATIONAL LABORATORY
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FOREWORD

It is suggested that this programmed text be used as an aid in the study of reactor technology. It is not the intent of the author and editors that the text be considered a finished product. While field testing of both the subject matter and the continuity of thought has been limited, the need for study material in programmed form was a basic consideration in the decision to publish the text. Revisions may be made at any time to correct errors, to expand the subject matter coverage, or to update the reactor technology. If the text is used with these reservations, and in conjunction with other study helps, it can be the basis for very rewarding individual study on the part of the student.

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CONTENTS

REACTOR OPERATOR STUDY HANDBOOK
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Volume III - Reactor Physics

As a part of the Reactor Operator Training Program of Operations Division, Oak Ridge National Laboratory, five areas of instruction have been programmed for individual study. They are:

Volume I - Elementary Mathematics Review
Volume II - Radiation Safety and Control
Volume III - Reactor Physics
Volume IV - Heat Theory and Fluid Flow
Volume V - Instrumentation and Controls

These programmed studies are a part of a course in reactor operation that includes classwork, lectures, and on-the-job training. At the end of the course, the operator trainee is tested for competence in all areas of reactor operations before being certified to operate a particular reactor.

It is suggested that the programs be studied in the sequence given above; however, sequential dependence has been minimized so that they may be studied either individually or as an integrated group.

The authors and editors would like to especially acknowledge the patience and assistance of the members of the Operations Division clerical staff who worked on this report; namely, Gladys Carpenter, Linda Comstock, Milinda Compton, Joanne Nelson, and Barbara Burns.

INSTRUCTIONS

The material contained in this manual has been prepared using a technique called "programmed instruction". This technique of instruction consists of:

1. Presenting ideas or information in small, easily digestible steps called "frames".
2. Allowing you to set your own pace.
3. Encouraging response in an active way so that you have a stronger impression of the idea presented.
4. Letting you know immediately if your answer is right, thus reinforcing your impression.
5. Presenting many clues at first to help you arrive at the correct answer. (As you progress, the number of clues is reduced.)

A few sample frames are found on the next page. These will be used to illustrate the proper use of "programmed instruction". Most frames will require you to respond by filling in a blank, or blanks, to complete a sentence. Other frames will give you a choice of several responses. A few frames are for informational purposes only and require no response. The correct response to a given frame is always found on the right side of the page adjacent to the following frame. When reading a frame, a sheet (or strip) of paper should be used to cover the area below the dotted line which follows the frame. After completely reading a frame, you should write your response on a piece of paper. Next, move the paper down the page until you reach the next dotted line or turn the page. This will uncover the next frame and the correct response for the frame you have just completed. Compare your response with the correct response. If they do not match, read that frame again before moving on to the next one; do not proceed until you understand the information in the frame you are reading. If the responses do match, proceed to the frame you have just uncovered.

At the end of each section, there are self-test questions for review. If you miss one of the self-test questions, repeat the pertinent frames. It is not enough to respond correctly as you proceed through the material; you must remember correctly at the end of the program and even later. You should attempt to complete each section once you have started.

SAMPLE FRAMES

i. Programmed instruction is a method of presenting information in short paragraphs called "frames". These ____________ usually contain only one or two concepts for the student to grasp.

- - - - - - - - -

ii. By requiring you to think of the appropriate response and to write that ______________ on a piece of paper, you take an active part in the program, and thereby reinforce your learning.

frames

- - - - - - - - -

iii. This method of instruction, called _______________ _____________________, allows you to proceed with the material at a rate which you determine for yourself.

response

- - - - - - - - -

iv. Programmed instruction provides the appropriate response immediately and thus should reinforce the student's ____________________.

programmed

- - - - - - - - -

learning

SECTION III-1

NEUTRON REACTIONS

1.1. Types of Reactions

The purpose of this section is to describe the reactions of neutrons, which are of particular interest in the operation of nuclear reactors, and to introduce some of the terms which will be used throughout the study of reactor physics.

1. What is a neutron?

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> If you said that a neutron is a small uncharged particle which normally exists only in the nuclei of atoms, then you have given a very good answer. If you also said that a neutron has a mass of about one atomic mass unit which is about the same as the mass of a proton and is about 1836 times heavier than an electron, you are right. If you added that neutrons occasionally are emitted from radioactive atoms as radiation when these atoms decay, you are right again.

A neutron is a small (charged, uncharged) particle usually found in the __________ of atoms.

\- - - - - - - - -

2. Although neutrons occur in the nuclei of atoms, some types of radioactive atoms may decay and release some neutrons so that they are free to either exist by themselves for a short time or to react with other atoms. Therefore, we may say that free neutrons are sometimes produced when some types of radioactive __________ __________.

uncharged, nuclei

\- - - - - - - - -

3. Obviously, neutrons which are in the nuclei of atoms are not free to react with other atoms; so, our discussion of neutron reactions is primarily concerned with __________ __________.

atoms decay

- - - - - - - - -

4. Two neutron reactions which are of interest in reactor operations are scattering reactions and absorption reactions.

free neutrons

A scattering reaction is one in which a neutron collides with the nucleus of an atom and then continues traveling, but usually in a different direction.

An absorption reaction is one in which a neutron is absorbed into a nucleus forming a different isotope which may be stable, may emit radiation (alpha, beta, or gamma), or may undergo fission.

> A fission reaction is one in which a nucleus absorbs a neutron then splits into two smaller nuclei and releases two or three neutrons and some energy.

- - - - - - - - -

5. To get a better idea of the scattering reaction, let us think of the neutron as a ping-pong ball; and, since the nucleus of a hydrogen atom (a proton) is about the same size and weight as a neutron, we can think of it as another ping-pong ball.

- - - - - - - - -

6. Both the neutron and the hydrogen nucleus have a mass of about one atomic mass unit (amu). A ^{238}U nucleus has a mass of 238 amu's which makes it 238 times as heavy as a neutron. So, compared to a neutron, we can think of the ^{238}U nucleus as a big heavy bowling ball.

\- - - - - - - - -

7. Now, if you throw the ping-pong ball (neutron) at the bowling ball (^{238}U nucleus), you will notice that the neutron ball bounces off in a different direction (a scattering collision) with almost <u>no loss</u> of speed. You also may have noticed that the ^{238}U bowling ball did not move.

\- - - - - - - - -

8. In this particular reaction, the bouncing of the neutron off the heavier nucleus was called a __________ collision.

\- - - - - - - - -

9. In this type of reaction, where the particle that is hit is very much larger than the bombarding particle, the bombarding particle loses (most, very little) of its energy. — scattering

\- - - - - - - - -

10. Where there is almost no loss of energy, there is (a great, almost no) loss of speed. — very little

\- - - - - - - - -

11. Now, if you throw the neutron ball at the other ping-pong ball (hydrogen nucleus), you will notice that after the scattering reaction both balls move off in different directions and neither ball has as much speed as the neutron ball had before it collided with the hydrogen ball. — almost no

\- - - - - - - - -

12. Another analogy would be a cue ball striking a billiard ball. The speeds of both the cue ball and the billiard ball are __________ after the collision than the speed of the cue ball was before.

\- - - - - - - - -

13. The neutron ball has slowed down as a result of its ___________ reaction with the hydrogen ball. Figure III-1 illustrates these scattering reactions. less

\- - - - - - - - -

scattering

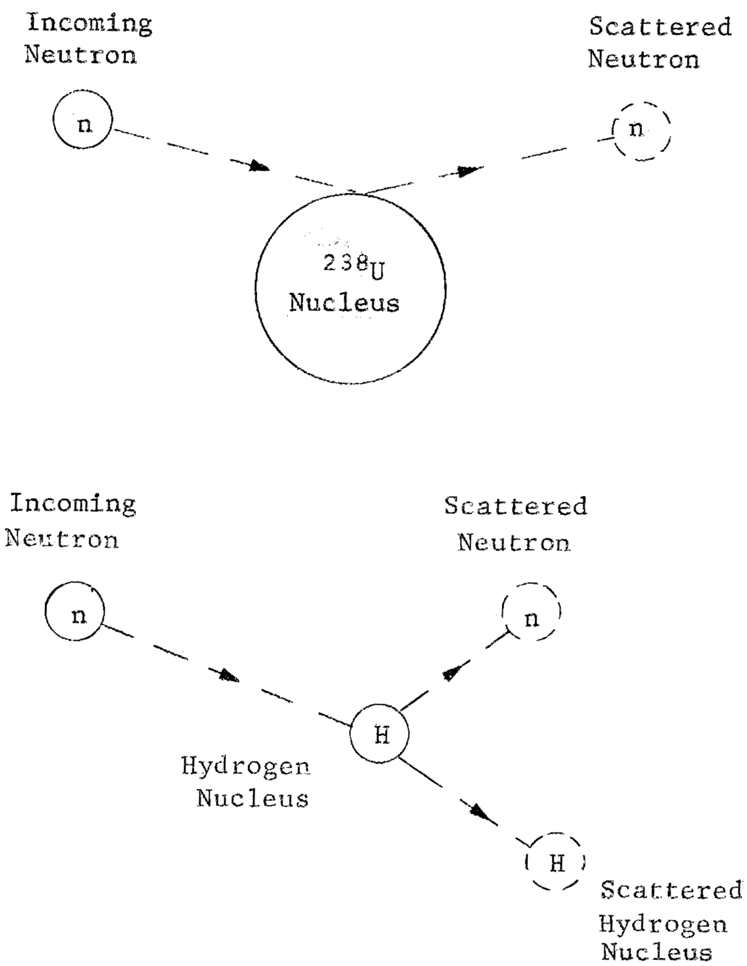

Fig. III-1. Scattering Reactions

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14. The reaction of the neutron with the ^{238}U nucleus is called a __________ reaction.

- - - - - - - - -

15. The reaction of the neutron with the hydrogen nucleus is called a __________ reaction. scattering

- - - - - - - - -

16. The scattering reaction with the ^{238}U nucleus resulted in (an increase, a decrease, no change) in the speed of the neutron. scattering

- - - - - - - - -

17. The scattering reaction with the hydrogen nucleus resulted in a (decrease, increase) of the neutron speed. no change

- - - - - - - - -

18. From the above frames, it is rather easy to infer that a neutron is slowed down more if it collides with a (large, small) nucleus. decrease

- - - - - - - - -

19. The speed of a very fast-moving neutron can be reduced drastically by several _______________ reactions with light nuclei. small

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20. Scattering is a fairly common every-day-type reaction. Some additional examples of scattering reactions are: cars bouncing off telephone poles or bouncing off other cars, people walking into each other and bouncing back, etc. scattering

- - - - - - - - -

21. A scattering collision familiar to many small boys is the "skipping" of stones across a lake or other body of water. The greater the speed of the stone, the greater the probability that it will rebound from the water surface two or three times.

\- - - - - - - - -

22. As the stone loses speed, it is less likely to __________ from the surface of the water.

\- - - - - - - - -

23. As the stone loses speed, there is a greater probability that it will plunge into the water (will be absorbed by the lake).

scatter or rebound

\- - - - - - - - -

24. A neutron absorption reaction is one in which a neutron is __________ into the nucleus of an atom.

\- - - - - - - - -

25. Since neutrons are (charged, uncharged), they are not repelled from or attracted to the nucleus. Somewhat like the stone "skipping" across the lake, if the neutron slows down enough and comes close enough to the nucleus, it will probably be __________.

absorbed

\- - - - - - - - -

26. The ability of atoms to absorb neutrons is different for different types of atoms.

uncharged, absorbed

\- - - - - - - - -

27. Atoms or materials which have a strong tendency to absorb neutrons are generally called neutron "poisons" in reactor terminology. A neutron poison is, therefore, a strong neutron ________.

- - - - - - - - -

28. Materials such as boron, cadmium, xenon, and samarium have a strong tendency to "devour" neutrons by absorption reactions and are usually referred to as neutron ________.

absorber

- - - - - - - - -

29. When a neutron is absorbed into the nucleus of an atom, the atom is transformed to a heavier isotope. The newly formed isotope will usually be highly excited and will emit one or more types of radiation in order to reach a more nearly stable state or condition.

absorbers or poisons

- - - - - - - - -

30. A typical example of a neutron absorption reaction is the absorption of a neutron by an atom of aluminum. The reaction is represented by the equation

$$^{1}n + {}^{27}Al \longrightarrow {}^{28}Al + {}^{0}\gamma.$$

This equation says that a neutron with a mass of 1 amu (atomic mass units) is absorbed by an atom of aluminum which has a mass of 27 amu and becomes transformed (indicated by $\longrightarrow$) to an atom of aluminum with a mass of 28 amu. The symbol $^{0}\gamma$ was added to indicate that generally the newly-formed isotope ^{28}Al is excited and emits a gamma ray immediately.

- - - - - - - - -

31. Another example of an absorption reaction is the reaction of a neutron with a uranium atom which has a mass of 235 amu. The equation is

$$^{1}n + {}^{235}U \longrightarrow {}^{236}U.$$

This equation says ____________________.

- - - - - - - - - -

> Yes, that is right; the equation says that the absorption of a neutron by an atom of ^{235}U forms the isotope ^{236}U. This, however, is only the beginning of another type of reaction called the "fission" reaction.

- - - - - - - - - -

32. The word "fission," according to the dictionary, means "to break into parts," and this is just exactly what happens to the newly-formed isotope, ^{236}U; it __________.

- - - - - - - - - -

33. About 85 percent of the time a newly-formed ^{236}U atom will break up to form two smaller atoms, and at the same time there will be from two to three neutrons emitted when the __________ takes place. fissions

- - - - - - - - - -

> While ^{235}U is a strong neutron absorber, it is not a poison because the ^{236}U formed usually fissions and emits two or three neutrons. A poison is a strong neutron absorber which does not emit neutrons.

fission

- - - - - - - - - -

34. The fission reaction may be represented by the equation

$$^{1}n + {}^{235}U \longrightarrow [{}^{236}U] \longrightarrow {}^{92}Kr + {}^{141}Ba + 3\ {}^{1}n.$$

This says that a neutron is absorbed by ^{235}U and forms ^{236}U which breaks up to form ^{92}Kr and ^{141}Ba and three neutrons are released.

- - - - - - - - - -

35. Krypton and barium were used only as illustrations. When the ^{236}U atom fissions, it usually breaks into roughly equal parts and the products formed may be almost any of the isotopes as long as the combined mass is 233 or 234--depending on whether three or two ______________ are emitted.

\- - - - - - - - -

neutrons

36. The main steps to remember about the fission reaction are that a neutron is absorbed by a ^{235}U atom, the __________ takes place, and ____________ neutrons are released. A simple illustration of the fission reaction is shown in Fig. III-2.

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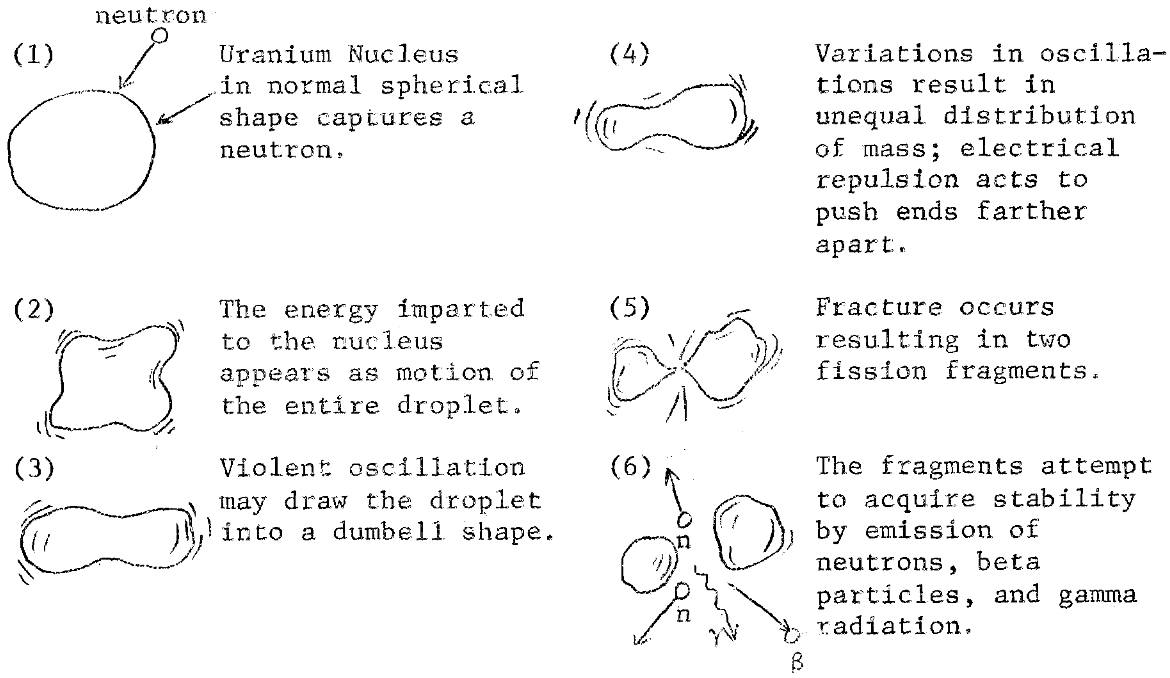


Fig. III-2. Liquid-Drop Analogy of Fission

\- - - - - - - - -

fission,
two or three

37. Neutrons are involved in the fission reaction in two ways. Neutrons are first ____________ ; and when fission occurs, they are ____________.

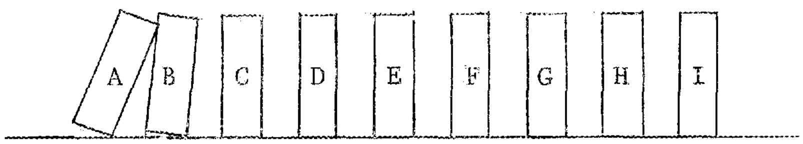
\- - - - - - - - -

38. Since neutrons are released when fission occurs and these neutrons can cause other fission reactions, a chain reaction is possible.

absorbed, released or emitted

- - - - - - - - -

39. Chain reactions are continuous-type reactions in which a preceding reaction causes a second reaction of the same kind to happen. The second causes a third, etc. For example, a long row of dominoes, where domino A falls against B, which falls against C, etc., is a continuous reaction which may be called a __________ __________.



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40. Figure III-3 is an illustration of a fission chain reaction. Note that, of the two or three neutrons released when fission occurs, at least one neutron is absorbed in another ^{235}U atom to continue the chain of reactions.

chain reaction

- - - - - - - - -

41. If at least one neutron is absorbed, from each fission, to cause another fission, a __________ __________ can continue.

- - - - - - - - -

42. If an average of more than one neutron becomes available to cause fission for each neutron causing fission, we would expect the number of fissions per second to (remain the same, decrease, increase) as time passes.

chain reaction

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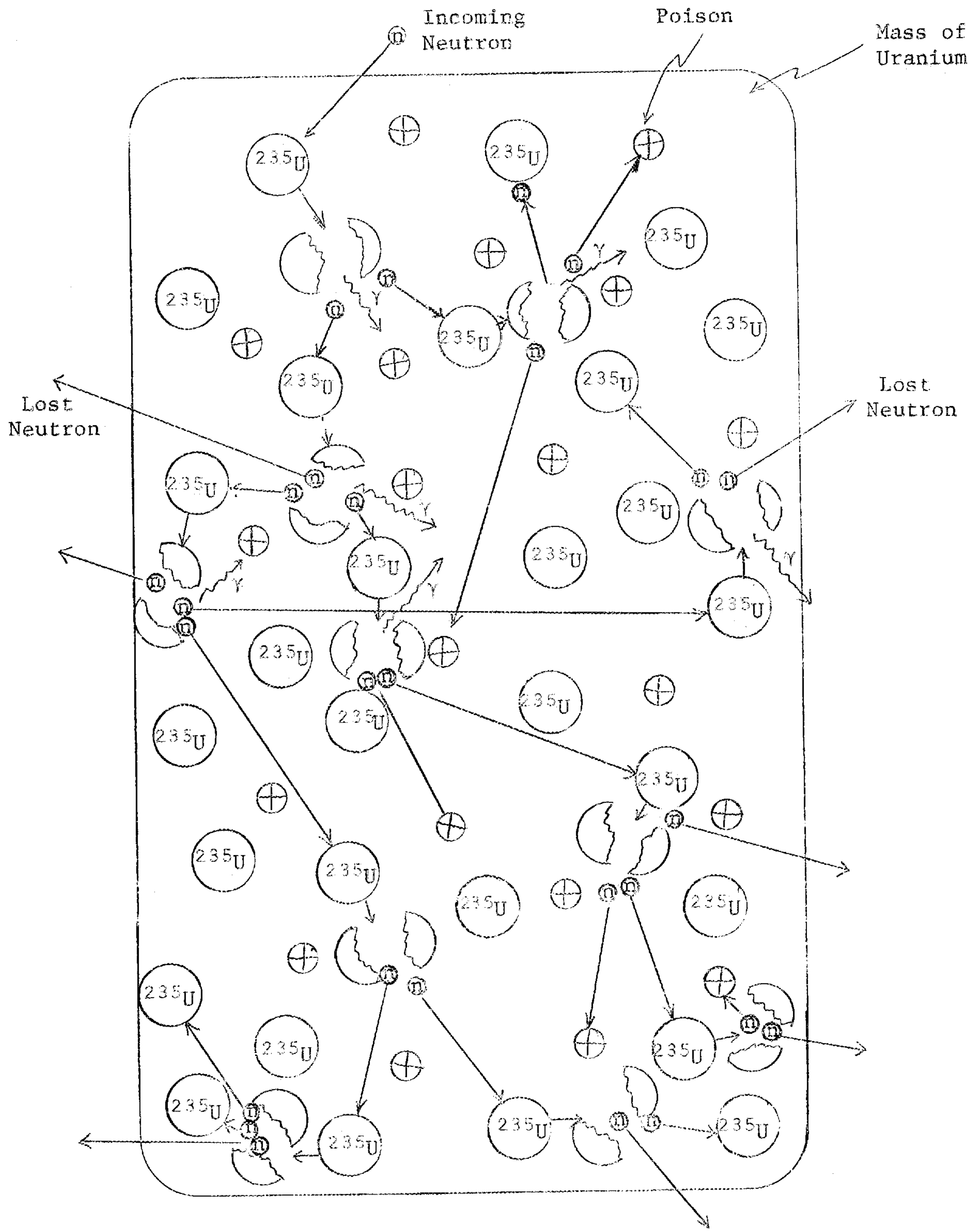

Fig. III-3. Fission Chain Reaction

43. With the proper conditions (from the two or three neutrons produced at fission, only __________ neutron causes another fission), the fission chain reaction can be controlled so that it is continuous and self-sustaining. — increase

- - - - - - - - -

44. The reason we want to control the fission chain reaction is so that we can effectively use the large amount of energy (ability to do work) which is also released when fission occurs. — one

- - - - - - - - -

1.2. Fast and Thermal Neutrons

45. The two or three neutrons which are released when fission occurs are traveling at a very high speed. For this reason, they are usually called "fast" neutrons.

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46. Neutrons which travel at a slow speed are usually called __________ neutrons.

- - - - - - - - -

47. The distinction between slow and fast neutrons is made because, although fast neutrons are emitted by fission, slow neutrons are needed to cause fission most efficiently in nuclear reactors. — slow

- - - - - - - - -

48. Since slow neutrons are most efficient in causing ^{235}U to fission, a chain reaction will be sustained with a smaller quantity of ^{235}U if the fast neutrons emitted from fission are __________ __________.

- - - - - - - - -

49. Fast neutrons can be slowed down by __________ reactions. — slowed down

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50. The best material for slowing down fast neutrons is that which is made up of (big, small) atoms. — scattering

\- - - - - - - - -

51. The process of slowing down a fast neutron by scattering reactions is called <u>moderation</u>. Materials which are used for slowing down fast neutrons are called (fuel, moderators). — small

\- - - - - - - - -

52. In order for a fast neutron to be slowed down, it must collide with atoms; and each time it makes a collision there is a possibility of the neutron becoming absorbed and thus lost. Therefore, a <u>good</u> moderator is one which slows neutrons quickly and at the same time does not readily __________ them. — moderators

\- - - - - - - - -

53. Water (H_2O) contains an abundant supply of hydrogen atoms; and since hydrogen does not absorb neutrons excessively but does slow neutrons quickly, water is a good __________. — absorb

\- - - - - - - - -

54. To be a good moderator, a material must __________ __________ quickly and must not __________ too many neutrons. — moderator

\- - - - - - - - -

55. Carbon in the form of graphite is a good moderator; deuterium (an isotope of hydrogen) is another. Beryllium and ordinary water are also good ________.

slow neutrons, absorb

- - - - - - - - -

56. The moderation or slowing-down process is sometimes referred to as "thermalization." The term "thermalization" results from the fact that atoms in any material are moving or vibrating with a speed which can be varied by increasing or decreasing the temperature of the material. Figure III-4 is an illustration of vibrating atoms in a material.

moderators

- - - - - - - - -

57. The speed at which atoms of any material are vibrating can be varied by heating or cooling the material. This phenomenon is noticed every day when you boil water. By adding heat to the water, the atoms (and, therefore, the molecules) start moving around so fast that they break through the surface and appear as steam.

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58. Heat is thermal energy. So, when a neutron slows down so that it is in equilibrium (at the same temperature) with the atoms of the material it is traveling in, then the neutron is said to be in thermal equilibrium. This is as much as the average neutron can be slowed down.

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59. The term thermalize, therefore, means to moderate (slow down) a neutron until it is in __________ equilibrium with the material.

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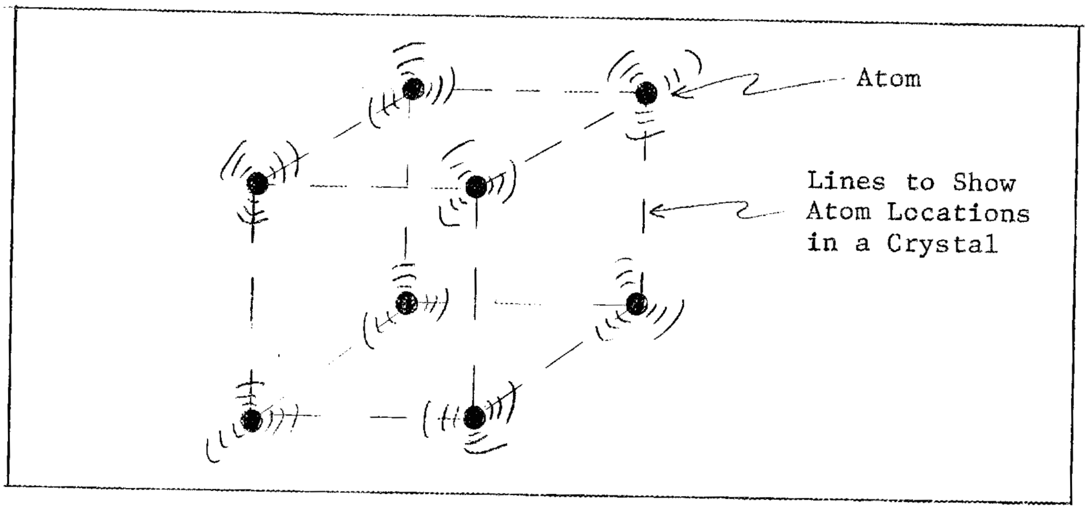
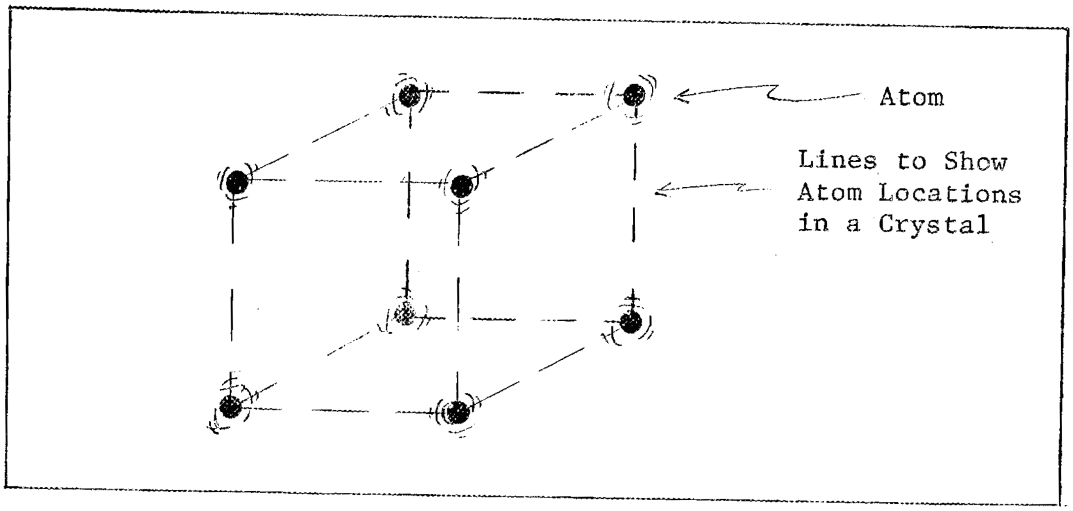


High-Temperature Vibrations



Low-Temperature Vibrations

Fig. III-4. Vibrations of Atoms

60. A group of neutrons which have been thermalized in a material should have speeds which are (very different, about equal). — thermal

- - - - - - - - - -

61. Neutrons in thermal equilibrium with a material are called (fast, thermal) neutrons. These are usually what are meant when one speaks of slow neutrons. — about equal

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62. To illustrate the effect of temperature on the speed of a neutron, let us assume that a neutron is moving around in thermal equilibrium with the air. If the temperature is 68°F, the neutron has a speed or velocity of about 4600 miles per hour. If the temperature were raised to 392°F, the neutron's velocity would be doubled. — thermal

- - - - - - - - - -

63. When neutrons are first emitted, they are moving too fast to cause fission in ^{235}U efficiently. They must be ____________ to a speed that will allow them to cause fission most effectively.

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64. Let us go over the fission reaction once more. A thermal neutron is absorbed into the nucleus of a ^{235}U atom and a ^{236}U atom is formed. These new ^{236}U atoms are so unstable (excited) that about 85% of them immediately split into two smaller nuclei which are called fission fragments. The remaining 15% manage to emit enough energy as gamma radiation to prevent fission from occuring. — thermalized, slowed down, or moderated

(continued)

64. (continued)

The excess energy of the ^{236}U nucleus is released in the form of kinetic energy of the fission fragments, which fly apart at great speed and generate heat as they collide with surrounding matter. Gamma radiation and two or three neutrons are also released. The free neutrons are very fast and are thermalized by scattering reactions with a moderator. When the fast neutrons become thermalized, they react readily with other ^{235}U atoms causing more fission, and so on.

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65. Now let us look, in more detail, at the release of the two or three neutrons from the fission reaction.

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66. For a large number of fission reactions, an average of about 2.5 neutrons are released. From 400 fission reactions, the number of neutrons released would be about __________.

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1.3. Prompt and Delayed Neutrons

67. Of the neutrons released when fission occurs, about 99.25% are released within about 10^{-14} seconds. Since they are released promptly, they are called prompt neutrons. 1000

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68. Since 10^{-14} seconds is a very short time, the term __________ neutrons is very apt.

- - - - - - - - -

69. Prompt neutrons make up (75%, 99%, 99.25%, 99.75%) of all the neutrons emitted in the fissioning of ^{235}U. — prompt

- - - - - - - - -

70. The other 0.75% of the neutrons are released over a period of minutes as the fission fragments, or products, decay. These are called <u>delayed</u> neutrons. — 99.25%

- - - - - - - - -

71. When fission products decay, they sometimes emit neutrons. Since these are emitted at a later time than the prompt neutrons, they are called ______________ neutrons.

- - - - - - - - -

72. Most fission products emit negative beta particles. Normally, this is the result of the neutron-to-proton ratio being too high so that a __________ will change into a proton and emit a __________ particle. No delayed neutrons are emitted by this reaction. — delayed

- - - - - - - - -

73. However, once in a while fission fragments will have so much energy that they can emit a whole neutron and become stable in one energy jump. — neutron, beta

- - - - - - - - -

74. Figure III-5 shows ^{87}Br fission fragments decaying by two paths. Note that by both paths they decay first to __________ by emitting a negative __________ particle.

- - - - - - - - -

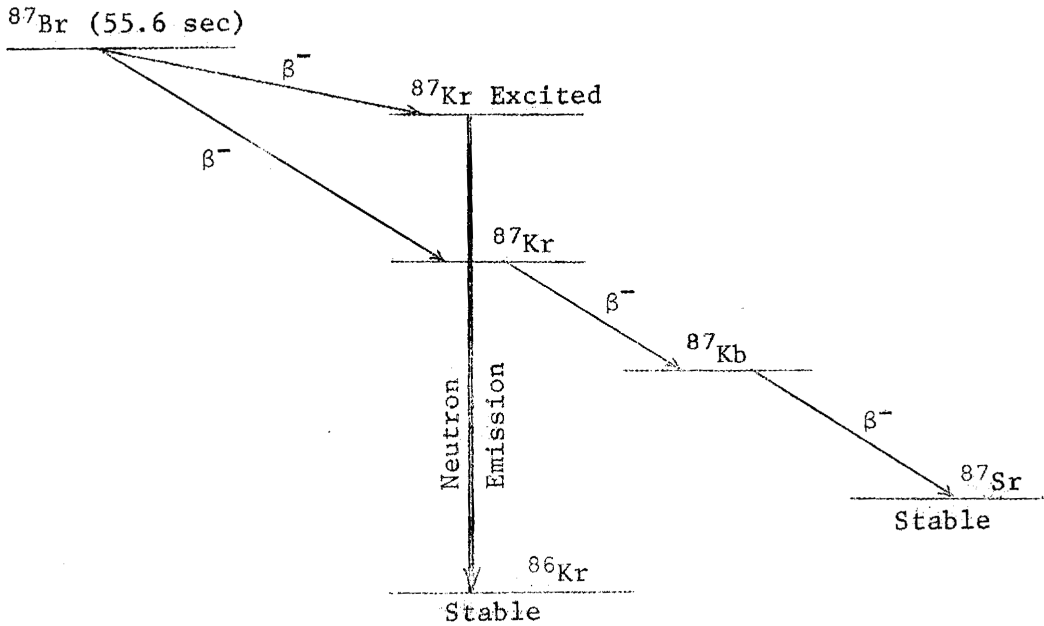

Fig. III-5. Mechanism of Delayed-Neutron Emission

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75. By one decay path the ^{87}Kr atom has much more energy than by the other and can emit a __________ to become stable ^{86}___ immediately. The other decay path is by a series of beta emissions and does not result in the emission of a __________.

^{87}Kr or krypton-87, beta

- - - - - - - - - -

76. Since all neutrons released from fission are very energetic and fast moving, both prompt and delayed neutrons are (fast, slow, thermal) neutrons.

neutron, Kr, neutron

- - - - - - - - - -

77. Neutrons released as the result of fission are fast neutrons; the only difference between prompt and delayed is __________ after fission occurs.

fast

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78. Gamma and beta radiation which accompany the fission reaction are also classified as prompt and delayed. Both gamma and beta radiations, given off over a period of time by the radioactive decay of fission products, are called __________ radiation.

the time it takes to be released

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79. The term fission products applies to the various decay products of the fission fragments as well as to the fission fragments themselves.

delayed

\- - - - - - - - -

1.4. Multiplication Factor

80. The fact that an average of 2.5 neutrons is released per fission means that if 10 neutrons are absorbed by ^{235}U and cause fission, 25 neutrons will be released. If all of these 25 neutrons cause fission, there will be 25×2.5 which is 62 (or 63) neutrons. If these 62 neutrons all cause fission, then we will have $62 \times 2.5 = 151$ neutrons, etc. The point is that the number of neutrons increases.

\- - - - - - - - -

81. Let us look at three examples of multiplication.

Example 1 $1 \times 1 = 1$

$1 \times 1 \times 1 = 1$

$1 \times 1 \times 1 \times 1 = 1$

$1 \times 1 \times 1 \times 1 \times 1 = 1$

Example 2 $1 \times 2 = 2$

$1 \times 2 \times 2 = 4$

$1 \times 2 \times 2 \times 2 = 8$

$1 \times 2 \times 2 \times 2 \times 2 = 16$

Example 3 $1 \times 0.9 = 0.9$

$1 \times 0.9 \times 0.9 = 0.81$

$1 \times 0.9 \times 0.9 \times 0.9 = 0.729$

$1 \times 0.9 \times 0.9 \times 0.9 \times 0.9 = 0.6561$

- - - - - - - - -

82. Example 1 shows that when the multiplication factor, k, is one, the result is always the same.

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83. If the multiplication factor, k, is greater than one, such as two, in Example 2, the result of each succeeding multiplication is (an increase, a decrease).

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84. If the multiplication factor, k, is less than one, as in Example 3, the result of each succeeding multiplication is __________. an increase

- - - - - - - - -

85. This principle of multiplication can also be applied to people, rabbits, neutrons, etc. Take a look at the family trees of two different families as shown in Fig. III-6. In one family, the multiplication factor, k, is greater than one and the family tree has increased; but the other family has a k less than one. a decrease

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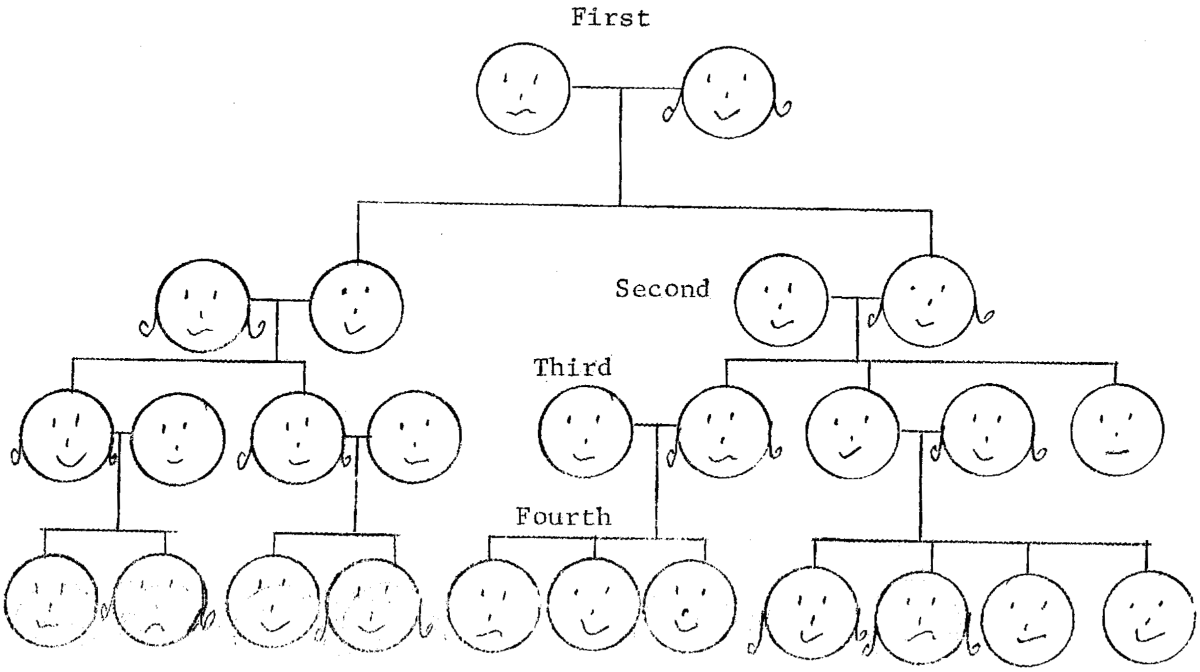
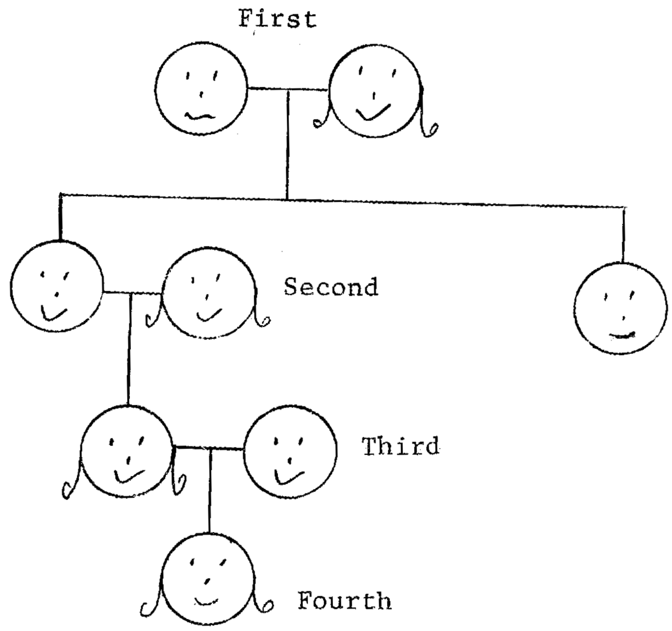


k greater than 1



k less than 1

Fig. III-6. Family Trees

86. If a husband and wife have two children, the multiplication factor is one--they just replace themselves. If they have three children, the multiplication factor is 1.5 (2 parents × 1.5 = 3 children).

\- - - - - - - - -

87. The population of neutrons also increases or decreases in a similar manner depending on the value of the neutron __________ __________, for which we use the symbol k.

\- - - - - - - - -

88. Neutrons are "born" when ^{235}U fissions and they "die" when absorption reactions occur. Thus, if the birth rate is greater than the death rate, the neutron multiplication factor, k, must be __________________.

multiplication factor

\- - - - - - - - -

89. If more neutrons are absorbed than are produced from fission, the neutron multiplication factor must be ____________________.

greater than one or >1

\- - - - - - - - -

90. Any material which absorbs neutrons without producing fission removes these neutrons so that they are unable to cause fission reactions. Therefore, it is desirable to know how readily various materials absorb neutrons.

less than one or <1

\- - - - - - - - -

1.5. Cross Section

91. The neutron-absorbing ability of materials is usually expressed in terms of a "cross section." The expression "cross section" is used because the absorbing atoms are considered to be presenting a target area for the neutrons as shown in Fig. III-7.

\- - - - - - - - -

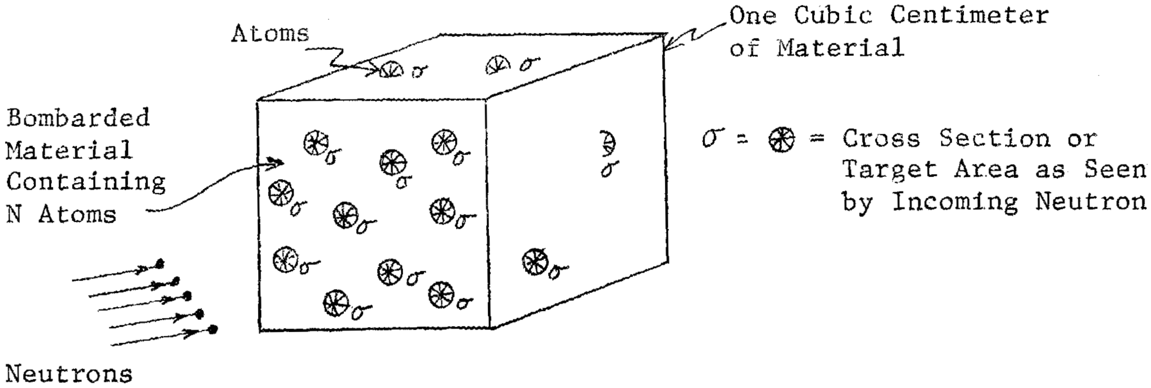


Fig. III-7. Cross Sections

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92. The target area of one atom is called the "microscopic ____________." Microscopic means "so small that it is invisible to the naked eye."

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93. The microscopic cross section of one atom is usually represented by the symbol σ (sigma). The value of σ is often given in the unit "barns," which is 10^{-24} square centimeters (cm^2). — cross section

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> The story is told that the term "barn" was first used to illustrate the size of an atom in relation to the size of the neutron. To the neutron, the atom was "as big as a barn."
>
> There has been some endeavor to replace the term "barn" with "Fermi," in honor of that famous physicist; however, the term "barn" seems to be firmly established.

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94. Thus, we could read the mathematical statement, $\sigma = 3 \times 10^{-24} cm^2$ as "the microscopic cross section is __________ __________."

- - - - - - - - - -

95. If there are N atoms in a cubic centimeter of material and each has a cross section σ, then the sum of the __________ sections of all of the atoms in that cubic centimeter is $\sigma_1 + \sigma_2 + \sigma_3 + ---$ or $N \times \sigma$. The total of the cross sections in a cubic centimeter, that is $N \times \sigma$, is called the macroscopic cross section. — three barns

- - - - - - - - - -

96. If the amount of material that we are discussing is large enough to be seen by the naked eye, and we can see a cubic centimeter of material, we use the word __________ to differentiate between this size and microscopic. — microscopic

- - - - - - - - - -

97. The macroscopic cross section is usually represented by the symbol Σ (capital sigma). So, in equation form, — macroscopic

$$\Sigma = N \times \sigma$$

where N is the number of atoms per cm^3 and σ is the __________ cross section.

- - - - - - - - - -

98. Since σ is different for different kinds of atoms and since materials usually have more than one kind of atom (water has both hydrogen and oxygen), each kind of atom and its associated cross section has to be considered in order to determine the overall effect, that is Σ.

microscopic

\- - - - - - - - - -

99. For example, to determine the absorbing ability of water, we would have to know the microscopic __________ for both hydrogen atoms and oxygen atoms since each water molecule is composed of two hydrogen atoms and one oxygen atom.

\- - - - - - - - - -

100. Other reactions besides absorption are also represented by a microscopic cross section. σ_a represents the absorption cross section, σ_f the fission cross section, and σ_s the scattering cross section. The same is true for the macroscopic cross section.

cross sections

\- - - - - - - - - -

101. We would read $\Sigma_a^{H_2O}$ as "the macroscopic __________ cross section of __________."

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102. We would read Σ_s^{O} as "the macroscopic __________ cross section of oxygen."

absorption, water

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103. The symbol for the microscopic scattering cross section is __________.

scattering

\- - - - - - - - - -

104. The cross section for scattering of neutrons produced by a cubic centimeter of beryllium would be written __________ of beryllium. σ_s

- - - - - - - - - -

105. According to Table III-1, there is no σ_f for boron. This is reasonable because boron does not __________. Σ_s

- - - - - - - - - -

Table III-1 is a list of some thermal neutron cross sections for various materials. fission

Table III-1. Some Frequently Used Cross Sections

Element	Σ_a $\left(\frac{\text{reactions}}{\text{cm}}\right)$	σ_a (barns)	Σ_s $\left(\frac{\text{reactions}}{\text{cm}}\right)$	σ_s (barns)	σ_f (barns)
Al (aluminum)	0.015	0.210	0.084	1.40	---
H_2O (water)	0.022		3.450	~80.0*	---
B (boron)	103.000	750.000	0.346	4.00	---
Cd (cadmium)	114.000	2400.000	0.325	7.00	---
^{235}U (uranium)	32.100	7.420	0.397	7.42	577
Be (beryllium)		0.009		7.00	---

*For hydrogen bound in a molecule.

- - - - - - - - - -

106. While σ is usually considered the target area of one atom, we should think of Σ as being "the number of reactions which a neutron will experience as it travels a distance of one centimeter."

- - - - - - - - - -

107. From Table III-1, we see that a neutron traveling in boron will have __________ chances to be absorbed, while traveling one cm, and only 0.346 of a chance to be __________ in the same distance.

- - - - - - - - -

108. From this information it seems reasonable that boron should be used as an __________ in a control rod and (not, also) as a moderating material. 103, scattered

- - - - - - - - -

109. By thinking of Σ as the number of reactions per centimeter of travel by a neutron, we can multiply by the velocity--which is the number of centimeters traveled per second--and obtain the number of reactions per second per neutron. That is, absorber, not

$$\Sigma \times v = \frac{\text{reactions}}{\text{cm}\cdot\text{neutron}} \times \frac{\text{cm}}{\text{sec}} = \frac{\text{reactions}}{\text{sec}\cdot\text{neutron}}$$

- - - - - - - - -

110. If a neutron is traveling in a material with a speed of 300 cm/sec (actually a very slow speed for a neutron) in a material which has a scattering cross section Σ_s = 10 reactions/cm, the scattering reactions per sec will be:

$$\Sigma_s \times v = 10 \,\frac{\text{reactions}}{\text{cm}} \times 300 \,\frac{\text{cm}}{\text{sec}} = \_\_\_\_ \,\frac{\text{reactions}}{\text{sec}\cdot\text{n}}$$

- - - - - - - - -

111. $\Sigma \times v$ is the number of possible reactions per second for only one neutron. If we now multiply this by the number of free neutrons (n) we have per cubic centimeter (cm^3), we will obtain the total number of reactions per second in each cubic centimeter. That is, 3,000

$$\Sigma \times v \times n = \frac{\text{reactions}}{\text{sec}\cdot\text{neutron}} \times \frac{\text{neutrons}}{cm^3} = \frac{\text{reactions}}{\text{sec}\cdot cm^3}$$

\- - - - - - - - - -

112. The quantity $n \times v$, which is the neutron density times the velocity, is usually called the neutron flux and is represented by the symbol ϕ (pronounced fee). Thus, nv = __________.

\- - - - - - - - - -

113. Then ϕ, which is equal to $n \times v$ and is the symbol for __________ __________, may be thought of as the distance traveled in one second by all the neutrons in one cubic centimeter. Although the neutron flux is often expressed as $\phi = \frac{\text{neutrons}}{cm^2 \times \text{sec}}$, it can also be expressed as $\phi = \frac{\text{neutron centimeters/sec}}{cm^3}$. ϕ

\- - - - - - - - - -

114. If we had 300 neutrons in one cubic centimeter which were traveling with a velocity of 20 centimeters per second, then the neutron flux would be: neutron flux

$$\phi = n \times v = 300\ \frac{\text{neutrons}}{cm^3} \times 20\ \frac{cm}{\text{sec}} = \_\_\_\_\_\_\_\_\_\_$$

\- - - - - - - - - -

115. If Σ_f represents the macroscopic fission cross section, that is, the number of fission reactions per centimeter of neutron travel, and ϕ is the number of centimeters traveled in one second by the free neutrons in a cubic centimeter, then $\Sigma_f \times \phi$ is the number of fission reactions per second in one cubic centimeter of material. (Remember that neutrons can move rather freely through the spaces between atoms and can penetrate deeply into some solids before being absorbed in the nuclei of some of the atoms.)

$6000 \frac{\text{n cm/sec}}{\text{cm}^3}$
or
$6000 \frac{\text{n}}{\text{cm}^2 \cdot \text{sec}}$

- - - - - - - - -

116. Let us assume that Σ_f is 5 reactions/cm and the neutron flux, ϕ, is $10 \frac{\text{neutron centimeters/sec}}{\text{cm}^3}$, then in one second, the number of fission reactions per cubic centimeter is $\Sigma_f \times \phi$ which is

$$5 \frac{\text{reactions}}{\text{cm}} \times 10 \frac{\text{neutron centimeters/sec}}{\text{cm}^3} = 50 \frac{\text{reactions}}{\text{sec} \cdot \text{cm}^3}$$

- - - - - - - - -

117. Now we have found that in one cubic centimeter there are $50 \frac{\text{fissions}}{\text{second}}$ occurring. If we had a gallon bucket full of this material (a gallon is equal to 3785 cm^3), then in the bucket there would be, to three significant figures,

$$3785 \text{ cm}^3 \times 50 \frac{\text{fissions}}{\text{sec} \cdot \text{cm}^3} = \underline{\hspace{3cm}} \frac{\text{fissions}}{\text{sec}}.$$

- - - - - - - - -

118. This says that in a gallon bucket of material where Σ_f is 5 reactions/cm and ϕ is 10 $\frac{\text{neutron centimeters/sec}}{\text{cm}^3}$, there are 189,000 fissions occurring each second. To carry this one step further--if we knew the energy release per fission, then we could determine the power produced by that bucket of material. If the energy produced in that bucket could be converted to electrical energy, then we would know how many light bulbs we could light or how many cooling fans and air conditioners we could operate. 1.89×10^5

- - - - - - - - -

1.6. Neutron Spectrum

119. Before we leave the study of neutrons, we should mention the range of energies that we find among free neutrons. The energy of a free neutron is related to its velocity; and while we speak of a neutron as having a specific energy such as 0.5 ev or 4 Mev, we often do not assign an energy but speak of them as being slow or fast neutrons.

- - - - - - - - -

> In the above frame, we used the energy unit Mev. The unit is million electron volts. It is a small amount of energy when compared with the calorie and the footpound which are units of heat and mechanical energy. One electron volt (ev) is the amount of energy gained by one electron when it moves through an electric circuit powered by a one-volt battery. Even though one Mev is a million times one ev, it is a small amount of energy since it takes 2.6×10^{13} Mev to equal 1 calorie. However, 200 Mev
>
> (continued)

(the energy release when one atom fissions) is a tremendous amount of energy to be produced by one atom. In the ORR, 9.55×10^{17} atoms fission each second, and the total energy release is about seven million calories each second.

120. The term used to include all neutron energies, from the slowest to the fastest, is the neutron "spectrum."

- - - - - - - - -

121. The whole range of neutron energies, from very slow neutrons to very fast neutrons, is called the neutron __________.

- - - - - - - - -

122. Very generally speaking, the neutron spectrum can be divided into three very broad energy groups. The lowest neutron energy group found in reactors, that of the slow or thermal neutrons, has average energies from about 0.026 ev (at room temperature) to about 0.075 ev at 1100°F (a probable fuel temperature). These energies represent neutron velocities of from ∿2200 to ∿4000 meters/sec. — spectrum

- - - - - - - - -

123. A broader definition of slow neutrons includes those with energies below 1 ev.

- - - - - - - - -

124. Slow or thermal neutrons are often referred to as being at the low end or slow portion of the neutron __________. These neutrons have the __________ energies of all the neutrons in the reactor.

- - - - - - - - -

125. At the other end of the neutron spectrum is that group called the fast neutrons. This group includes those neutrons with the greatest velocities. — spectrum, lowest

\- - - - - - - - -

126. Fast neutrons have energies from about 0.1 Mev to about 10 Mev and speeds of about one-tenth the speed of light. — highest or greatest

\- - - - - - - - -

127. A 2-Mev neutron would be considered a __________ neutron.

\- - - - - - - - -

128. Neutrons produced by the fission of fuel atoms in a reactor will have energies between about 0.1 and 10 Mev and will move with speeds of about __________ the speed of light. — fast

\- - - - - - - - -

129. The third group of neutrons have energies in a range between the slow and fast neutrons. This <u>intermediate</u> neutron range includes neutrons with energies higher than 1.0 ev and lower than 0.1 Mev. For this reason they are often called __________-energy neutrons. — one-tenth

\- - - - - - - - -

130. In a reactor core, these are the neutrons that are losing energy in scattering collisions with the nuclei of atoms of moderator, coolant, structural materials, etc. When the energy of those neutrons becomes less than ____________, they are no longer considered intermediate-energy neutrons, having become __________ or thermal neutrons due to energy losses.

intermediate

- - - - - - - - -

131. Briefly, then, the neutron energy range from the slowest neutrons up through the group called intermediate-energy neutrons to the highest energy of the fast neutrons, is called the neutron energy __________.

1 ev,
slow

- - - - - - - - -

132. Generally, a graphic plot of the neutron spectrum indicates the relative number of neutrons in each energy range.

spectrum

- - - - - - - - -

1.7. Self Test

133. What is a neutron? (If you made an incorrect response, repeat frame 1.)

- - - - - - - - -

> A small uncharged particle about the size of a proton, about 2000 times heavier than an electron. It usually exists in the nuclei of atoms but may be obtained in the free state when released from some types of radioactive atoms.

- - - - - - - - -

134. Two neutron reactions of interest in reactor operation are __________ and __________. (If you made an incorrect response, repeat frame 4.)

- - - - - - - - -

135. A scattering reaction is one in which a neutron collides with an atom and then continues traveling usually in a __________ __________. The neutron will slow down quicker if the reaction is with a (large, small) atom. (If you made an incorrect response, repeat frames 5 through 19.)

scattering, absorption

- - - - - - - - -

136. An absorption reaction is one in which a neutron is __________. (If you made an incorrect response, repeat frame 24.)

different direction, small

- - - - - - - - -

137. Strong neutron absorbers are called __________. (If you made an incorrect response, repeat frames 27 and 28.)

absorbed into the nucleus of an atom

- - - - - - - - -

138. The equation $^{1}n + {}^{27}Al \longrightarrow {}^{28}Al + {}^{0}\gamma$ says ______________. poisons

- - - - - - - - -

A neutron is abosrbed by ^{27}Al which is transformed into ^{28}Al, an excited atom which loses energy immediately by emitting a gamma ray.

- - - - - - - - -

139. The term fission, according to the dictionary, means __________. (If you made an incorrect response, repeat frame 32.)

- - - - - - - - -

140. The main events which occur in a fission reaction are ____________. (If you made an incorrect response, repeat frame 36.) break into parts

- - - - - - - - -

Neutrons are absorbed by ^{235}U atoms, fission takes place, and 2 or 3 neutrons are released.

- - - - - - - - -

141. Neutrons are involved in fission reactions in two ways; they are __________ and __________. (If you made an incorrect response, repeat frame 37.)

- - - - - - - - -

142. Chain reactions are (fission, continuous) reactions. Since neutrons are released when fission occurs, a (fission, chain) reaction is possible. (If you made an incorrect response, repeat frame 39.) absorbed, released

- - - - - - - - -

143. Neutrons released from fission are (slow, fast, thermal) neutrons. (If you made an incorrect response, repeat frame 45.)

continuous, chain

- - - - - - - - - -

144. Fission of ^{235}U is more readily produced by (slow, fast) neutrons. (If you made an incorrect response, repeat frame 48.)

fast

- - - - - - - - - -

145. The process of slowing down fast neutrons is called __________. The materials used for this purpose are called __________. (If you made an incorrect response, repeat frame 51.)

slow

- - - - - - - - - -

146. A good moderator is one which slows neutrons quickly and does not readily __________ them. (If you made an incorrect response, repeat frame 52.)

moderating or moderation, moderators

- - - - - - - - - -

147. Thermalization is the process of __________ __________ neutrons until they are in __________ __________ with the material they are in. (If you made an incorrect response, repeat frames 55 through 61.)

absorb

- - - - - - - - - -

148. Prompt neutrons are __________. (If you made incorrect response, repeat frame 67.)

slowing down, thermal equilibrium

- - - - - - - - - -

Released instantaneously when fission occurs, and comprise 99.25% of the fission neutrons. They are fast neutrons.

- - - - - - - - - -

149. Delayed neutrons are __________. (If you made an incorrect response, repeat frame 70.)

- - - - - - - - -

Emitted over a period of minutes from the fission products and comprise 0.75% of the fission neutrons. They are fast neutrons.

- - - - - - - - -

150. The term fission products includes the decay products as well as the fission __________. (If you made an incorrect response, repeat frame 79.)

- - - - - - - - -

151. If the neutron multiplication factor, k, is greater than one, the population of neutrons will __________. If k is less than one, it will __________. (If you made an incorrect response, repeat frames 80 through 90.)

fragments

- - - - - - - - -

152. The neutron-absorbing ability of an atom is usually referred to as the microscopic absorption __________ __________, which is represented by the symbol __________. (If you made an incorrect response, repeat frames 91 through 93.)

increase, decrease

- - - - - - - - -

153. The whole absorption cross section of a cubic centimeter of a material is called the __________ __________ cross section and is represented by the symbol ______. (If you made an incorrect response, repeat frames 95 through 97.)

cross section, σ_a

- - - - - - - - -

154. Σ_f is the ________ ________ cross section. | macroscopic absorption, Σ_a
Σ_s is the ________ ________ cross section.
(If you made an incorrect response, repeat frames 97 through 102.)

- - - - - - - - -

155. The number of scattering reactions which a neutron will experience as it travels a distance of one centimeter is the ________ scattering cross section. (If you made an incorrect response, repeat frames 104 through 106.) | macroscopic fission, macroscopic scattering

- - - - - - - - -

156. The number of reactions per second caused by the neutrons in a cubic centimeter is (nv, $\Sigma\phi$). (If you made an incorrect response, repeat frames 109 through 111.) | macroscopic

- - - - - - - - -

157. The neutron flux is (Σn, nv) and is represented by the symbol _____. (If you made an incorrect response, repeat frame 112.) | $\Sigma\phi$

- - - - - - - - -

158. $\Sigma_f \times \phi$ is ________. (If you made an incorrect response, repeat frames 115 through 118.) | nv, ϕ

- - - - - - - - -

The number of fission reactions per second in one cubic centimeter of material.

- - - - - - - - -

SECTION III-2

NUCLEAR REACTORS

The purpose of this section is to discuss the factors which affect a continuous, self-sustaining fission chain reaction in a nuclear reactor.

2.1. Description of Reactor Components

1. What is a nuclear reactor? A nuclear reactor is an apparatus in which fission reactions can be started and then controlled as a continuous self-sustaining chain reaction.

- - - - - - - - - -

2. The principal parts of a reactor are the fuel, moderator, reflector, cooling system, and control system.

- - - - - - - - - -

3. Figure III-8 is a sketch of a vertical section through a very simplified reactor showing a possible grouping of the components.

- - - - - - - - - -

4. The fuel (fissionable material) and moderator (to slow down neutrons) were discussed in Section III-1. The reflector is a neutron-saving device.

- - - - - - - - - -

5. The reflector causes many neutrons that might be lost from the reactor core (the core is the region containing the fuel) to be returned to the core where they can cause fission. This is the reason for the above statement that the reflector is a ______________-______________ device.

- - - - - - - - - -

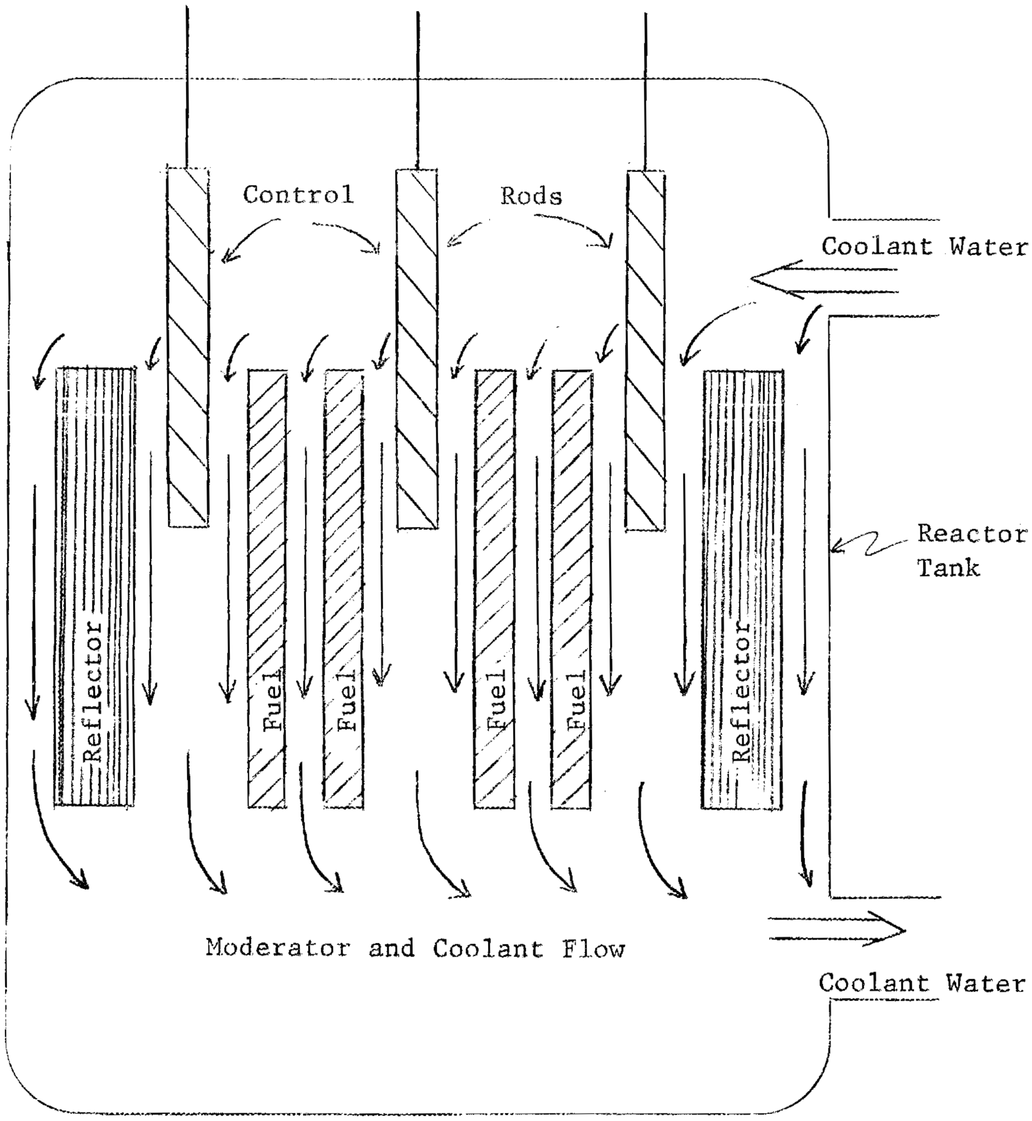

Fig. III-8. Simplified Sketch of Reactor Components in a Tank

- - - - - - - - - -

6. Neutrons produced near the outer edge of the core could travel away from the core and have no opportunity to produce fission. The reflector is placed around the core to scatter many of these neutrons back into the core where they can produce fission.

neutron-saving

- - - - - - - - - -

7. The actual "reflecting" process is more complex than Frame 6 would infer; however, the purpose of the reflector is to (increase, decrease) the number of neutrons lost from the core.

- - - - - - - - -

8. Neutrons which are most likely to be lost from the core are those produced near the edge of the core. These fast neutrons need not only to be returned to the core but also to be ___________ or slowed down. — decrease

- - - - - - - - -

9. A good reflector, then, is one which can act as a moderator as well as a reflector. Many of the elements with small nuclei, such as hydrogen, deuterium, helium, beryllium, and carbon, are good moderators as well as ________________. — thermalized

- - - - - - - - -

10. Also, water (H_2O) and heavy water (D_2O) are good reflectors and moderators because of the hydrogen and deuterium in their molecules. — reflectors

- - - - - - - - -

11. Since water is a good heat absorber as well as moderator, it is often used as both coolant and moderator.

- - - - - - - - -

12. Water as a coolant must flow over the fuel surface. Fast neutrons from fissions in the fuel pass from the fuel into the water and are ____________ by collisions with hydrogen atoms in the water. A neutron may have to pass through several of the thin layers of water and fuel before being slowed down enough to be classed as a thermal neutron.

- - - - - - - - -

13. The design of a reactor depends on many factors, one of which is the purpose of the reactor. Figure III-9 is a schematic representation of the core of the High Flux Isotope Reactor (HFIR). The fuel is ^{235}U; the moderator-coolant is light water (H_2O) which flows downward through the core; and the reflector is beryllium.

slowed down

- - - - - - - - -

14. In some reactors the fuel and moderator are homogeneous mixtures. In others, the fuel and moderator are separate. Some reactors are large; others are small. In some, the operating power level is high; in others, the power level is so low as to be insignificant.

- - - - - - - - -

The reactors operated at ORNL by the Reactor Operations Department are classified as research reactors. The purpose of these reactors is to produce neutrons (rather than power) for use in experimental research. In addition, some radioisotopes are produced for use in medicine, agriculture, etc.

- - - - - - - - -

15. The fuel used in reactors may be in liquid or solid form, but usually it is in the solid form. The shape of the solid fuel may be plates, pellets, rods, etc., which are usually assembled into units called "fuel elements".

- - - - - - - - -

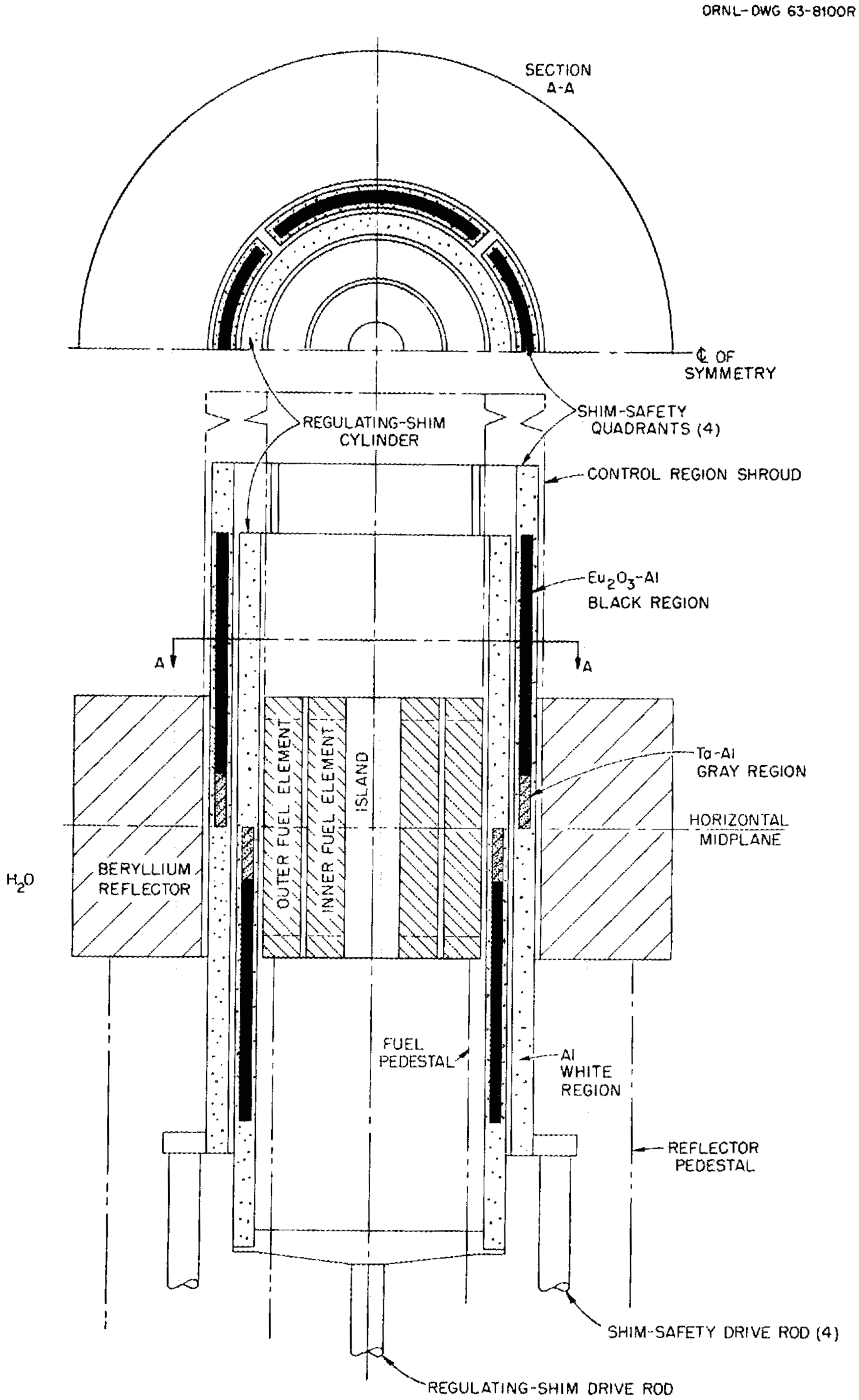

Fig. III-9 Schematic Representation of HFIR Core

16. Figure III-10 shows an ORR fuel element; Fig. III-11 shows an HFIR element. The ORR element contains 19 fuel plates placed as shown in Fig. III-12. The channels between the plates allow water to flow through to remove heat and, at the same time, to act as the neutron moderator.

- - - - - - - - - -

17. Only the fuel region in a reactor is called the core. The core may also contain moderator material, but it does not include the reflector.

- - - - - - - - - -

18. In Fig. III-8, the region inside the reflector which contains both fuel rods and moderator is called the

__________________.

- - - - - - - - - -

19. The core of a reactor may contain 2, 10, 100, or any number of fuel elements. The core of the ORR, for example, usually contains 25 to 30 fuel elements surrounded by several beryllium reflector elements. Figure III-13 illustrates a loading of fuel and beryllium reflector elements which has been used in the ORR.

core

- - - - - - - - - -

20. As noted in Frame 16, Fig. III-11 is an illustration of the HFIR core which consists of fuel plates of a different design from those of the ORR. This is actually two elements--an inner and outer element. These two elements and the moderator between the plates compromise the __________ of the HFIR reactor.

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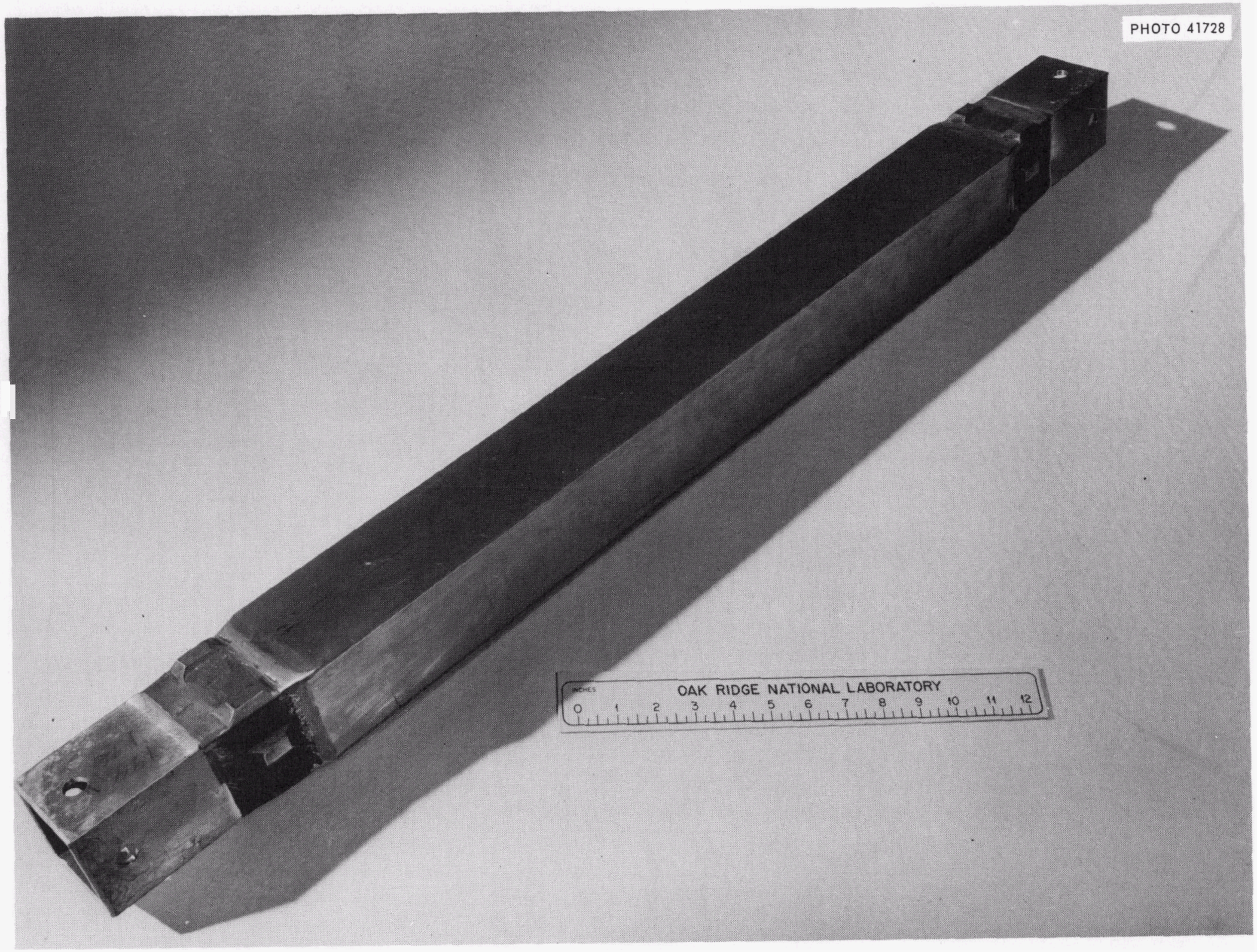

Fig. III-10. ORR Fuel Element

ORNL-LR-DWG 61472AR3

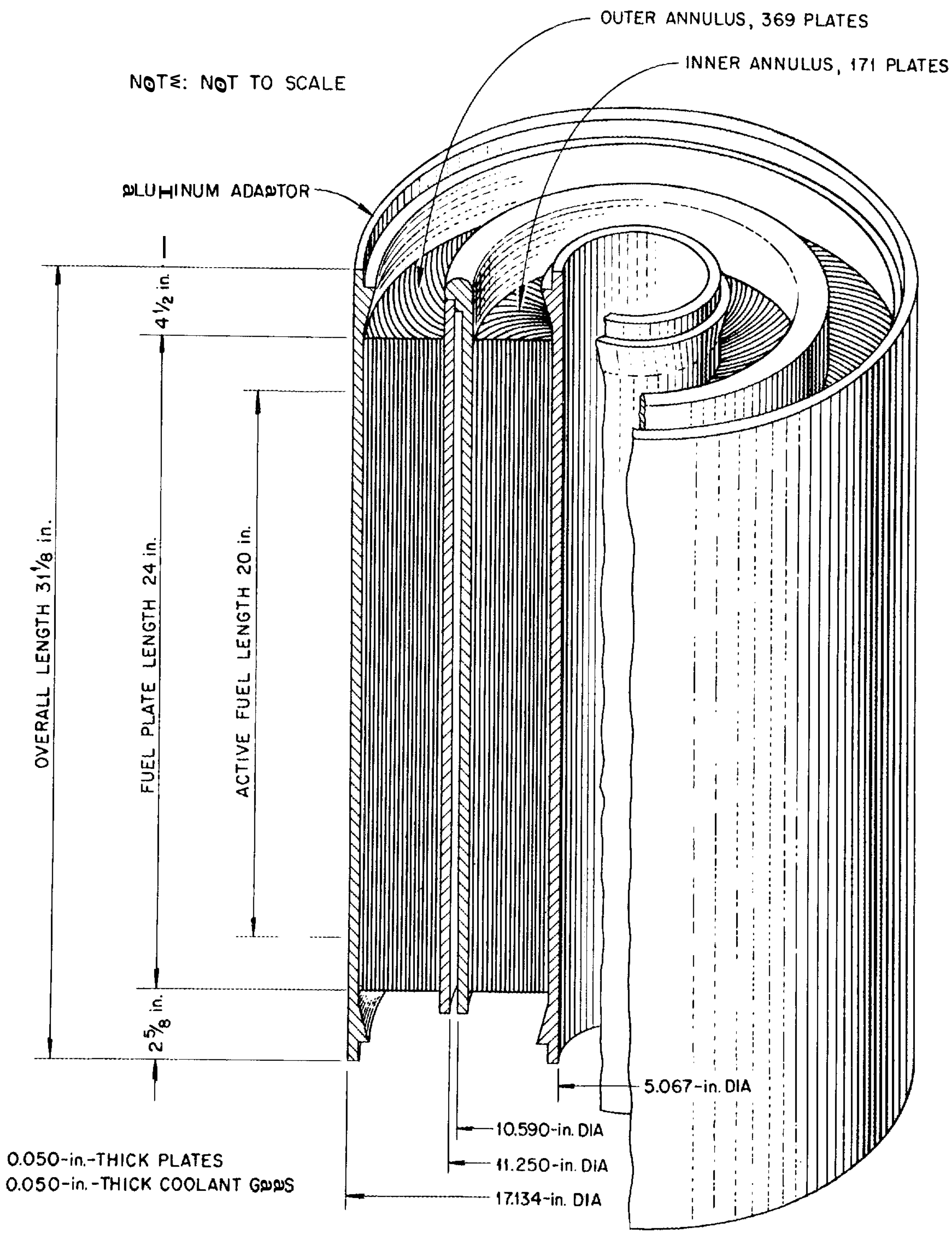

Fig. III-11. HFIR Core

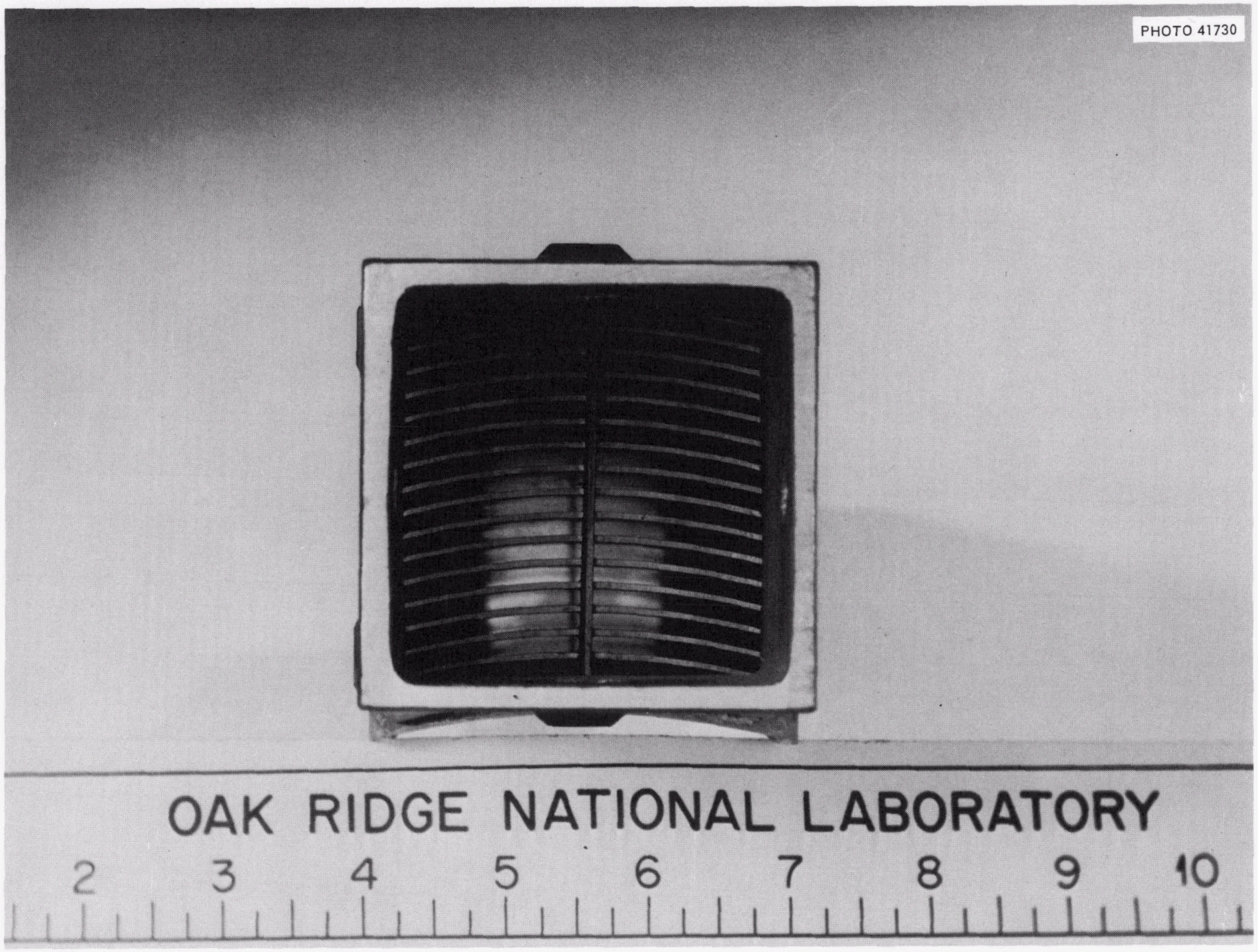

Fig. III-12. ORR Fuel Element - End View

ORNL DWG. 68-4395

POOL

W

S — N

A-1 E	A-2 E	A-3 I	A-4 190.13	A-5 201.19	A-6 182.17	A-7 I	A-8 Be	A-9 Be
B-1 E	B-2 Be	B-3 201.74	B-4 CR 74.29	B-5 184.03	B-6 CR 83.93	B-7 201.97	B-8 E	B-9 Be
C-1 E	C-2 Be	C-3 154.83	C-4 150.92	C-5 157.49	C-6 157.39	C-7 151.67	C-8 174.34	C-9 Be
D-1 131.80	D-2 201.23	D-3 176.37	D-4 CR 114.21	D-5 157.40	D-6 CR 115.12	D-7 158.03	D-8 I	D-9 Be
E-1 195.93	E-2 187.20	E-3 201.35	E-4 185.16	E-5 201.07	E-6 188.50	E-7 201.21	E-8 137.17	E-9 Be
F-1 Be	F-2 Be	F-3 Be	F-4 CR-Al	F-5 Be	F-6 CR-Al	F-7 Be	F-8 I	F-9 E
G-1 Be	G-2 Be	G-3 Be	G-4 Be	G-5 Be	G-6 Be	G-7 Be	G-8 Be	G-9 Be

E

Be-------Beryllium Reflector Element

CR--------Control Rod of Part Cadmium, Part Fuel

E---------Experiment Rig

CR-Al----Control Rod of Part Cadmium, Part Aluminum

I---------Radioisotope Production Facility

Total Mass = 4867.85 grams of ^{235}U

Control-Rod Positions at Critical = 17.25 inches

Fig. III-13. ORR Core Configuration at Startup of Cycle 55-D

21. The moderator in a reactor is that material which causes fast neutrons produced by fission to be ____________ ____________ by scattering reactions. — core

- - - - - - - - -

22. Water, which contains hydrogen nuclei (about the same size as neutrons), is a very common (fuel, moderator). — slowed down

- - - - - - - - -

23. In the system shown in Fig. III-8, water is used as both moderator and coolant. It is a good moderator because it contains ______________. — moderator

- - - - - - - - -

24. Hydrogen nuclei in the water absorb energy from neutrons which ____________ with them and thereby cause the neutrons to _________ speed. — hydrogen

- - - - - - - - -

25. When the core of a reactor is not large, it is possible for many neutrons to be lost from the core by "leaking out" and not be available to be absorbed by fuel atoms and cause ______________. — collide, lose

- - - - - - - - -

26. If the core is surrounded by a material which will cause neutrons to bounce back into the core, they will again be available to cause fission. — fission

- - - - - - - - -

27. A good moderating material surrounding the core will cause the "leakage" neutrons to have scattering collisions which will cause many of them to bounce back into the core. Such a surrounding blanket of moderating or scattering material is called a neutron

________________________.

\- - - - - - - - -

28. Although water can be used as a neutron reflector, beryllium is used wherever possible because it is almost as good as water for slowing down neutrons and does not absorb as many neutrons as water does. The thermal neutron microscopic absorption cross section of hydrogen is 33 times larger than that of beryllium.

reflector

\- - - - - - - - -

29. When either fast or slow neutrons escape from the core, they can have ______________ reactions with the reflector atoms and return to the fuel region. Thus, a reflector scatters neutrons back into the _____________.

\- - - - - - - - -

30. When fission occurs, the fission fragments fly apart and collide with the surrounding matter in the core. The collisions of the fragments with the core material generates heat. This heat is removed by the

________________________.

scattering, core or fuel region

\- - - - - - - - -

31. Water is probably the most common coolant material. Therefore, water may serve three purposes in a nuclear reactor: __________, _________________,

__________________.

coolant or cooling system

\- - - - - - - - -

32. The higher the power level of a reactor, the more heat a cooling system will have to remove. If heat is not removed fast enough, the fuel elements in a reactor can melt, resulting in a prolonged shutdown of the reactor.

coolant, moderator, reflector

- - - - - - - - - -

33. So, the power level at which a reactor can operate is limited by the rate at which __________ can be removed by the __________ __________.

- - - - - - - - - -

34. Control of the operating power level of a reactor is achieved by regulating the neutron population (or flux). Generally, a large neutron flux indicates a high power level and a small flux, a low power level.

heat, cooling system

- - - - - - - - - -

35. Control of the neutron flux (or power level) may be achieved by using neutron absorbing materials, materials which have a high σ_a for neutrons. The symbol σ_a means __________ __________ __________.

- - - - - - - - - -

36. If a poison material (a strong, nonfissioning absorber of neutrons) is inserted into the reactor, neutrons will be absorbed and thus the neutron population will decrease. There will be fewer neutrons for causing fission, and the power level will __________.

absorption cross section

- - - - - - - - - -

37. If the poison material is removed from the reactor, fewer neutrons will be absorbed, more will be available to cause __________, and the power level will __________.

decrease

- - - - - - - - - -

38. Poison materials are usually inserted into or removed from a reactor by means of movable rods called control rods. — fission, increase

- - - - - - - - -

39. Adjustment of control rods in a reactor either inserts or removes poison, thus changing the neutron loss rate, which results in a change in the multiplication factor, k.

- - - - - - - - -

> You should recall that the neutron multiplication factor, k, is the ratio of the neutron production rate to the neutron loss rate.

- - - - - - - - -

40. When a control rod (poison) is inserted into the reactor, neutrons are absorbed and k (decreases, increases, remains the same).

- - - - - - - - -

41. When a control rod is withdrawn, there is less poison in the reactor; consequently, fewer neutrons are absorbed and k ________________. — decreases

- - - - - - - - -

42. When enough poison is removed so that k is <u>one</u>, the neutron flux will become steady at a constant level and remain at that level even when the neutron source used during startup is removed. — increases

- - - - - - - - -

43. When conditions in a reactor are established so that k is equal to one and the neutron flux is steady, then a continuous, steady-state fission chain reaction occurs. When this condition exists, the reactor is said to be just critical.

- - - - - - - - -

2.2. Reactivity and Criticality

44. Criticality exists when k is equal to ____________.

- - - - - - - - -

45. When conditions in a reactor are such that a steady self-supporting fission chain reaction occurs, the reactor is said to be ____________. one

- - - - - - - - -

46. Criticality is the condition such that ____________. critical

- - - - - - - - -

> k = 1, or a continuous steady-state fission chain reaction occurs.

- - - - - - - - -

47. In order for appreciable power to be produced in a reactor, a neutron multiplication factor slightly greater than one must be possible. By raising or lowering the value of k or holding its value constant at one, the power level in a reactor is raised, lowered, or held constant.

- - - - - - - - -

48. If k is less than one, the power level of a reactor will decrease until the reactor is completely shut down. If k is greater than one, the power level will increase. By adjusting the control rods, k can be made equal to ________ so that a constant power level is maintained.

- - - - - - - - -

49. Let us take a minute here and imagine that we can build a reactor so big that it is impossible to determine where it starts or ends. We would say that this reactor is infinitely big. (Obviously, this is an imaginary reactor.) one

- - - - - - - - -

50. An infinitely large reactor core would not have any sides because it would take up all of space. The point is that neutrons could not escape from an infinite reactor core because there are no sides from which they can escape.

- - - - - - - - -

51. In a small reactor, neutrons are lost when they are absorbed (by poison and other materials), and some are lost when they ______________ from the core.

- - - - - - - - -

52. In an infinite reactor core, neutrons would be lost only by ______________ reactions. escape or leak

- - - - - - - - -

53. Neutrons which are lost by escaping from the core are called "leakage" neutrons because, in a manner of speaking, they do ________ out from the sides of the core. absorption

- - - - - - - - -

54. An infinite reactor (does, does not) have leakage neutrons. leak

- - - - - - - - -

55. In a reactor, whether small or infinite, neutrons are lost by absorption reactions. These neutrons may be absorbed by the poison in the control rod, by the coolant, moderator, structural material, and fuel. Some small, real reactors lose neutrons by _______________ reactions and by __________; in an infinite reactor, neutrons can be lost only be ______________________. does not

- - - - - - - - -

56. In both the infinite and real reactors, neutrons are produced from ____________ reactions. In both types of reactors, neutrons are lost by _________________ reactions. Loss of neutrons by leakage occurs only in ________________ reactors. absorption, leakage, absorption

- - - - - - - - -

57. As you have learned already, the neutron multiplication factor, k, in any type of reactor may be defined as the ratio of the neutron production rate to the neutron loss rate; that is, in equation form: fission, absorption, real or small

$$k = \frac{\text{neutron production rate}}{\text{neutron loss rate}}$$

- - - - - - - - -

58. To identify k for an infinite reactor, k is usually written k_∞, where ∞ is the symbol for infinity. k_∞ is pronounced "k infinity". The k for an actual reactor is written as k_{eff}, where "eff" is an abbreviation for effective. k_{eff} is pronounced "k effective".

- - - - - - - - -

59. Since there is no neutron leakage from an infinite reactor, k_∞ may be written as:

$$k_\infty = \frac{\text{neutron production rate}}{\text{neutron absorption rate}}$$

where "neutron absorption rate" has been substituted for "neutron ______________ rate".

- - - - - - - - -

60. An infinite reactor will be critical when $k_\infty = 1$; that is, when the neutron production rate is ______________ to the neutron absorption rate. loss

- - - - - - - - -

61. In a real reactor, there is neutron leakage so k_{eff} may be written as: equal

$$k_{eff} = \frac{\text{neutron production rate}}{\text{absorption rate + leakage rate}}$$

- - - - - - - - -

62. A real reactor will be critical when $k_{eff} = 1$; that is, when ____________________.

- - - - - - - - -

The neutron production rate is equal to the absorption rate plus the leakage rate.

- - - - - - - - -

63. The infinite multiplication factor, k_∞, is a property of an imaginary reactor; whereas k_{eff} is the property of a reactor which can be built. They are related to each other as shown by the equation: $k_{eff} = k_\infty P$. P is called the "nonleakage probability" because it is the probability that neutrons will not leak out of a reactor.

- - - - - - - - -

64. Probability should not be hard to understand. Any time you make a bet such as on the weather or at cards, there is a probability that you will lose your bet. If nine chances out of ten you win, then we could say that the probability of your winning is 9/10 or 0.9. Another way of saying the same thing is "the probability of <u>not</u> losing is 0.9"; that is, the <u>non</u>losing probability is ________.

\- - - - - - - - -

65. Let us suppose that there are ten neutrons in a reactor and two neutrons are lost by leakage. By dividing the number which did <u>not</u> leak out by the total number of neutrons, we can obtain the <u>non</u>leakage probability. In this case, it is: 0.9

$$P = \frac{8}{10} = 0.8.$$

\- - - - - - - - -

66. Now, if the nonleakage probability (P) is 0.8 and we have 50 neutrons in a reactor core, how many neutrons will probably <u>not</u> leak out? (4, 13, 40, 48)

\- - - - - - - - -

67. The value of P for a real reactor is always less than one; however, for an infinite reactor, the value of P would be equal to ________. 40

\- - - - - - - - -

68. The value of P for a real reactor can be calculated if both the size and shape of the reactor core are known. one

\- - - - - - - - -

69. The multiplication factor, k_∞, for an infinite reactor can be calculated if we know the type of fuel and moderator and the manner in which they are put together.

- - - - - - - - - -

70. The value of k_∞ does not depend upon the size of the core, but P does; and, since $k_{eff} = k_\infty P$, the value of k_{eff} (does not depend, depends) on the size of the core.

- - - - - - - - - -

71. If we have a very small container of fuel and moderator, we can calculate the value of k_∞ by imagining an infinite reactor composed of this fuel and moderator arranged as in the small container. If the value of k_∞ is greater than one, it would indicate that criticality could be achieved in an actual reactor made of this material. depends

- - - - - - - - - -

72. The size of the container would then be used to calculate P. P will be less than one because only for an infinite reactor can P be ____________. For smaller reactors, the value of P decreases. Now if it turns out that $k_\infty \times P$ is less than one, then criticality in this container (will, will not) be possible even though k_∞ might be greater than one.

- - - - - - - - - -

73. It should be apparent that criticality cannot be achieved in a reactor merely by having fuel and moderator arranged in a particular way. There must also be enough of this material so that ____________ is equal to one. equal to one, will not

- - - - - - - - - -

2.3. The Four-Factor Formula

k_{eff} or $k_{\infty} \times P$

74. Before we consider the calculation of k, let us review the fission process. Neutrons (mostly slow ones) are absorbed by ^{235}U atoms which are transformed into ^{236}U. About 85% of these ^{236}U atoms fission releasing an average of about 2.5 fast neutrons per fission. These fast neutrons experience scattering reactions and slow down until they are lost by leakage or are absorbed by poison materials, fuel, etc. When they are absorbed by the fuel, more fission reactions occur and the process is repeated.

- - - - - - - - - -

75. Let us assume that a certain number of fast neutrons, which we shall represent by n, have just been released by fissions caused by thermal neutrons. This n may be any number you choose--1, 100, etc. But rather than give you a specific example, just let n represent any number.

- - - - - - - - - -

76. These n fast fission neutrons need to be slowed down to thermal energies so that the ^{235}U can absorb them more easily and cause additional fissions. However, it is possible that while they are still fast, they may cause some ^{235}U to fission and even some ^{238}U. This will (increase, decrease, not change) the number of fast fission neutrons which are being slowed down.

- - - - - - - - - -

77. The increase in the total number of fast neutrons, as a result of fissions caused by fast neutrons, is known as the "fast fission effect". increase

- - - - - - - - - -

84. The fast neutrons, $n \times \varepsilon$, are then slowed down by scattering reactions with the moderator. However, not all of them make it down to the thermal energy level. During the slowing down process, some are also absorbed in nonfission reactions. more, ε

- - - - - - - - -

85. Of the $n \times \varepsilon$ fast neutrons that are slowing down, some are absorbed in the moderator, coolant, reflector, structural components, etc. All of these reactions are called ______________ reactions.

- - - - - - - - -

86. That fraction of the fast neutrons which escape absorption while slowing down and make it down to thermal energies is represented by the symbol p, called the "resonance escape probability" and is the ratio of neutrons which become thermal to the total number of fast neutrons. nonfission

$$p = \frac{n_{th}}{n \times \varepsilon}$$

- - - - - - - - -

87. If we have ten fast-fission neutrons ($n \times \varepsilon = 10$) available for slowing down and one is absorbed while slowing down so that nine escape absorption, the resonance escape probability, p, is _________.

- - - - - - - - -

88. Looking at it in a different way, if the resonance escape probability is 0.8, the chances are that eight out of ten neutrons will escape absorption while slowing down. 9/10 or 0.9

- - - - - - - - -

78. The fast fission effect results in an increase in the number of __________ neutrons as a result of ____________ caused by __________ neutrons.

- - - - - - - - -

79. The fast fission effect is represented by the symbol ε (epsilon), which is called the fast-fission factor.

fast, fission, fast

- - - - - - - - -

80. The fast-fission factor, ε, is defined as the ratio of the total number of fast neutrons produced by fissions caused by neutrons of all energies (fast and thermal) to the number resulting from fissions caused only by thermal neutrons.

$$\varepsilon = \frac{\text{fast neutrons produced by both fast and thermal neutrons}}{\text{fast neutrons produced by thermal neutrons only}}$$

- - - - - - - - -

81. The fast fission factor, _____, is always greater than one.

- - - - - - - - -

82. For a reactor which uses natural uranium (99.3% ^{238}U and 0.7% ^{235}U), ε is about 1.03. Therefore, if n in this reactor is 100 neutrons, the fast fission effect will increase the number of fast fission neutrons per generation to $100 \times 1.03 = 103$; that is, $n \times \varepsilon$.

epsilon or ε

- - - - - - - - -

83. Due to the fast fission effect, there will always be (more, less, the same) fast neutrons being slowed down than are produced by fissions resulting from thermal neutrons. The number will be the product of $n \times$ _____.

- - - - - - - - -

89. We can say that, out of $n \times \varepsilon$ fast neutrons, $n \times \varepsilon \times p$ neutrons will become thermal neutrons. If p is 0.9 and $n \times \varepsilon$ is 20, ________ neutrons will escape resonance absorption.

- - - - - - - - -

18, because $n \times \varepsilon \times p$ is $20 \times 0.9 = 18$

- - - - - - - - -

90. The reason the term "resonance" was used here can be understood by considering what actually happens during the slowing down process. Generally, as the neutron slows down, the absorption cross section (absorbing ability) of most materials increases smoothly as shown in Fig. III-14.

- - - - - - - - -

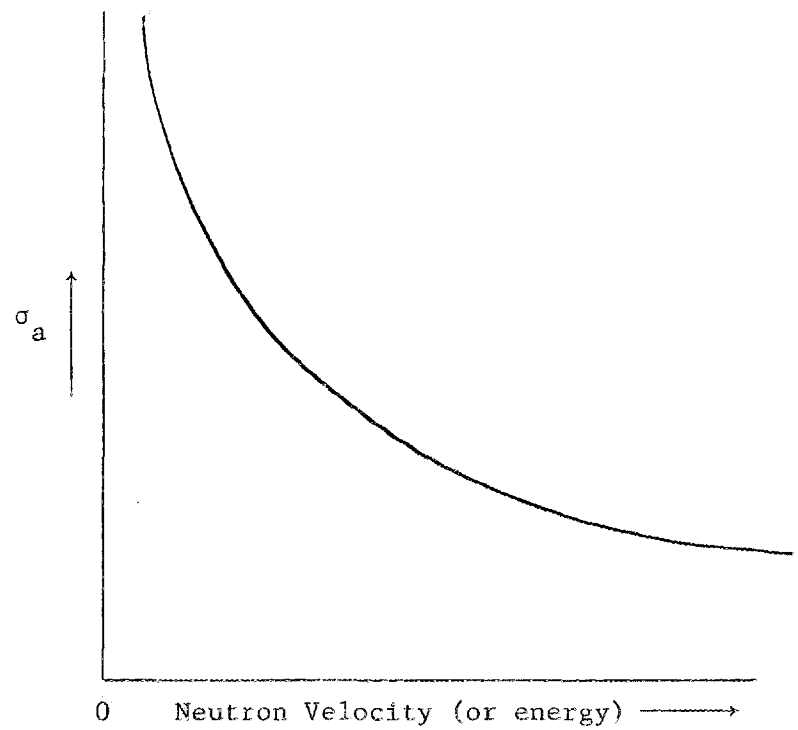

Fig. III-14. Neutron Cross Section

- - - - - - - - -

91. It has been found that at certain neutron velocities, the absorption is very much greater in some materials than at other velocities, both higher and lower, so that the cross section actually varies as shown in Fig. III-15.

\- - - - - - - - - -

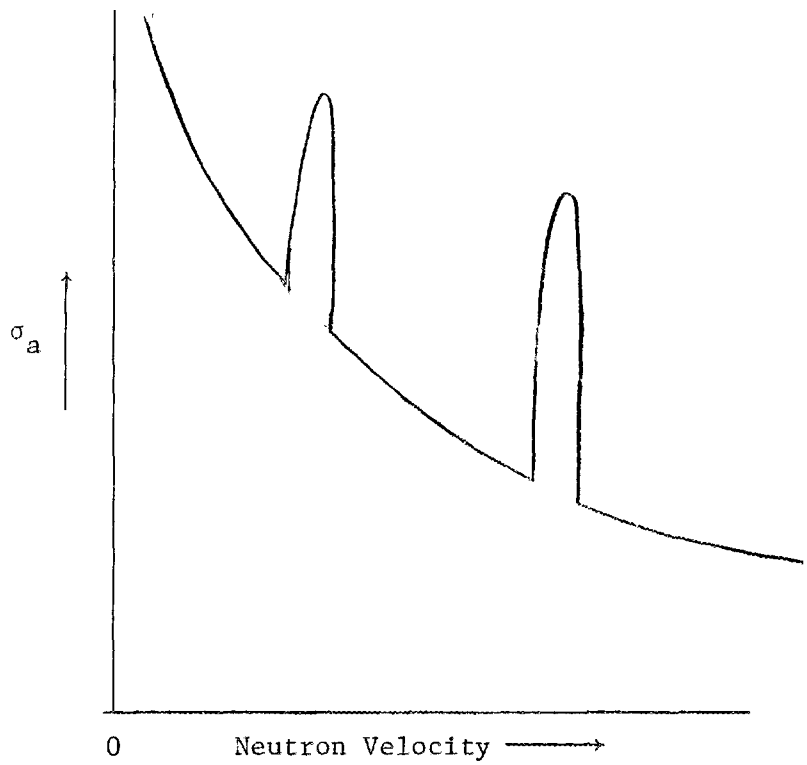

Fig. III-15. Neutron Cross Section

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92. As the neutron slows down and at some stage acquires the velocity which coincides with that of a resonance absorption peak for the material it is in, the neutron is very likely to be ________________.

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93. You might think of a neutron slowing down in a material which has resonance absorption peaks as a marble rolling down an inclined plank which has holes of various sizes in it. If the marble rolls down the plank smoothly, it will most likely fall into one of the holes. But if the marble is bounced down the plank, it is more likely to reach the bottom because it will bounce over some of the holes. This is similar to the reactions of neutrons. If the neutrons are scattered by heavy nuclei, such as uranium, each energy loss is small and they slow down slowly and smoothly; but if they are scattered by light nuclei, such as hydrogen, they slow down quickly and in large jumps. Figure III-16 illustrates this process. absorbed

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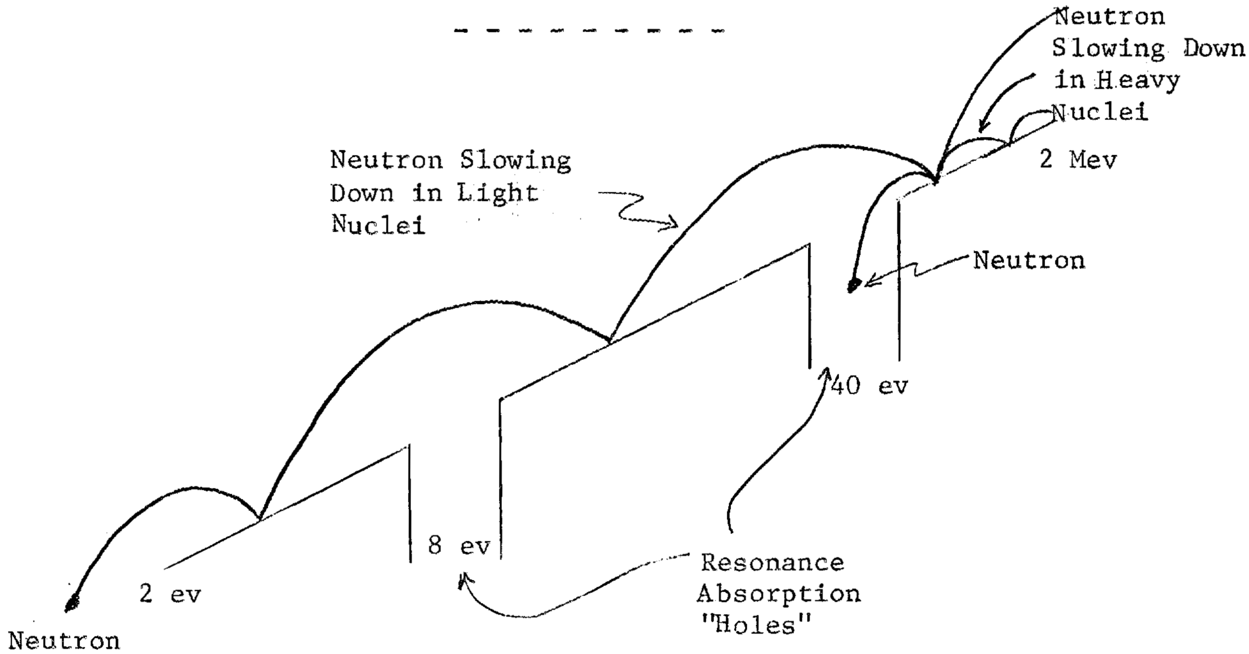

Fig. III-16. Resonance Absorption Illustration

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94. The resonance escape probability, then, is the probability that neutrons, while slowing down to thermal energies, will not be ______________ as a result of the resonance peaks which occur in the absorption cross section.

- - - - - - - - -

95. Assuming we have 20 fast neutrons and 15 of these are slowed down to thermal energies, the resonance escape probability, p, is ______________. absorbed

- - - - - - - - -

96. If $n \times \varepsilon$ is 100 fast neutrons and the resonance escape probability is 0.9, then we could expect __________ neutrons; that is, $n \times \varepsilon \times p$ (or $n\varepsilon p$), to slow down to thermal energies. $\frac{15}{20} = 0.75$

- - - - - - - - -

97. To review, the original n neutrons resulting from fission caused by thermal neutrons became $n\varepsilon$ neutrons due to the fast-fission effect. Of these, $n\varepsilon p$ neutrons escaped resonance absorption and were slowed down to thermal energies. Therefore, we now have $n\varepsilon p$ slow neutrons which are available for absorption by the fuel to cause more ______________ reactions. 90

- - - - - - - - -

98. All of the $n\varepsilon p$ neutrons are not absorbed by the fuel, however. Some are absorbed in nonfission processes by the moderator, structural materials, etc. fission

- - - - - - - - -

99. The fraction of slow neutrons which is absorbed in the fuel is represented by the symbol, f, called the "thermal utilization factor".

- - - - - - - - -

100. The thermal utilization factor, f, is a measure of the number of neutrons absorbed in the __________. This factor, f, is defined as the ratio of the number of thermal neutrons absorbed in the fuel to the total number of thermal neutrons absorbed in all of the materials. In equation form, that is:

$$f = \frac{\text{number of thermal neutrons absorbed in fuel}}{\text{number of thermal neutrons absorbed in fuel and all other materials}}$$

- - - - - - - - -

101. Suppose nεp is 10 neutrons. If six are absorbed by the fuel and the other four are absorbed by other materials, then the thermal utilization factor, f, would be __________. fuel

- - - - - - - - -

102. If nεp is 20 thermal neutrons and the thermal utilization factor is 0.9, then the total number of neutrons absorbed in the fuel is __________. $\frac{6}{6 + 4} = 0.6$

- - - - - - - - -

$(n\varepsilon p) \times f = 20 \times 0.9 = 18$

- - - - - - - - -

103. By multiplying nεp times f we obtain the number of thermal neutrons which are __________.

- - - - - - - - -

104. We can also say that nεpf is the number of fuel atoms which have absorbed neutrons and could possibly fission. Actually, however, only about 85% of these atoms undergo fission. absorbed by the fuel

- - - - - - - - -

105. The ratio of the fuel macroscopic fission cross section to the fuel macroscopic absorption cross section, $\frac{\Sigma_f}{\Sigma_a}$, is the fraction of the fuel atoms which will undergo fission. For ^{235}U, this fraction is about 0.85 or 85%.

\- - - - - - - - -

106. The expression $\frac{\Sigma_f}{\Sigma_a} = 0.85$ means that, if 100 neutrons are absorbed by fuel atoms, ___________ of these fuel atoms will undergo fission.

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85, because 100 × 0.85 = 85

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107. Since an average of 2.5 neutrons is released for each fission reaction and since $\frac{\Sigma_f}{\Sigma_a}$ may be considered as the ratio of neutrons causing fission to the total neutrons absorbed, we can multiply $2.5 \times \frac{\Sigma_f}{\Sigma_a}$ and obtain the average number of neutrons released for each neutron absorbed in the fuel. For ^{235}U this value is about $2.5 \times 0.85 = 2.1$.

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108. The average number of neutrons released from fission per neutron absorbed in the fuel, $2.5 \times \frac{\Sigma_f}{\Sigma_a}$, is usually represented by the symbol η (pronounced eta). For ^{235}U, $\eta = 2.5 \times$ _________.

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109. η is the average number of neutrons released from fission for each neutron absorbed in the __________. $\frac{\Sigma_f}{\Sigma_a}$ or 0.85

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110. Since $n\epsilon pf$ is the number of thermal neutrons absorbed by the fuel atoms and η is the average number of fast neutrons released per thermal neutron absorbed in the fuel, $n\epsilon pf\eta$ is the total number of "new" fast neutrons which are released. That is, $n\epsilon pf\eta$ is the number of fast neutrons released as a result of the ____________________ reactions caused by the $n\epsilon pf$ neutrons. — fuel

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111. Let us suppose that $n\epsilon pf$ is 50 neutrons which are absorbed in the fuel. If eta, η, is 2.1, then the new generation of fission neutrons will have __________ fast neutrons. — fission

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105, because $n\epsilon pf\eta$ is 50×2.1

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112. In the past few frames we have studied four factors that determine what happens to neutrons from one generation of fast neutrons to the next. While they are still fresh in your mind, let us use the next few frames for review.

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113. The symbol for the fast-fission factor is _____.

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114. The fast-fission factor (increases, decreases) the number of fast neutrons that need to be thermalized. — ϵ

\- - - - - - - - -

115. Due to the possibility that a neutron will be absorbed before reaching thermal velocity, we have a resonance escape probability (the symbol is ________) which is a measure of the number of neutrons not absorbed at ______________ velocities. — increases

- - - - - - - - -

116. The neutrons that escape resonance absorption and continue to slow down are __________ neutrons. — p, resonance

- - - - - - - - -

117. All thermal neutrons are not absorbed by the fuel. Some are absorbed by ________________. — thermal

- - - - - - - - -

118. The fraction of all thermal neutrons that is absorbed in the fuel is represented by the symbol ________, called the thermal ____________ factor. — moderator or structural members

- - - - - - - - -

119. If there are 500 thermal neutrons in a reactor and 450 are absorbed in the fuel, f is equal to _________. — f, utilization

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120. So far we have adjusted the number of fast neutrons, n, in the generation that we started with by ______________, ε, __________________, p, and the resulting thermal neutrons by ___________, f. — 0.9

- - - - - - - - -

121. All of the neutrons absorbed by the fuel (do, do not) cause fission.

fast fission factor, resonance escape probability, thermal utilization factor

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122. The next symbol we are interested in is η, which is the factor that determines the number of ________ neutrons in the next generation.

do not

\- - - - - - - - -

123. Figure III-17 summarizes the reactions involved in the life cycle of n fission neutrons. Note that we start with n fast neutrons and wind up with $n\varepsilon pf\eta$ neutrons as the start of the next neutron generation.

fast

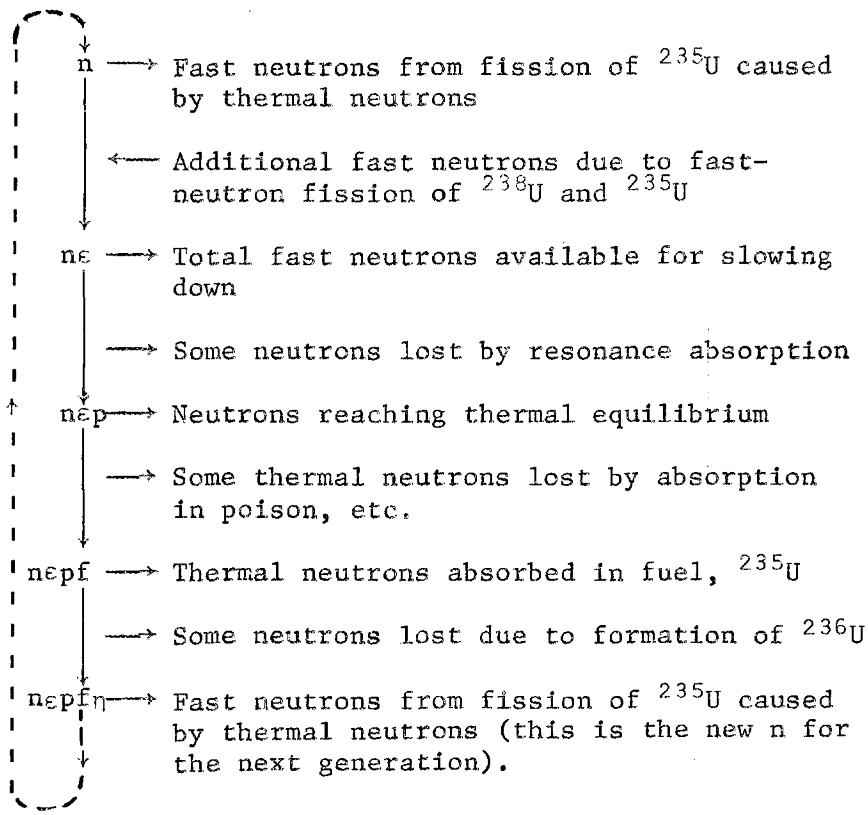

Fig. III-17. Neutron Life Cycle

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124. During this life cycle of the n neutrons, all of the n neutrons were lost and $n\varepsilon pf\eta$ neutrons were produced. Since the multiplication factor k has been defined as the production rate divided by the loss rate, k will be equal to ________________.

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$$k = \frac{n\varepsilon pf\eta}{n} = \varepsilon pf\eta$$

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125. The multiplication factor k, then, is k = ________, which is known as the "four-factor formula".

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126. Nothing in the four-factor formula has considered neutron leakage from the reactor; and, since it has not yet been considered, $\varepsilon pf\eta$ must be equal to (k_∞, k_{eff}). $\varepsilon pf\eta$

- - - - - - - - - -

127. The four-factor formula for k_∞ can be used to determine whether or not reactor criticality is possible from a materials consideration only. If calculations show that k_∞ is less than one, then criticality (will, will not) be possible for the materials used in the reactor. k_∞

- - - - - - - - - -

128. The materials of a reactor and sometimes their arrangement will determine the value of ε, p, f, and η, and consequently, k_∞. The value of k_∞ for any geometrical arrangement of natural uranium and water is less than one, so it would be a waste of time to build this kind of reactor. will not

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129. It is possible to take some natural uranium which contains 99.3% ^{238}U and 0.7% ^{235}U and, by a separation process, increase the amount of ^{235}U to almost any enrichment. In the ORR and HFIR reactors, the fuel is 7% ^{238}U and 93% ^{235}U. Water is used as the neutron moderator.

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130. For a real reactor, the effective multiplication factor, k_{eff}, which equals $k_\infty P$ (P is the nonleakage probability), must be equal to one in order for ______________ to be achieved.

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131. Criticality is not necessarily guaranteed if k_∞ is greater than one, but it does indicate the possibility. Any real reactor which is built will have some neutron leakage. So criticality for an actual reactor requires that __________ be equal to one. criticality

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132. If we have a reactor in which P is equal to 0.9, then for criticality to be possible, k_∞ would have to be ________________. k_{eff} or $k_\infty \times P$

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1.11 because k_{eff} must equal at least one, and since $k_{eff} = k_\infty P = k_\infty 0.9 = 1$

$$k_\infty = 1/0.9 = 1.11$$

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133. Actually, both thermal neutrons and fast neutrons leak out of a reactor, so P should be broken down so that we have: $P_{nlth} \times P_{nlf} = P$; where P_{nlth} is the probability that the thermal neutrons will not leak out and P_{nlf} is the ________________.

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Probability that fast neutrons will not leak out.

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134. We should now write $k_{eff} = k_{\infty} P_{nlth} P_{nlf}$ for the real reactor. Since $k_{\infty} = \epsilon p f \eta$, we can also write k_{eff} = ______________.

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$\epsilon p f \eta P_{nlth} P_{nlf}$

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135. So, the all-inclusive equation for k_{eff} is:

$$k_{eff} = \epsilon p f \eta P_{nlth} P_{nlf}$$

The factors for k_{eff} are summarized in Table III-2.

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Table III-2. k_{eff} Factors

Symbol	Name	
ϵ (epsilon)	Fast-fission	Ratio of the total number of fast neutrons due to fissions caused by neutrons of all energies to the number caused by thermal neutrons only.
p	Resonance escape probability	Fraction of neutrons which are not absorbed before becoming thermalized.
f	Thermal utilization factor	The ratio of the number of thermal neutrons absorbed only in the fuel to the total number of thermal neutrons absorbed in the whole core.
η (eta)		The number of fast neutrons from fissions caused by thermal neutrons per thermal neutron absorbed in the fuel.

(continued)

Table III-2. k_{eff} Factors (continued)

Symbol	Name	
P_{nlf}	Fast nonleakage	The probability that fast neutrons will not leak out of a core.
P_{nlth}	Thermal nonleakage	The probability that thermal neutrons will not leak out of a core.

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136. Criticality in a real reactor occurs when (k_{eff}, k_∞) is equal to one.

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137. Not only does k_{eff} tell us whether or not criticality is possible, it also is an indication of whether the fission rate is rising, falling, or remaining constant. k_{eff}

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138. A reactor is either shut down or in the process of shutting down if k_{eff} is ______________.

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139. If k_{eff} is less than one, the neutron flux is either decreasing or it is at a very low stable level significantly below what it would be at criticality. In this condition, a reactor is said to be "subcritical". less than one or <1

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140. A reactor is subcritical if k_{eff} is ____________.

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141. If k_{eff} is greater than one, the neutron flux is increasing and the reactor power level is increasing. When k_{eff} is greater than one, the reactor is said to be "supercritical". less than one or <1

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142. A reactor is supercritical if k_{eff} is __________.

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143. The power level of a supercritical reactor is ____________________. — greater than one or >1

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144. By adjusting the control rods containing poison, the loss rate of neutrons can be made to balance the production rate so that ________ equals one and criticality can be exactly maintained. — increasing

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145. By positioning control rods so that there is more poison in the reactor core than at criticality, more neutrons will be absorbed each second than are produced so that k_{eff} is less than one. The neutron flux and power level will ________. When k_{eff} is less than one, the reactor is _______________. — k_{eff}

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146. If the control rods are positioned so that less poison is in the core than at criticality, k_{eff} will be greater than one and the neutron flux and power level will __________. When k_{eff} is greater than one, the reactor is ______________. — decrease, subcritical

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147. The equation $k_{eff} = k_{\infty}P$ tells us that to obtain a value of $k_{eff} = 1$, it is not enough to have some fissionable material; it must be arranged in a particular manner so that k_{∞} will have a high value. We also must have enough of this material so that the neutron leakage is not too great and the nonleakage probability, P, will have a high value. — increase, supercritical

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148. The smaller the core, the more likely it is that neutrons will leak out before they have a chance to be absorbed in the core. Therefore, there is a minimum size for any shape (sphere, cube, cylinder, etc.) below which criticality ($k_{eff} = 1$) is not possible for a given set of materials. When the size of the core is just big enough that criticality can be achieved, that size is called the "critical size".

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149. A mass of fissionable material less than the critical size cannot be made critical because of neutron ____________________.

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150. We said that there was a certain minimum size (and, therefore, mass or weight) of fuel required for criticality to be obtained. Let us consider this statement while we discuss a coal fire. Have you ever tried to start a fire with one little piece of coal the size of a golf ball? Try it some time; chances are you will never get it to burn. Why? Because a piece of coal will not burn unless it is kept very hot. Oh yes, it produces heat when it burns, but it radiates heat from all of its surface so fast that it loses heat at a faster rate than it generates it so, by itself, cannot stay hot enough to continue burning. If you make a small pile of coal, it <u>will</u> burn; but again, if you spread this pile out on a flat surface, the flame will go out even if you keep the pieces of coal close together. Stack the coal back into a pile and you will be able to start it burning again. The reason for this is that as long as the coal is in a pile the outer <u>surface area</u> is <u>small</u> and heat is lost only at the outer surface.

leakage

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151. When you spread the coal out on a flat surface, the surface area is (increased, decreased) so that heat is lost at a faster rate than it is being generated.

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152. The burning of the coal illustrates the necessity of a critical mass of coal as well as critical size and shape. In a like manner, there is a minimum mass and size for any shape of fissionable material required before criticality, k_{eff} = ______, is possible. — increased

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153. Let us keep the idea of a minimum critical mass in the back of our minds while we construct an experiment. Assume that we have a reactor such as the ORR which contains a nonfission source of free neutrons, a moderator, a control system, and a neutron instrument which tells us the number of neutrons in the core. — one

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154. While there is no fuel in the core, we note that the neutron instrument is indicating the presence of the source neutrons only. Now we take a single ORR fuel element and place it in the core. We notice that there is a sudden, very slight increase in the number of neutrons, but the number does not continue to increase.

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155. We would expect a slight increase because some of the source neutrons would be absorbed in the fuel and would cause some of it to ________________.

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156. However, an ORR fuel element has a large surface area, so we would expect a lot of ____________ neutrons from the surface. fission

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157. Other factors such as p and f would combine to limit the ______________ output. leakage

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158. Then we add three more fuel elements and we notice that the neutron population is considerably greater than it was before, but it still does not continue to increase. neutron

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159. Even with the four fuel elements, the amount of fuel in the core is still not a __________ mass.

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160. As we add the fifth, sixth, seventh, and eighth, we notice that, with each addition of a fuel element, there is an increase in the ____________ population. critical

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161. However, the neutron population does not increase except when fuel is added. It is as if the neutron output, as seen by the counter, is merely amplified as each fuel element is added. neutron

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162. If we should calculate the multiplication factor after each fuel element is added, we might find values like k = 0.857 after the first fuel element is added and k = 0.938 after the fourth is added.

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163. After the eighth fuel element is added, k might equal 0.986. Although the multiplication factor is (increasing, decreasing), it is still less than one and the fuel arrangement is still a subcritical mass.

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164. We add the ninth and tenth fuel elements and note that k = 0.992.

increasing

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165. After we add the eleventh and twelfth, k = 0.999. The fuel element configuration that we have now is very nearly a ______________ mass.

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166. Let us imagine that, in our experiment, we add one more fuel element to the configuration and note that the neutron population increases again; but, instead of remaining at a new steady-state level, it continues to increase. We calculate k and find it to be 1.00012.

critical

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167. The additional fuel has caused the subcritical mass to become a ________________ mass.

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168. In this experiment, each time a fuel element was added to the core, the neutron population increased but did not continue to increase until the _________ mass was reached.

supercritical

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169. Each time we added a fuel element, we increased the value of k until finally criticality was reached. The value of k became greater than 1.0 when the amount of fuel in the core became a ________________ mass.

critical

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170. By adding the fuel in the thirteenth element, we went from subcriticality, through criticality, to a state of supercriticality. In this state the neutron population continued to ________________.

supercritical

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171. To prevent the neutron population from increasing indefinitely, we must insert some ________________ material in the form of control rods so that a balance is obtained between the fission-neutron-production rate and the loss rate (due to absorption and leakage).

increase

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172. If adjustments of the control rods were not made, more and more fissions would occur and more and more heat would be generated until finally the reactor would melt.

poison or absorbing material

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173. The increase in the neutron population, which occurred with each fuel addition before criticality was reached, was a result of what is called "subcritical multiplication".

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174. A subcritical reactor with a source of neutrons, therefore, has a higher neutron population than that due to the source alone as a result of fission reactions caused by some of the source neutrons. This increase in the neutron population of a subcritical reactor above the source level is due to

_________________________.

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175. The subcritical multiplication factor M is defined as the ratio of the neutron population with fuel to the neutron population without fuel. In equation form, this is:

subcritical multiplication

$$M = \frac{\text{neutron population with fuel}}{\text{neutron population without fuel}}$$

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176. As we said before, the neutron population in a reactor can be determined by an instrument which counts neutrons. This instrument can be made to indicate the neutron population (as a function of the number of neutrons it counts per sec) on a recorder known as a counting-rate (CR) recorder. So, M is sometimes written as:

$$M = \frac{CR_x}{CR_o}$$

where CR_x stands for the counting rate with x grams of fuel in the reactor and CR_o stands for the counting rate without fuel.

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We do not wish to discuss here the operation of neutron detection instruments. However, one should mention that while no instrument can count <u>all</u> of the neutrons produced by a reactor, instruments can and do count a precisely determined fraction of the neutrons. From this count, the total number of neutrons, or what is of more value, the neutron flux of the reactor, can be determined when related to other types of neutron measurements within the core.

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177. Now, suppose that we have a source of neutrons which causes three counts per second on the counting-rate recorder without any fuel in the core. Then we add 1000 g of fuel and we find that the counting rate is 20 counts per second. By using the equation, $M = \frac{CR_x}{CR_o}$, we find that the subcritical multiplication factor M is equal to __________.

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6.7 because $M = \frac{20 \text{ counts/sec}}{3 \text{ counts/sec}} = 6.7$

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178. When a few more grams of fuel are added, we notice the counting rate increases to 240 counts/sec so that M is now ______________.

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80 because $\frac{240}{3} = 80$

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179. By observing the neutron population as indicated by a ________________-_____________ recorder, we can determine when criticality is about reached. We <u>must know</u> when criticality is reached because, if we add too much extra fuel, so that k_{eff} is much greater than one, the power level of the reactor might increase so fast that the reactor core would melt down before corrective action could be taken.

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> It should be noted that an increase in either power, neutron flux, or neutron density causes a corresponding increase in each of the other two. If power level is changed by a factor of 2 or 200, both neutron flux and neutron density change by the same factor.

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180. One way we can determine when criticality, $k_{eff} = 1$, is reached is by determination of the subcritical multiplication factor and using an equation to determine k_{eff}. The equation is:

counting-rate

$$M = \frac{1}{1 - k_x} \text{ or } k_x = 1 - \frac{1}{M},$$

where k_x is the effective multiplication factor (k_{eff}) when x grams of fuel are in the reactor, and M is the ____________________ _______________ factor.

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181. The equation, $M = \frac{1}{1 - k_x}$, should be remembered, so let us work a few problems using this equation in order to become more familiar with it.

subcritical multiplication

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182. Let us assume that we know the value of k_x and determine M. If $k_x = 0.85$, a calculation of M would be:

$$M = \frac{1}{1 - 0.85} = \frac{1}{0.15} = \_\_\_\_.$$

So, if we initially had 3 counts/sec from source neutrons, we would get an indication on the counting-rate recorder of 3 counts/sec × 6.7 or about 20 counts/sec.

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183. If we now add enough fuel so that $k_x = 0.99$, M is equal to ____________. 6.7

\- - - - - - - - -

100 because $M = \frac{1}{1 - 0.99} = \frac{1}{0.01} = 100$

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184. When k_x is equal to 0.99, the indication on the counting-rate recorder for a 3 counts/sec source would be ______ counts/sec. When k_x is 0.999, M would be _______ and the recorder would indicate ________ counts/sec.

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185. You can see that there is an increase in the counting rate as k_x gets closer and closer to one. 300, 1000, 3000

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186. A typical fuel buildup to a critical mass is shown in Fig. III-18. The data for this figure were taken from an actual experiment in which fuel elements were added to a reactor until a critical mass was reached. The reciprocal counting rate ($\frac{1}{CR_x}$) was plotted against fuel mass because k_x is proportional to $1 - \frac{1}{CR_x}$; as CR_x increases, $\frac{CR_o}{CR_x}$ becomes smaller and k_x approaches 1.0.

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187. In the experiment, when the fuel loading reached 2522 g, $\frac{1}{CR_x} = .000306$ and $k_x = 1 - .000306 = .999694$.

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188. When the fuel loading was 2800 g, $\frac{1}{CR_x} = .000133$. k_x is now $= 1 - .000133 =$ ____________.

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189. When the fuel loading was 3079, $\frac{1}{CR_x} = .000068$. k_x is now ________________. .999867

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190. You can easily see that as CR_x becomes greater, as criticality is approached, k_x becomes more difficult to calculate exactly. Usually when criticality is approached by fuel additions, extrapolations (graph extensions) are made after each fuel addition and the critical mass is predicted by noting where the extrapolated curves cross the line $\frac{1}{cpm} = 0$.

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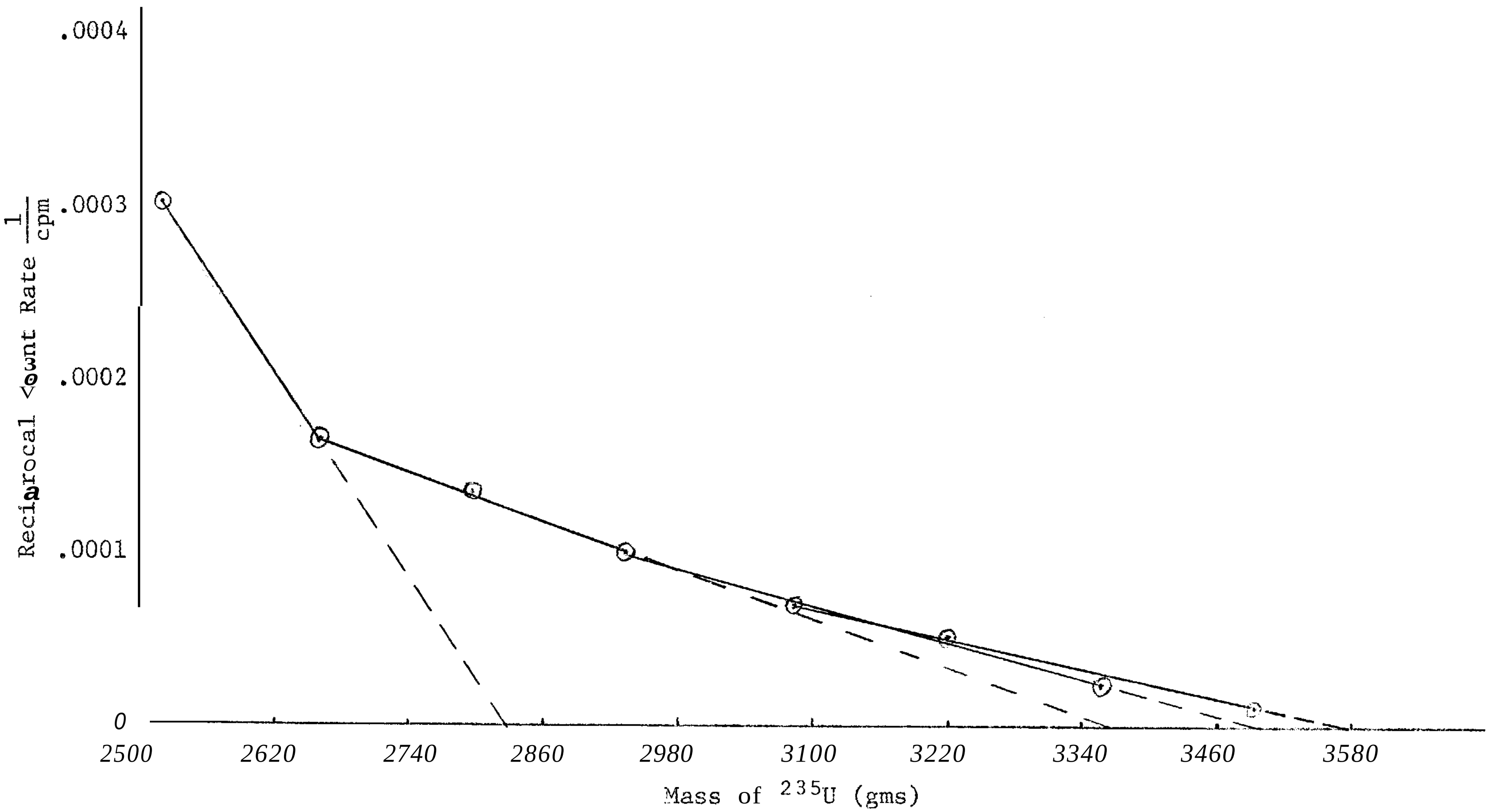

Fig. III-18. Plot of Reciprocal Counting Rate Versus Fuel Mass During Approach to Criticality by Fuel Addition

In this experiment which was done at the PCA, fuel was added by placing an additional fuel element adjacent to the fuel elements already loaded. This method of adding fuel increases the size of the reactor with each fuel addition. It also causes the last fuel additions to be in less important positions than the earlier additions since the fuel elements must be placed farther and farther from the center of the core. These circumstances cause each extrapolation of the graph to underestimate the critical mass. If the additional fuel could be simply distributed throughout the existing core rather than adding a new fuel element, the extrapolated curve would predict the critical mass quite closely.

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191. From the graph, Fig. III-18, we would predict that an extrapolation of the curve would probably cross the zero line between the 3460-g mark and the 3580-g mark, probably at about 3500 g. We would consider a 3460-g loading a ____________ mass and a 3580-g loading a _____________ mass.

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192. In this experiment, the critical mass was shown to be 3495 grams of fuel, very near our predicted 3500 g.

subcritical
supercritical

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193. During the routine loadings of some reactors such as the ORR in which the critical mass is already known, the control rods are positioned so that all of the poison used for control is inserted into the fuel region. Then the fuel elements (usually about 25) are placed in the core, one by one, while the counting-rate recorder is observed for any significant changes.

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194. When the core is fully loaded, the control rods are withdrawn until criticality is reached. By observing the counting-rate recorder as the rods are withdrawn, a prediction can be made as to what the position of the rods will be when criticality is reached. Therefore, "approach to criticality" by poison-rod withdrawal from a fully loaded reactor has similar characteristics to an approach to criticality by fuel additions alone.

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195. In order to predict the rod position at criticality, when $k_y = k_{eff} = 1$, we let CR_y represent the counting rate when the rods are y inches withdrawn and CR_o the counting rate when the rods are zero inches withdrawn. We use the equation:

$$k_y = 1 - \frac{1}{M} = 1 - \frac{CR_o}{CR_y}$$

so that, as the rods are withdrawn, the counting rate CR_y will increase and the value for $\frac{1}{M}$ will approach zero as M increases in value.

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196. In other words, as the counting rate increases, the reactor gets closer to _______________. This can readily be seen when each step is plotted on a graph as in Fig. III-19.

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197. When CR_y is so large that $\frac{1}{M}$ is zero, then $1 - k_{eff}$ is zero which is the point at which the reactor is ____________ because k_{eff} = __________________. criticality

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198. An experiment such as this was conducted at the ORR. The results are shown in Fig. III-19. Criticality was predicted to be when the rods were about 15 inches out; the reactor actually went critical when the rods were 14.89 inches out. critical, 1

- - - - - - - - -

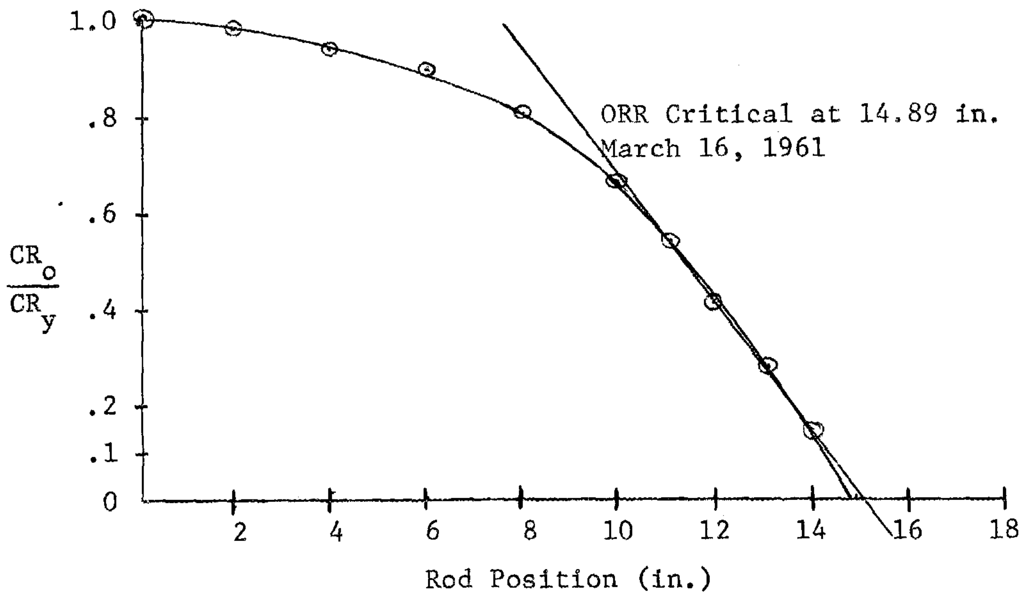

Fig. III-19. Plot of $\frac{CR_o}{CR_y}$ Versus Rod Position During Approach to Criticality by Control-Rod Withdrawal

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199. In Fig. III-19, $\frac{CR_o}{CR_y}$ is plotted with reference to control-rod position in inches withdrawn. Obviously the whole graph is not a straight line. However, as $\frac{1}{M}$ becomes smaller (the counts on the counting-rate recorder are getting very large), the last three or four points plotted are very nearly in a straight line.

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200. A straight line drawn through these last three points will give a very close approximation of the distance the rods will be withdrawn when $\frac{CR_o}{CR_y}$ = ________ and the reactor is ____________________.

- - - - - - - - -

zero, critical

For those of you who are interested, the initial criticality experiments conducted at the ORR to establish the critical mass are discussed in detail in the report ORNL-2559, entitled "Initial Post-Neutron Measurements".

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2.4. Self Test

201. What is a nuclear reactor? (If you made an incorrect response, repeat Frame 1.)

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A reactor is an apparatus in which fission reactions are started and controlled as a continuous self-sustaining chain reaction.

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202. The principal parts of a reactor are ____________. (If you made an incorrect response, repeat Frame 2.)

- - - - - - - - -

fuel, moderator, reflector, cooling system, control system

203. The region containing fuel in a reactor is called the ____________________. (If you made an incorrect response, repeat Frame 5.)

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204. Material which is placed around a core for the purpose of scattering neutrons back into the core is called the ________________. (If you made an incorrect response, repeat Frames 5-17.) | core

- - - - - - - - -

205. Heat generated in a reactor is removed by the ____________ ____________. Water is a common moderator, reflector, and ____________. (If you made an incorrect response, repeat Frames 11 and 12.) | reflector

- - - - - - - - -

206. A poison is a strong ______________ of neutrons. Control of the neutron flux in a reactor may be achieved by using ______________. (If you made an incorrect response, repeat Frames 35-41.) | cooling system, coolant

- - - - - - - - -

207. Control of the multiplication factor of a reactor is accomplished by adjusting ____________ ________. (If you made an incorrect response, repeat Frames 35-41.) | absorber, poison or neutron absorbers

- - - - - - - - -

208. When conditions in a reactor are such that k = 1 and there is a continuous fission chain reaction, a reactor is said to be ______________. (If you made an incorrect response, repeat Frame 43.) | control rods

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209.	An imaginary reactor, so big that it is impossible to determine where it starts and where it ends, is called an ________________ reactor. Loss of neutrons in an infinite reactor can occur only by ________________; there can be no loss by ________________. (If you made an incorrect response, repeat Frames 49-56.)	critical

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210.	The neutron multiplication factor of a reactor is defined as the ratio of the ______________ rate to the ______________ rate. (If you made an incorrect response, repeat Frame 57.)	infinite, absorption, leakage

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211.	In an infinite reactor, $k_\infty = 1$ when the production rate equals the absorption rate. In an actual reactor, $k_{eff} = 1$ when the production rate equals the ____________. (If you made an incorrect response, repeat Frame 62.)	production, loss

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212.	The nonleakage probability, P, is the probability that neutrons ________________________. (If you made an incorrect response, repeat Frame 63.)	absorption rate plus the leakage rate

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213.	If we had 10 neutrons and 2 of them leaked out of a reactor, the nonleakage probability would be equal to ________________. P for an infinite reactor is ________ because ______________________. (If you made an incorrect response, repeat Frames 64-66.)	will not leak out of a reactor

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214. The fast-fission effect is ________________. (If you made in incorrect response, repeat Frames 75-81.)

$P = \frac{8}{10} = 0.8$, 1, there is no leakage

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The increase in the total number of fast neutrons as a result of fission caused by fast neutrons.

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215. The resonance escape probability, p, represents the fraction of neutrons which ________________. (If you made an incorrect response, repeat Frames 86-96.)

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Are not absorbed as they slow down to thermal energies.

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216. The thermal utilization factor represents ____________. (If you made an incorrect response, repeat Frames 99-104.)

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The fraction of thermal neutrons absorbed in the fuel.

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217. The ratio $\frac{\Sigma_f}{\Sigma_a}$ for ^{235}U represents the fraction of ^{235}U atoms which will undergo ______________ compared to the total number which absorb neutrons. (If you made an incorrect response, repeat Frames 105-108.)

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218. The symbol η represents the average number of neutrons released per neutron ______________ by the fuel atoms. (If you made an incorrect response, repeat Frames 108-111.) — fission

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219. The four-factor formula is k = ___________. (If you made an incorrect response, repeat Frames 124 and 125.) — absorbed

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220. Reactor criticality is not necessarily guaranteed if $k_\infty = 1$. In order for criticality to be possible (P, k_{eff}) must be equal to ____________. (If you made an incorrect response, repeat Frames 130-132.) — $\epsilon p f \eta$

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221. In equation form, k_{eff} is: — k_{eff}, one

$$k_{eff} = \text{———— } P_{nlf} P_{nlth}.$$

(If you made an incorrect response, repeat Frames 133-135.)

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222. A reactor is said to be subcritical if ____________. (If you made an incorrect response, repeat Frames 139 and 140.) — $\epsilon p f \eta$

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223. The neutron population in a supercritical reactor is ___________________. (If you made an incorrect response, repeat Frames 141-143.) — k_{eff} is less than one

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224. The materials and arrangement in a reactor determine the value of k_∞, but the nonleakage probability depends only on the ____________. (If you made an incorrect response, repeat Frames 147-152.)

increasing

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225. Subcritical multiplication due to the addition of some fuel causes the neutron population to ________ to a higher steady level even though the reactor is still ________________. (If you made an incorrect response, repeat Frames 173-175.)

size and shape

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226. The subcritical multiplication factor M is defined as ________________________. (If you made an incorrect response, repeat Frame 175.)

increase, subcritical

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> The neutron population with fuel divided by the neutron population without fuel.

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227. The equation showing the relationship between M and k is M = ________________. (If you made an incorrect response, repeat Frames 180-184.)

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228. Remembering that $\frac{1}{M} = \frac{1 - k_x}{1}$ and $\frac{1}{M} = \frac{CR_o}{CR_x}$, where CR_o is the counting rate with no fuel and CR_x is the counting rate with fuel, how can you tell when criticality is nearly reached as fuel is being added? (If you made an incorrect response, repeat Frames 186-200.)

$\frac{1}{1 - k}$

- - - - - - - - - -

By plotting on a graph the value $\frac{1}{M}$ and observing when $\frac{1}{M}$ is nearly zero so that k_x is nearly one.

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SECTION III-3

REACTIVITY AND REACTOR PERIOD

The purpose of this section is to give you an understanding of the terms reactivity and period by discussing the effects of reactivity on the rate of change of the neutron population and the resulting effects on the operation of a reactor.

3.1. Reactivity Calculations

1. Reactivity is a term used to express the ability of a reactor to increase its neutron population. Thus when a reactor is made supercritical, its __________ has been made greater than zero.

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2. In equation form, reactivity, ρ (rho), is expressed as   reactivity

$$\rho = \frac{k_{eff} - 1}{k_{eff}}$$

where the multiplication factor of the reactor before the change was 1 and k_{eff} is the factor after the change.

- - - - - - - - - -

3. If we had made the change when the reactor was already supercritical, we would have to write:

$$\rho_2 - \rho_1 = \Delta\rho = \frac{k_{eff_2} - 1}{k_{eff_2}} - \frac{k_{eff_1} - 1}{k_{eff_1}} = \frac{k_{eff_2} - k_{eff_1}}{k_{eff_1} k_{eff_2}}$$

in which:

$\Delta\rho$ = the change in reactivity

k_{eff_1} = k_{eff} before the change

k_{eff_2} = k_{eff} after the change.

- - - - - - - - - -

4. When a reactor is exactly critical, $k_{eff} = 1$ so that:

$$\rho = \frac{k_{eff} - 1}{k_{eff}} = \frac{1 - 1}{1} = 0$$

- - - - - - - - -

5. Let us assume that k_{eff} in a reactor is 1 and an adjustment of the control rods is made until k_{eff} becomes 1.005. The reactivity as a result of the change in k would be ________________.

- - - - - - - - -

$$\boxed{\rho = \frac{1.005 - 1}{1.005} = \frac{0.005}{1.005} = 0.00497}$$

- - - - - - - - -

6. The equation, $\rho = \frac{k_{eff} - 1}{k_{eff}}$ is usually written $\Delta k/k$, pronounced "delta k over k" (usually Δ means "the change in"). The quantity Δk is equal to the resulting change in the multiplication factor, that is, $k_{eff} - 1 = \Delta k$.

- - - - - - - - -

7. In equation form, reactivity $= \frac{\Delta k}{k} =$ ______________.

- - - - - - - - -

8. Reactivity, $\Delta k/k$, is sometimes expressed as a percent. If $\Delta k/k$ is 0.15, then it might also be expressed as 15%, since $0.15 \times 100\% = 15\%$. $\frac{k_{eff} - 1}{k_{eff}}$

- - - - - - - - -

9. Control of a reactor is usually accomplished by inserting or withdrawing a control rod containing a neutron-absorbing material, which results in a change in the multiplication factor, k. A reactor which is critical (k = 1) can be made subcritical by inserting the control rod (poison), thus causing k to become __________. The reactor becomes supercritical when the control rod is withdrawn, causing k to become __________.

- - - - - - - - -

10. Knowledge of the effects of control rods on reactivity is essential to the safe operation of a reactor. Figure III-20 shows some values of the reactivity worths of control rods at the ORR reactor.

less than one, greater than one

- - - - - - - - -

11. Since the withdrawal of a control rod results in an increase in k, it is said to have a positive __________ effect.

- - - - - - - - -

12. The insertion of a control rod (poison) into a reactor results in a __________ reactivity effect because k __________.

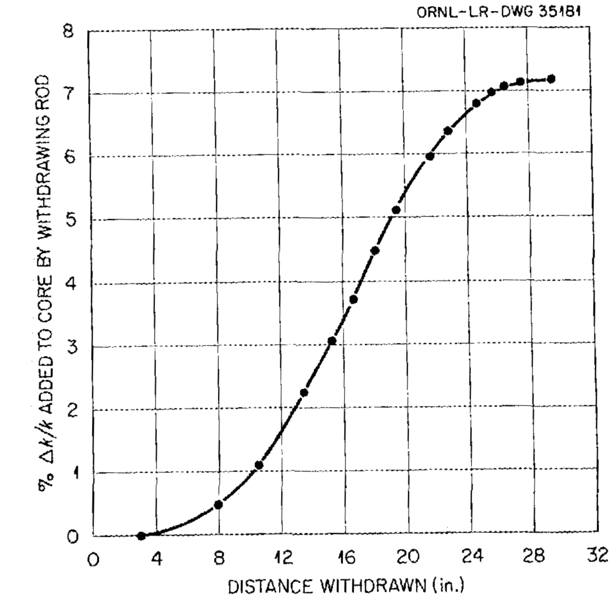
reactivity

- - - - - - - - -

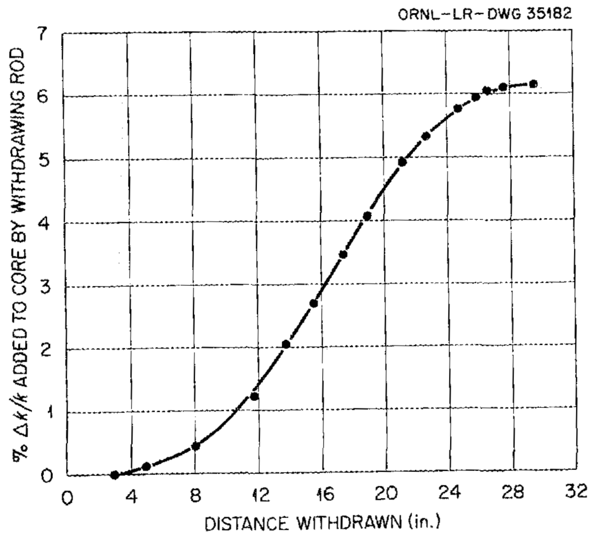
13. The insertion of a control rod results in a negative reactivity effect, whereas withdrawal results in a positive reactivity effect. In a similar manner, putting other materials into a reactor or removing them may also cause either a positive or a negative effect.

negative, decreases

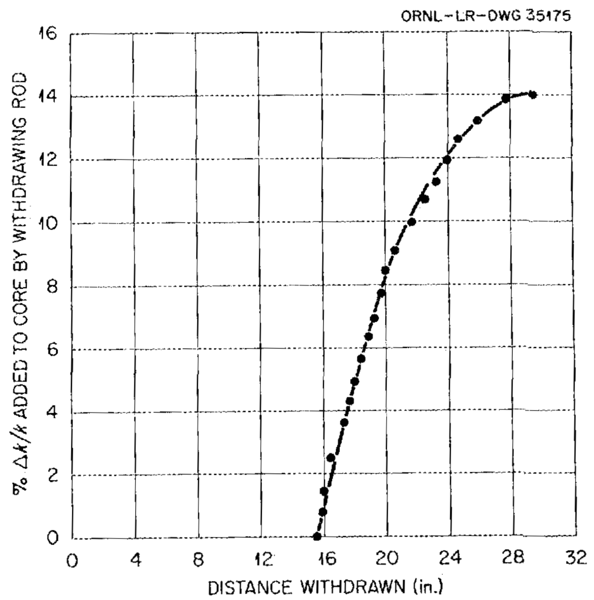
- - - - - - - - -



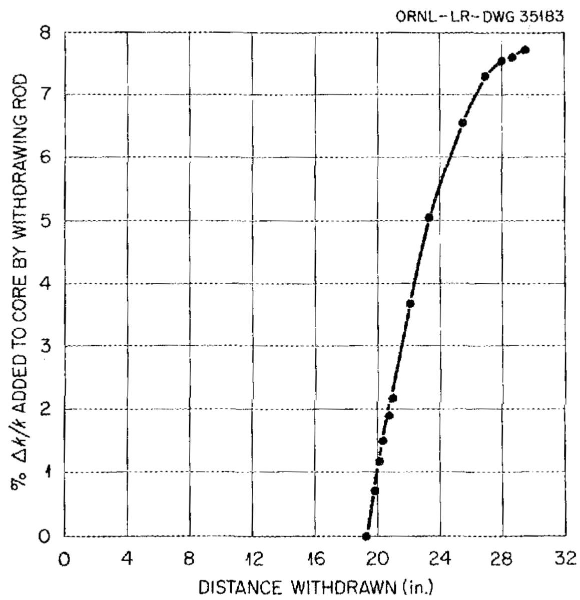
Number 5 Rod Calibration for Clean Operating Core. Total worth, 7.16% Δk/k; central slope, (0.47% Δk/k)/in.



Number 6 Rod Calibration for Clean Operating Core. Total worth, 6.14% Δk/k; central slope, (0.39% Δk/k)/in.



Gang Rod Calibration for 4 x 7 Test Core. Core worth, 13.94% Δk/k; central slope, (1.73% Δk/k)/in.



Gang Rod Calibration for Operating Core with Experiments. Core worth, 7.72% Δk/k; central slope, (1.30% Δk/k)/in.

Fig. III-20. Control-Rod Reactivity Worths

14. Anything which will increase the multiplication factor of a reactor is said to have a ____________ ________________ effect. Anything which will decrease the multiplication factor of a reactor is said to have a ______________ ________________ effect.

reactivity

- - - - - - - - -

15. Fissionable material usually has the opposite effect to that of a neutron poison when put into a reactor. If fissionable material is added to a reactor core, the result usually is a ______________ ____________ effect. If fuel is removed from the reactor core, the result usually is a ______________ _____________ effect. (In some types of reactors adding more fuel may reduce the reactivity if it displaces some of the moderator.)

positive reactivity, negative reactivity

- - - - - - - - -

16. Almost anything can cause a reactivity change if it is introduced into or placed near the fuel region of a reactor. The reactivity effect will be positive or negative, depending on whether the neutron _________________ _____________ is increased or decreased.

positive reactivity, negative reactivity

- - - - - - - - -

17. To obtain criticality, $k_{eff} = 1$, it is necessary to have a certain amount of fuel. Now, if there were no additional fuel besides that required for a critical mass, the reactor would not operate very long before becoming subcritical and shutting down. Can you guess the reason why?

multiplication factor

- - - - - - - - -

18. The answer is "fuel burnup". As fissioning occurs in a reactor, the fuel is consumed (atoms of ^{235}U are changed to atoms of fission products) until finally the amount of fuel is less than the critical mass. When this occurs, k becomes ___________ and the neutron population (and fission reactions) decrease.

\- - - - - - - - -

19. To keep a reactor operating for any length of time, there must be some extra ____________ in addition to the critical mass. — less than one

\- - - - - - - - -

20. If extra fuel is added to a critical mass, the multiplication factor will usually increase because the addition of fuel usually has a __________________ ______________ effect. — fuel

\- - - - - - - - -

21. To maintain criticality (that is, to prevent an increase in the fission rate as a result of the extra fuel) a control rod is inserted to compensate for the positive reactivity effect of the fuel addition. — positive reactivity

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22. As the fuel is burned up, causing a ______________ in k_{eff} (a negative reactivity change), the control rod is slowly withdrawn (a positive reactivity change) just enough to maintain k_{eff} at one.

\- - - - - - - - -

23. In addition to fuel burnup, there are other things which can cause reactivity changes and must be compensated for by the control rods. For example, most experiments which are inserted into a research reactor cause either a positive or negative reactivity change depending on whether the experiment contains an appreciable amount of fissionable material or poison material or if it displaces or adds neutron-moderating material. decrease

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24. An increase in the temperature of the core, as when the power level is raised, generally results in a negative reactivity effect.

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25. Many fission products such as ^{135}Xe and ^{149}Sm are strong neutron absorbers. These fission products would have a ________________ effect.

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26. In order to compensate for the various reactivity changes in a reactor such as those caused by experiments, temperature, fission products, and fuel burnup, an extra amount of fuel is loaded into the core before operation is started. The positive reactivity effect of adding the extra fuel is balanced by insertion of the ________ ________ which may also be withdrawn or inserted as needed when other reactivity changes occur. negative

- - - - - - - - -

27. The positive reactivity effect resulting from loading extra fuel into the core to compensate for later fuel burnup may be considered as available reactivity. It is ______________ reactivity because it will not be used until the control rod is withdrawn to increase k to maintain criticality as the fuel is depleted. — control rods

- - - - - - - - -

> We have used the term "available reactivity" because when some people speak of excess reactivity they really mean k_{excess}, which is Δk or $k - 1$. Since reactivity is $(k - 1)/k$ or $\Delta k/k$, for a person to say excess reactivity when he really means k_{excess} ($k - 1$ or Δk) is to give the word "reactivity" two meanings.

available

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28. Available reactivity must be compensated for at all times because, if it is not, the neutron population and power level would increase to such an extent that the reactor would melt down. Available reactivity is necessary but can be hazardous if it is not controlled.

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29. It might be of interest at this point to consider the theoretical determination of reactivity, $\Delta k/k$. You should remember that $k_{eff} = k_{\infty}P$; where k_{∞} depends only upon the materials used and their physical arrangement. P depends upon the size and shape of the reactor. In the equation, $\rho = \frac{k_{eff} - 1}{k_{eff}}$, let us replace ρ with $\Delta k/k$ and use k'_{eff} for the multiplication factor at criticality, which is <u>one</u>. We now have:

$$\frac{\Delta k}{k} = \frac{k_{eff} - k'_{eff}}{k_{eff}}.$$

(continued)

By substituting $k_\infty P$ for k_{eff}, we can write:

$$\frac{\Delta k}{k} = \frac{k_\infty P - k'_\infty P}{k_\infty P} = \frac{P}{P}\left(\frac{k_\infty - k'_\infty}{k_\infty}\right)$$

And, since $\frac{P}{P} = 1$, we have:

$$\frac{\Delta k}{k} = \frac{k_\infty - k'_\infty}{k_\infty}$$

We know that $k_\infty = \eta\varepsilon pf$, so we can write:

$$\frac{\Delta k}{k} = \frac{\eta\varepsilon pf - \eta'\varepsilon'p'f'}{\eta\varepsilon pf}.$$

η is constant for a particular fissionable material; and if we assume that the product $\varepsilon \times p$ will not appreciably change (small changes in the amount of fuel have opposite effects on the factors so that the product does not change appreciably) then $\eta\varepsilon p = \eta'\varepsilon'p'$; and we can write:

$$\frac{\Delta k}{k} = \frac{f - f'}{f}$$

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30. It is shown in ORNL-2559 that $\frac{f - f'}{f}$ is equivalent to $\frac{\Sigma_{ap}}{\Sigma_{ac}}$ where Σ_{ap} is the macroscopic absorption cross section for poisonous material, and Σ_{ac} is the macroscopic cross section for all material in the core. So we can now write:

$$\frac{\Delta k}{k} = \frac{\Sigma_{ap}}{\Sigma_{ac}}.$$

- - - - - - - - -

31. The equation: $\frac{\Delta k}{k} = \frac{\Sigma_{ap}}{\Sigma_{ac}}$ tells us that if we had some poison material we could determine the reactivity effect of this material by dividing the value of Σ_{ap} by Σ_{ac}.

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32. Let us say that we have enough boron to give a Σ_{ap} of 3200. Boron is a good absorber and is considered a poison. For the total core let us assume Σ_{ac} for Al is 500, Σ_{ac} for ^{238}U is 200, Σ_{ac} for water is 300, Σ_{ac} for ^{235}U is 50,000. Total Σ_{ac} = ________.

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33. The ratio of $-\frac{\Sigma_{ac}}{\Sigma_{ac}} = -\frac{3200}{54,200} = -0.0058$. So, in this case, the negative reactivity effect of the boron poison is $\Delta k/k = -$ __________. 54,200

- - - - - - - - -

34. In the report ORNL-2559, it is also shown that if some fuel (^{235}U) were added to a core the reactivity effect could be predetermined by the equation: 0.0058

$$\frac{\Delta k}{k} = C \frac{\Delta M}{M_o} \frac{\overline{\phi}_i}{\overline{\phi}_c}$$

where ΔM is the mass of fuel added, M_o the original total ^{235}U fuel mass in the core, and $\overline{\phi}_i/\overline{\phi}_c$ the ratio of the average neutron flux in that particular fuel position to the average flux throughout the core. c is some constant number found by experiment to make the equation true.

- - - - - - - - -

You do not have to remember how to derive these equations. The equations were given here just in case you might want to try to calculate $\Delta k/k$ some time and check to see how close you were to the actual value. Also, to make you aware that the effect on k, in making changes in cores or experiments, can be estimated.

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35. If the reactivity of a critical reactor is increased, the neutron population in each succeeding generation will increase. The question is, "How fast does the neutron population increase?"

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36. The rate of increase in the neutron population depends on the amount of reactivity added and the "neutron lifetime".

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37. The neutron lifetime is the time it takes the neutron to complete its life cycle from birth as a fast neutron to absorption as a thermal neutron.

\- - - - - - - - -

38. To say it another way, <u>the lifetime of a neutron</u> is the time it takes for a neutron to be born from fission, go through the slowing down process, and be ______________, either to cause a fission reaction releasing more neutrons or to be lost in a nonfission reaction.

\- - - - - - - - -

39. Neutron lifetimes are surprisingly short--shorter than the time it takes for you to blink your eye. Neutron lifetimes also vary in different kinds of reactors. In the OGR, for example, the neutron lifetime was about 0.001 sec. In the ORR the lifetime is about ten times shorter, or 0.0001 sec. — absorbed

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40. If the multiplication factor is much greater than one, it takes only a very short time for the neutron population density (and therefore the flux) to increase tremendously, since the neutron __________ is so short.

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3.2. Reactor Period

41. Let us assume that the neutron lifetime in a make-believe reactor is 1 sec instead of a more realistic value such as 10^{-4} sec. Now, if k = 1.1 and n, the neutron density, is originally 100 neutrons, then after 1 sec, n will be equal to 110 neutrons; after 2 sec, n will be 110 × 1.1 = _________ neutrons, etc. Now let us compile a table (Table III-3) showing time and neutron density for k = 1.1 and the neutron lifetime = 1 sec. — lifetime

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42. As we can see from the table, the time it takes for the number of neutrons to increase by 100 keeps getting shorter and shorter; that is, to go from a density of 100 to 200 takes about 7 sec; to go from 200 to 300 takes about 5 sec; to go from 300 to 400 takes about 3 sec, and so on. (All the while the number of fissions per second is increasing at this same rate; and, therefore, the power is also.) — 121

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43. Now, if we consider the doubling time, that is, the time it takes for the neutron density to become twice as much as it was before, we see that to go from 100 to 200 takes about 7 sec; to go from 200 to 400 takes about 7 sec; to go from 400 to 800 takes about 7 sec; etc. The point is that the doubling time is constant, whereas the time it takes for an increase of 100 keeps changing; so, it is much easier to discuss the increase in population by talking about a constant period of time, such as the _____________ time, than it is to talk about the time for an increase of 100.

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Table III-3. Neutron Multiplication

(Lifetime = 1 second and k = 1.1)

Time, t (seconds)		Neutron Density (1.1 × n)	
0		100	
1		110	
2		121	
3		133	
4	7 sec	146	∿7 sec
5		161	
6		177	
7		195	
8		214	
9		235	
10	5 sec	256	
12		309	∿7 sec
14		374	
15	3 sec	411	
17	2 sec	497	
19	1 sec	602	∿7 sec
22		823	

- - - - - - - - -

44. We could just as easily talk about the time it takes the neutron density to triple in value or to quadruple, but the number 2.72 (represented by e) is generally used because it simplifies many calculations. (This number represented by e has no exact value, but 2.72 is close enough for our purposes. Written out to 15 decimal places, e = 2.718281828459045 and still keeps going.) doubling

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45. The term <u>period</u>, therefore, is usually considered to be the time it takes for the neutron flux (population or density) to change by a factor of e, about 2.72.

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46. The symbol τ (spelled tau and pronounced tow to rhyme with how) is used to represent the period. Therefore, τ is the time it takes for the neutron flux to ________________.

- - - - - - - - -

Change by a factor of 2.72.

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47. If we know the value of τ, then there is an equation which can be used to determine the neutron density or the neutron flux after a lapse of time. The equation is:

$$n = n_o e^{t/\tau}$$

where n_o is the neutron density or the neutron flux at time, $t = 0$, t is the amount of time we want to consider; τ is the period caused by a change in k, $e = 2.72$, and n is the density or flux which will exist after the time interval equal to t which is any amount of time we want to choose. Both τ and t are usually expressed in seconds.

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48. To illustrate the use of the equation, let us assume we have a neutron density of 100 neutrons/cm^3 at time $t = 0$ and the reactor has a period of $\tau = 10$ sec. The equation, then, is: $n = (100)(e^{t/10 \text{ sec}})$.

- - - - - - - - -

49. Now, if we want to know the neutron density 10 sec from now, t = 10 sec, the equation would be:

$$n = (100)(e^{\frac{10\ \text{sec}}{10\ \text{sec}}}) = (100)(e^1) = \_\_\_\_.$$

Thus, after 10 sec, the neutron density is ________________ neutrons/cm^3.

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50. After 20 sec, the neutron density, using the same problem as in Frame 48, is ________________. 272, 272

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> You learned that the proper units of flux are that ϕ = (neutrons/cm^3)(cm/sec). However, the most common usage is to cancel to get cm/cm^3 = 1/cm^2 and have ϕ = neutrons/cm^2 • sec, often written ϕ = n cm^{-2} sec^{-1} because the typist can put it all on one line. The text will conform to this common usage; however, please remember how it should be written.

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51. Let us now assume that we have a reactor period of 30 sec and an initial neutron flux somewhere in the reactor of 10 n cm^{-2} sec^{-1}, and we want to know the neutron flux after a time lapse of 90 sec. The equation is: 740 neutrons/cm^3

$$n = (10)(e^{\frac{90\ \text{sec}}{30\ \text{sec}}}) = (10)(e^3).$$

Now $e^3 = 3 \times \log 2.72 = 3 \times .4346 = 1.3038$, so

$$\text{antilog } 1.3038 \simeq 20.1$$

$$n = (10)(20.1) = \_\_\_\_\ \text{n cm}^{-2}\ \text{sec}^{-1}.$$

- - - - - - - - - -

The value of e^3 or e^x where x may be any number can be obtained from various books such as the Handbook of Physics and Chemistry or from a slide rule. We suggest that you practive using either logarithms or sliderule. 201

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52. If n_o is 2 and τ is 10, after a time lapse of 20 sec n will be ______________.

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$$n = 2\ e^{\frac{20}{10}} = (2)(2.72)^2 = (2)(7.4) = 14.8$$

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53. Since power level is directly proportional to either the neutron flux or the neutron density, this same type of equation can be used to calculate the future power level of a reactor. (This is because the fission rate depends upon the supply of neutrons.) The equation is $P = P_o e^{t/\tau}$ where P_o is the initial power and P is the ____________ after a time lapse of t sec.

- - - - - - - - -

54. Let us assume that a reactor is operating at a power level of 2 Mw (megawatts) and a period of 30 sec is established. After a time lapse of one and one-half minutes, the power level will be about (6 Mw, 20 Mw, 40 Mw, 60 Mw). power level

- - - - - - - - -

40 Mw because:

$$P = 2\ \text{Mw}\ (e^{\frac{90}{30}}) = 2(e^3) = 2 \times 20 = 40\ \text{Mw}$$

- - - - - - - - -

55. It should be apparent that if there is a short period such as 1 or 2 sec, the power level (or neutron flux) will increase quickly. For example, if τ is 2 sec and P_o is 1 Mw, after 10 sec, P will be ____________ Mw.

\- - - - - - - - -

56. If the period is longer, say 20 sec, P, after the 10 sec allowed in the above problem will be only ________________. 149

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57. If the period is essentially infinite (too long to be measured), the power level will ____________. 1.65 Mw

\- - - - - - - - -

> If the power level changes at all, the period is measurable.

remain constant

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58. A short period means the neutron flux is increasing at a (slow, fast) rate. The longer the period, the (slower, faster) the rate of increase. A reactor which is just critical will therefore have ____________________ period.

\- - - - - - - - -

59. If a reactor is just critical, it will have an infinitely long period. If the power level is increasing, then the period will be positive such as +500 sec, or +100 sec, or an even shorter period such as +10 sec. fast, slower, an infinite

\- - - - - - - - -

60. If the power level is decreasing, the period is negative. It may be short such as -10 sec or long such as -500 sec, but still the power is decreasing. If the period is -10 sec, the power is decreasing much (slower, faster) than if τ = -500 sec.

\- - - - - - - - -

61. The point is that a reactor which is just critical has to have an infinite period. If the value of the period becomes smaller than infinite, then the power and neutron density will change at a rate depending on the period; and it will decrease if the period is ____________ and increase if the __________ is ________________.

faster

\- - - - - - - - -

62. By using an instrument which detects neutrons, a value for the neutron population can be displayed on a recorder. Figure III-21 shows a strip of chart paper from a recorder used for this purpose. The instrument is called a log-N recorder because its calibration gives the logarithm of the neutron population.

negative, period, positive

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63. Note that the scale of Fig. III-21 has numbers which are not evenly spaced. This is because, as on a slide rule, the spacing is for the logarithms of the numbers. On the log-N instrument scale, the spacing is for the ________________ of the _____________ population.

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ORNL DWG. 68-4396

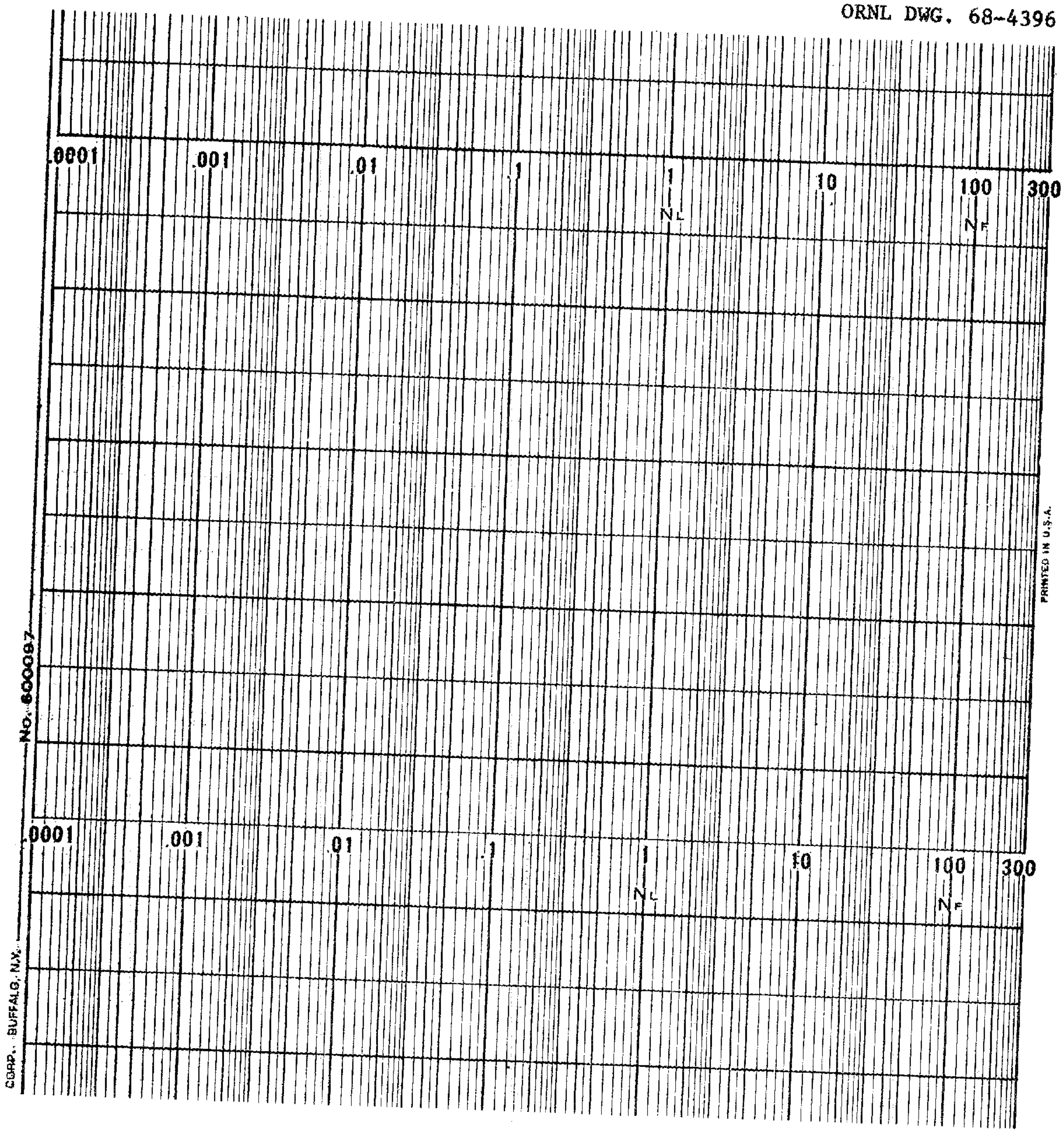

Fig. III-21. Chart Paper from a Log-N Recorder

ORNL DWG. 68-4397

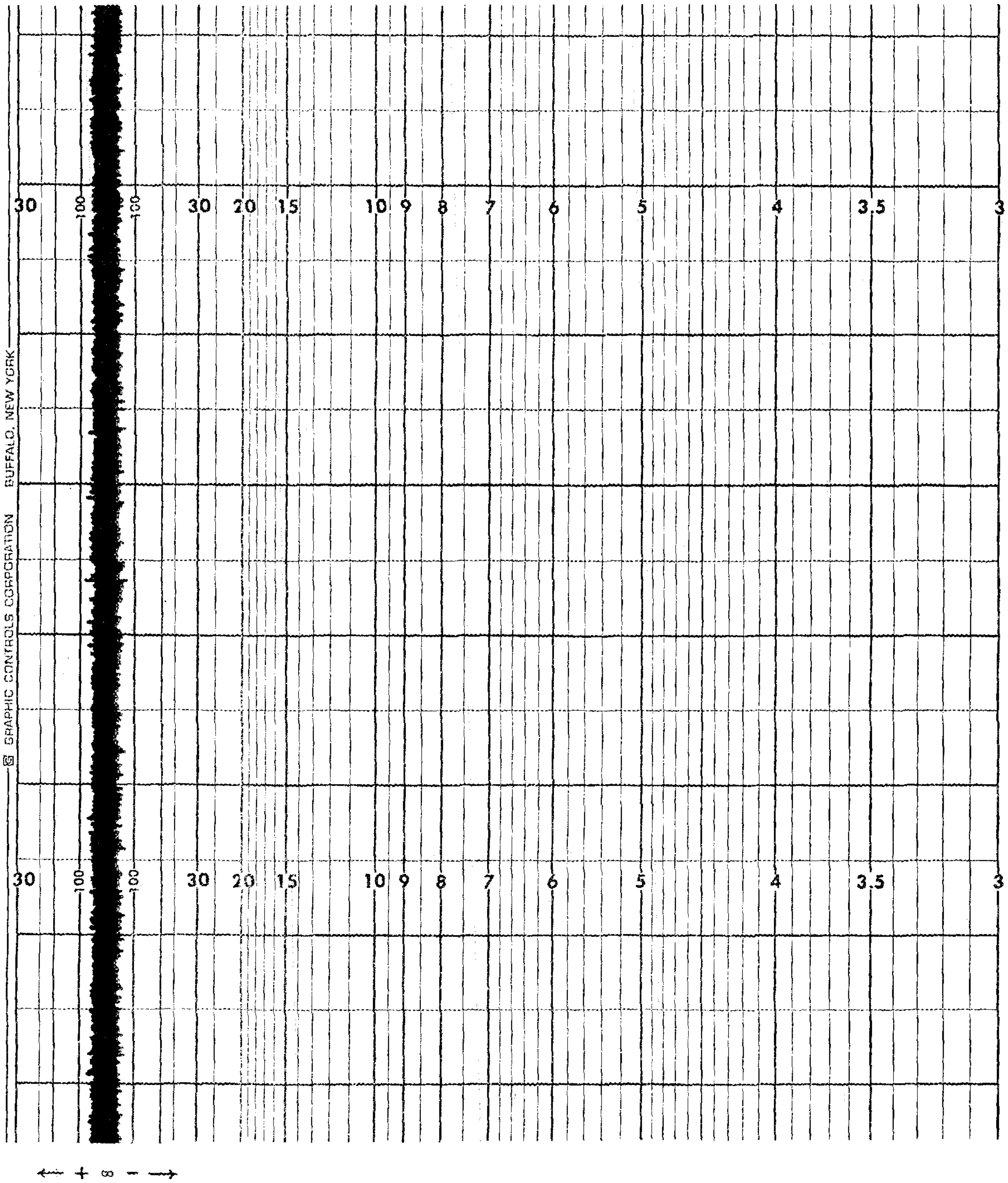

Fig. III-22. Chart Paper from a Log-N Period Recorder

64. By observing the recorder, it can be determined whether or not the reactor power level is steady with an ____________________(∞) period, decreasing with a _____________ period, or increasing with a _________________ period.

logarithm, neutron

\- - - - - - - - -

65. Figure III-22 shows a piece of chart paper from a recorder which indicates the period of a reactor. The reactor period is the time necessary for the neutron population to increase by a factor of e, which is ___________________.

infinite, negative, positive

\- - - - - - - - -

> The details of the instrumentation are discussed in Part V, entitled Instrumentation and Controls. For our purposes now, it is enough to know only that this information is displayed on recorders.

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66. If we did not have a period recorder, we would have to calculate the period by using an equation and observing the time interval for a change in the neutron flux as indicated on the log-N recorder. This kind of calculation can be relatively slow; and, when operating a reactor, we need to know every instant at what rate the neutron flux or reactor power is increasing.

2.72

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67. In order to become familiar with the relationship between the neutron flux as indicated on a log-N recorder and the period as indicated on a period recorder, let us consider an equation which illustrates the relationship. Remembering that the period recorder is based on powers of e and the log-N recorder is based on powers of 10, we must have some way to relate one to the other. The relation is: $e^y = 10^{y/2.3}$.

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68. If we allow $y = t/\tau$, the equation $n = n_o e^{t/\tau}$ can be changed to $n = n_o \times 10^{t/2.3\tau}$. It is easier to remember if we write the ratio n/n_o = ________.

- - - - - - - - -

69. Now, if we observed that it takes 23 sec for the neutron flux to increase from 1 to 10, then substitution of t = 23 sec, $n_o = 1$, and n = 10 into the equation $\frac{n}{n_o} = 10^{t/2.3\tau}$ will give us $\frac{10}{1} = 10^{23/2.3\tau}$. This is equivalent to $10 = 10^{10/\tau}$ or $10^1 = 10^{10/\tau}$. $10^{t/2.3\tau}$

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70. If you remember your logarithms, you should remember that if $10^a = 10^b$ then a = b. You can verify this by substituting any number for a and then determining the value of b. So, if $10^1 = 10^{10/\tau}$, 1 = ____; and, solving for τ, τ = ________ sec.

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71. In the above problem the reactor period is _____ sec. This means that the neutron population is ________ by a factor of e every 10 sec. $10/\tau$, 10

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72. If, instead of the above answer, we found that the reactor period was -10 sec, we would know that the neutron population was ____________________.

10, increasing

- - - - - - - - - -

73. We have calculated the period by timing the increase in neutron population from 1 to 10, which took 23 sec; but we had to wait 23 sec and then do the calculating, whereas if we had a period recorder, we would have known shortly after the increase started what the population would be 23 sec later or any time after the increase started.

decreasing

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74. Knowledge of the period is very, very important because it tells us immediately the ______________ population growth rate so that we can predict n at any later time.

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75. Suppose the neutron flux, Φ, in a reactor has gone from 1 to 100 in 23 sec. Calculate the period that the reactor was on during this time.

neutron

$$\frac{n}{n_o} = 10^{t/2.3\tau}$$

$$\frac{100}{1} = 10^{23\ \text{sec}/2.3\tau}.$$

We know that:

$$100 = 10^2,$$

so we substitute 10^2 in the above problem as:

$$10^2 = 10^{10/\tau}$$

$$\tau = \underline{\qquad\qquad}.$$

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76. A prediction of the eventual power level of a reactor can also be made using the same equation by substituting power level for neutrons. 5 sec

$$P = P_o 10^{t/2.3\tau}.$$

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77. Let us assume that a reactor is critical and operating at some power level, P_o. Then the operator withdraws a control rod so that the power level starts increasing. By observing the log-N recorder, he notices that the power level, P_o, which was 2 kw before he pulled the rod is 200 kw 30 sec later. By using the same equation for the neutron flux, what τ did the reactor have during the increase?

- - - - - - - - -

$$\frac{200 \text{ kw}}{2 \text{ kw}} = 10^2 = 10^{\frac{30 \text{ sec}}{2.3\tau}}$$

$$2 = \frac{30 \text{ sec}}{2.3\tau} = \frac{13 \text{ sec}}{\tau}$$

$$\tau = \frac{13 \text{ sec}}{2} = 6.5 \text{ sec}$$

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78. Note in the above problem that the power change was from 2 to 2×10^2 which is an increase by a factor of 2 powers of 10 (2 decades). We could have written our equation:

$$\text{number of decade changes} = \frac{\text{time (sec)}}{2.3\tau},$$

or,

$$\tau = \frac{\text{time (sec)}}{2.3 \times \text{number of decade changes}}.$$

- - - - - - - - -

79. A further simplification gives:

$$\tau = \frac{0.44t}{D},$$

where 0.44 is 1/2.3; t is time in sec; and D is the number of _____________ _______________.

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80. If a change in neutron population from 10 to 100 is 1 decade change, give the decade changes for the following: decade changes

n_o	n	Decade Changes
2	200	______
50	50,000	______
15	1,500	______
3	30	______
10	100,000	______

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It should be pointed out that this equation ($\tau = 0.44t/D$) should be used only when considering a whole number of decades, 1, 2, or 7, etc.; when a fraction of a decade is to be used, the equation $n = n_o e^{t/\tau}$ should be used.

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81. On a certain startup you note that the log-N reading goes from 0.005 to 0.5 in 20 sec. During that time the reactor was on a _______________ period. 2, 3, 2, 1, 4

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81. Table III-4 is a partial listing of power levels and periods as would be observed on the recorders of an operating reactor. Some of the spaces were left blank purposely so that you could use the equations given so far to determine these values and fill in the blanks. 4.4 sec

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Table III-4. Power Levels and τ

Log-N Recorder Reading		Number of Decades	Time Interval	τ
From:	To:			
1	10	1	20 sec	_____
1	100	2	20 sec	_____
1	1,000	3	20 sec	_____
1,000	100	-1	200 sec	_____
10	10	___	1 hr	_____
10	_____	___	92 sec	40.5 sec
100	10,000	___	_____	33.0 sec
100	_____	3	30 sec	_____

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83. Now that we have calculated the τ of a reactor by timing the decade change and using the equation $\tau = \frac{0.44(t)}{D}$, let us consider the determination of the rate at which a <u>decade change</u> occurs by observing the period. To do this we solve the equation for $\frac{D}{t}$, which is the rate at which __________ ____________ occur. Our new equation is:

$$\frac{D}{t} = \frac{0.44}{\tau}.$$

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84. This equation says that the number of decade changes in an interval of time t is equal to 0.44 divided by the period τ. Now the period is almost always given in seconds, but it may take several minutes for a decade change to occur; so by multiplying

decade changes

$$\frac{0.44}{\tau\ (\text{sec})} \times \frac{60\ (\text{sec})}{1\ (\text{min})}$$

we get

$$\frac{D}{t} = \frac{26}{\tau}$$

so that now by dividing 26 by the value of the period (in seconds) we can determine the number of decade changes per minute for the neutron flux (or the density, or the power level).

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85. In the equation $\frac{D}{t} = \frac{26}{\tau}$, t is time in ____________ and τ is in ______________________.

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minutes, seconds

86. The number of decades per minute increase in the neutron flux is a convenient measure of the "startup rate", and so we will write <u>decades per minute</u> $= \frac{26}{\tau\ (\text{in sec})}$. We could also write:

τ = 26 × minutes it takes for reactor power to increase one decade.

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87. Suppose we are observing a 10-sec period on a period recorder, then we could say the startup rate is ______________________________.

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2.6 decades per minute because decades per minute = 26/10 = 2.6.

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88. If the power level in Frame 87 was 100 kw when the 10-sec period was first noted, after a minute the power level would have increased __________ decades. From 100 kw (or 0.1 Mw) to 1 Mw is one decade and from 1 to 10 Mw is another decade. So the power would be at some level between 10 and 100 Mw.

- - - - - - - - -

89. To calculate where between 10 Mw and 100 Mw the power level actually is, we will need to use logarithms. The power increase started from 100 kw and went to $10^{2.6}$ above 100 kw. 2.6

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90. Recall that the exponent 2.6 is the logarithm of the number we want and 0.6 indentifies the number because it is the mantissa of the number. Look up 0.6 in a table of common logarithms and the antilog is three-nine-eight. We have already determined that the power level is between __________ and __________, so it is actually ______ Mw.

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91. A reactor which is on a 13-sec period would have a startup rate of 2 decades per minute; a period of 26 sec would give a startup rate of 1 decade per minute. What this says is that if a reactor is on a 13-sec period, then in 1 min the power level would increase from 1 Mw to 100 Mw or from 10 Mw to 1,000 Mw, etc.; that is, the power would increase by a factor of 100 in 1 min. A longer period such as 26 sec would give a slower startup rate, which would be 1 decade per minute, so that in 1 min the power level would increase from 1 Mw to _______ or from 10 Mw to __________.

10 Mw, 100 Mw, 39.8

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92. The relationship between reactivity and period may not have occurred to you yet, so let us discuss how these two things are related.

10 Mw, 100 Mw

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93. Reactivity is produced by a change in the multiplication factor from unity. Any change in the multiplication factor will change the rate at which the neutron population changes. The period describes the rate of change in the neutron population.

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94. You recall that when a control rod is withdrawn any amount from a critical reactor core, it causes a (positive, negative) reactivity change (by the removal of poison). By introducing this positive reactivity, the multiplication factor may be increased to a value (equal to, greater than) one, in which case the neutron population starts increasing. Indications of these changes can be observed on log-N and period recorders.

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95. The effects of control-rod withdrawal and insertion are shown in Fig's. III-23 and III-24. positive, greater than

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96. There is an interesting thing about the period recorder chart (Fig. III-24). You will notice that immediately after each rod withdrawal, the period changes from ∞ to a short, positive period at the instant the control rod is withdrawn; then it settles back to a longer, stable positive period. You can also see that when the rod is inserted, there is immediately a change in the period to a short, negative period; then it settles back to a longer, stable negative period.

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97. The immediate large change in the period is referred to as a transient period which is of very short duration, and the longer, stable period is called the stable period. The stable period is the reactor period that we have been discussing. We shall now consider the cause of the transient period.

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98. When a control-rod adjustment is made to increase the reactivity of the core, the period recorder indicates a small positive period for a very short time. This period is called a ______________ period.

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99. After the short transient period, the recorder pen settles back to an indication of a longer period. This period does not change quickly and is thus called a ______________ period. transient

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ORNL DWG. 68-4398

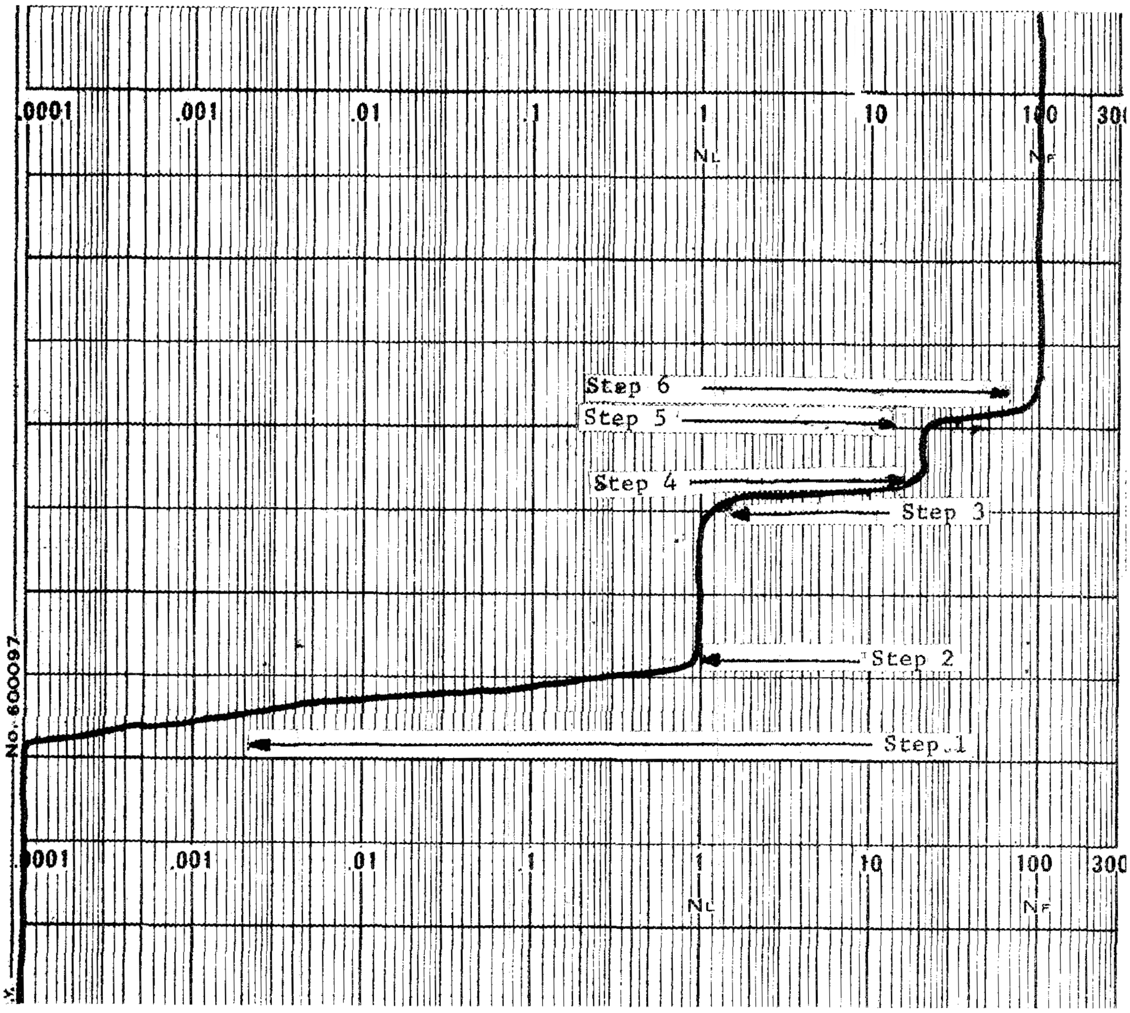

Fig. III-23. Log-N Chart Showing the Effect of Rod-Position Change

ORNL DWG. 68-4399

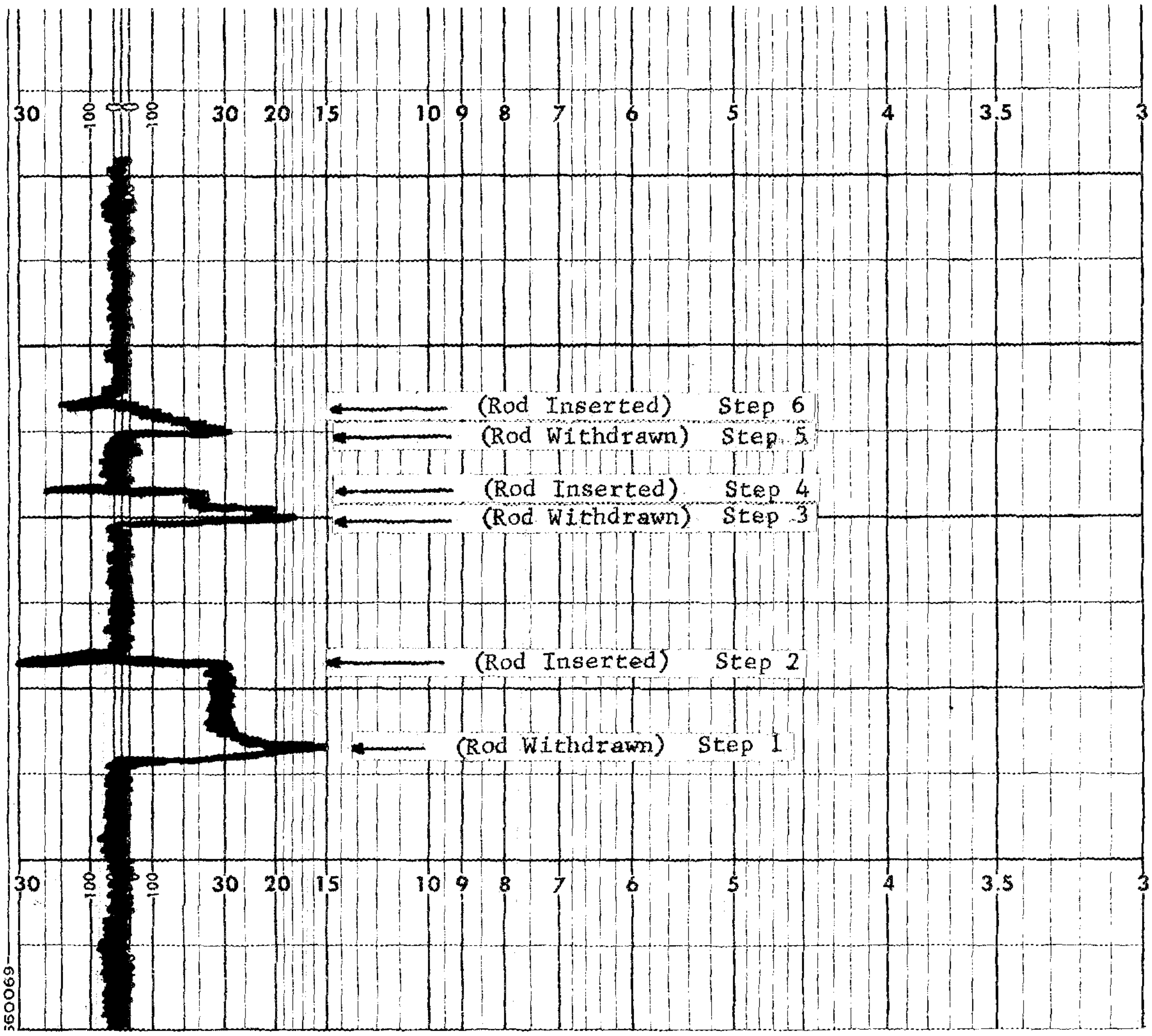

Fig. III-24. Log-N Period Chart for Rod Changes

100. The period that changes quickly with a control-rod change is the ____________ period. The period that is indicated <u>after</u> the control-rod movement has been made, and remains relatively constant, is the ____________ period.

stable

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101. You will recall that in a chain reaction involving billions of fission reactions about 99 and 25/100% of the neutrons emitted are released the instant (within 10^{-14} sec) atoms undergo fission. These neutrons are called ______________ neutrons.

transient, stable

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Prompt--If you said fast, you had better review Section 2.

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102. The other 0.75% of the fission neutrons are released from fission products over a period of several minutes. These neutrons are called ____________ neutrons.

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103. It should be obvious that both prompt and delayed neutrons can cause fission reactions resulting in more prompt and delayed neutrons. The only difference between them is the amount of time it takes for their release from the fission reaction. Prompt neutrons are released __________, whereas delayed neutrons are released ________________.

delayed

- - - - - - - - -

Immediately or instantaneously or within 10^{-14} sec,
Over a period of several minutes.

- - - - - - - - -

104. There are actually at least six distinct groups of delayed neutrons. These groups are categorized according to the decay half-life of the fission products which emit them. Table III-5 is a list of these groups. The "delayed neutron fraction" is that fraction of the total neutrons emitted which are delayed because they come from fission fragments.

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Table III-5. Delayed Neutron Groups from ^{235}U Fission

	Half Life of Emitter (sec)	Delayed Neutron Fraction (β_i)	Resultant Negative Reactor Period Following Scram (sec)
1	54.510	0.0002575	∿80.00
2	21.840	0.0014440	∿31.00
3	6.00	0.0012750	∿ 8.70
4	2.23	0.0027600	∿ 3.20
5	0.496	0.0008680	∿ 0.71
6	0.179	0.0001760	∿ 0.26

- - - - - - - - -

3.3. Prompt Criticality

105. It should be pointed out that if there were no delayed neutrons, the increase in the neutron flux and, therefore, the power level of a reactor would increase at a rate dependent on the prompt-neutron generation time (lifetime) which, generally, is less than 0.001 sec (depending on the moderator and other factors).

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106. This rate of increase of power level would be almost too fast to control. A reactor that operated without delayed neutrons would be (easy, difficult, very difficult) to control.

- - - - - - - - -

107. As long as any increase in k is small enough, the delayed neutrons make the effective generation time for neutrons rather long. Thus, for the reactor to be controlled, k must be small enough for the power increase to be dependent on ____________ neutrons. — very difficult

- - - - - - - - -

108. Figure III-25 shows the relative rate of increase in power level (also n and ϕ) which would result if there were no delayed neutrons as compared to an actual rate of increase. Note that in about 0.1 sec (the blink of an eye) the power level would have gone from 100% to roughly _____%. — delayed

- - - - - - - - -

109. The fact that an actual reactor does have both prompt and delayed neutrons does not mean that it cannot be hazardous. Actually, it is possible to introduce enough reactivity in a reactor so that it is critical on prompt neutrons only. This is called prompt criticality. — 200

- - - - - - - - -

110. Prompt criticality is a condition which should not be allowed to occur in a reactor because power increases would occur too rapidly for safe ______________.

- - - - - - - - -

111. The condition for prompt criticality occurs when $k_{eff} - 1$ or k excess is increased enough that $k_{eff} - 1$ is equal to the fraction of neutrons which are delayed. This fraction is represented by β, which, for ^{235}U, is 0.0075. — control or operation

- - - - - - - - -

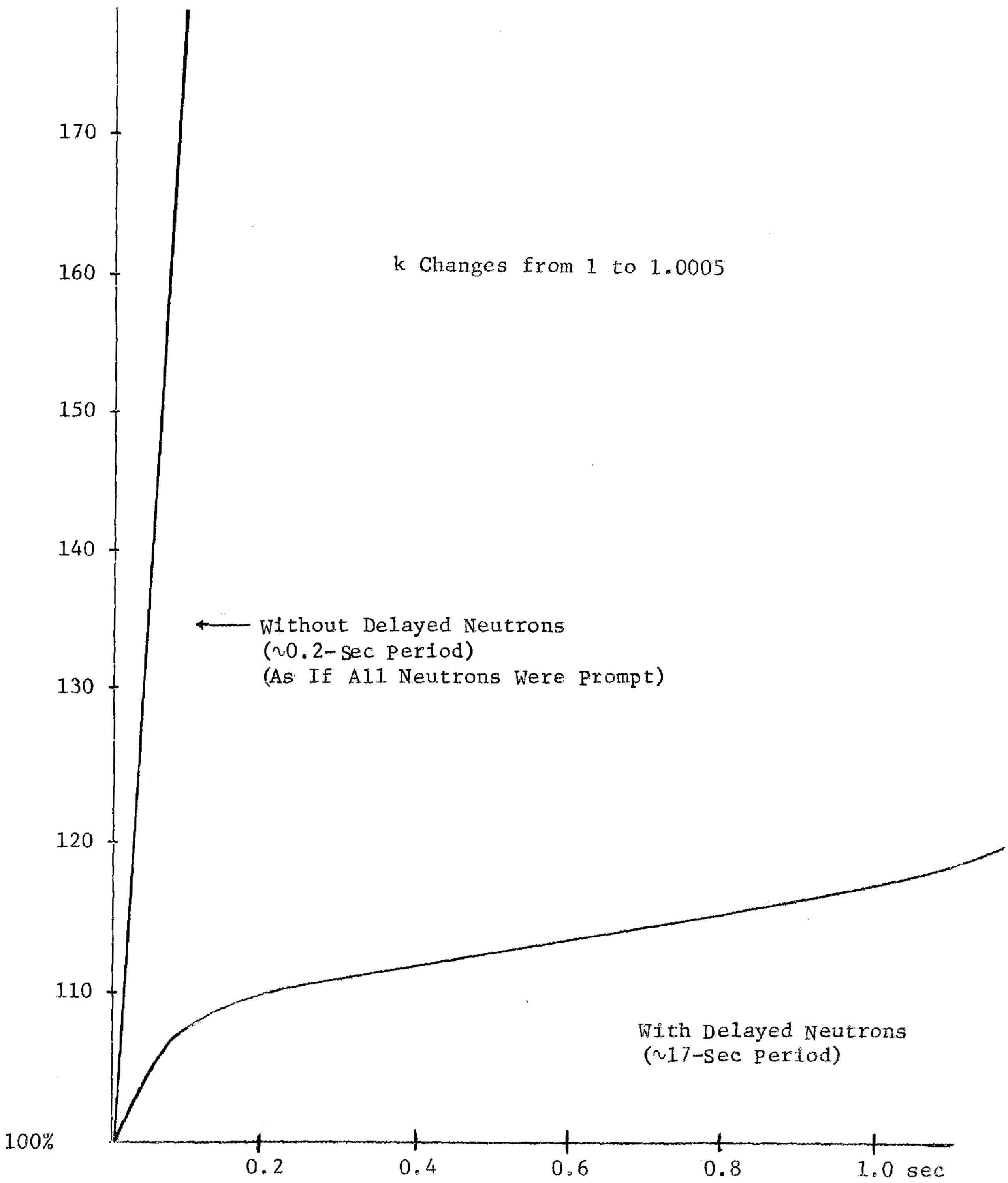

Fig. III-25. Delayed Neutron Effect on Power Increase

While β for ^{235}U is 0.0075, fast neutrons from sources other than fission are produced in some reactors. In water-moderated reactors, the predominant source of nonfission fast neutrons is the reaction of high-energy gamma photons with the small amount of deuterium normally present in water. Since the fission process itself and very short-lived fission products are sources of very high-energy gamma photons, the neutrons produced by the gamma photon deuterium interactions are produced almost simultaneously with the prompt neutrons from fission. This source of neutrons effectively increases the value of the prompt-neutron fraction, $1 - \beta$, and β is effectively lowered. Thus, the effective delayed-neutron fraction (β_{eff}) for ^{235}U in a water-moderated reactor usually has a value less than 0.0075.

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112. In equation form when $k_{eff} - 1 = \beta$, we have the unsafe condition which is called ____________ ____________________________.

- - - - - - - - -

113. Since $\Delta k/k$ is equal to $\frac{k_{eff} - 1}{k_{eff}}$, for the prompt-critical condition we would have: — prompt criticality

$$\frac{k_{eff} - 1}{k_{eff}} = \frac{\beta}{k_{eff}}.$$

If $\beta = 0.0075$, the effective multiplication factor would be 1.0075.

- - - - - - - - -

114. It is shown in some textbooks that for a reactor operating on prompt neutrons alone, the stable period would be

$$\tau = \frac{\text{neutron lifetime}}{k_{eff} - 1}$$

- - - - - - - - -

115. In a water-moderated reactor such as the ORR, the neutron lifetime is about 10^{-4} sec and β_{eff} is 0.0060; so, for a prompt-critical condition, the stable period would be:

$$\tau = \frac{0.0001\ \text{sec}}{0.0060} = \underline{\qquad}\ \text{sec}$$

\- - - - - - - - -

116. If at startup something should happen to place the ORR on a 0.017-sec period when the power level was 100 kw, in 0.23 sec the power level would be: 0.017

$$P = P_o(10^{t/2.3\tau})$$
$$P = 100\ \text{kw}(10^{0.1/\tau}) = 10^2\ \text{kw} \times 10^{0.1/0.017}$$
$$= 10^2\ \text{kw} \times 10^6$$
$$P = 10^8\ \text{kw or } 100{,}000\ \text{Mw.}$$

\- - - - - - - - -

117. Control of a reactor which is prompt critical would be extremely difficult; therefore, special precautions must be taken to ensure that this condition never occurs in reactor operation.

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118. Some of the precautions taken to prevent prompt criticality in a reactor are special core loading procedures, limiting control-rod drive speeds to prevent fast reactivity increases by the control rods, automatic reactor shutdown devices, and many others.

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119. A k_{eff} unit called the "dollar" is based upon β. A dollar is equal to $k_{eff} - 1$ divided by β. In equation form this is:

$$\$ = \frac{k_{excess}}{\beta}$$

where k_{excess} is $k_{eff} - 1$ and expresses how much greater than one the multiplication factor is.

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120. A "cent" is one-hundredth part of a dollar. When a reactor is prompt critical, it has a k_{excess} of one dollar. If β is 0.0075, a k_{excess} of fifty cents would give a neutron multiplication of:

$$0.50 \times 0.0075 = 0.00375$$
$$(\$) \times (\beta) = k_{ex}$$

and since $k_{ex} = k_{eff} - 1$, we would have a k_{eff} of 1.00375.

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121. If we have a critical reactor which has a β_{eff} of 0.0060 and k were to be increased by one dollar, this would result in an effective multiplication factor (k_{eff}) of ____________. The reactor would be ____________ critical.

- - - - - - - - -

1.006,
prompt

3.4. Self Test

122. The neutron multiplying properties of a reactor can be expressed as ________________. $\Delta k/k$ is equal to ______________/k_{eff}. (If you made an incorrect response, repeat Frames 1-6.)

- - - - - - - - -

123. An increase in k has a positive effect on __________. A negative effect on reactivity results from ______________ k. (If you made an incorrect response, repeat Frames 11-14.)

reactivity, $k_{eff} - 1$

- - - - - - - - -

124. The addition of fuel to a critical mass results in a _________________ reactivity. (If you made an incorrect response, repeat Frames 15-18.)

reactivity, decreasing

- - - - - - - - -

125. To compensate for various reactivity changes in a reactor such as those due to fuel burnup, temperature effects, etc., adjustments are made with the ____________ ________. (If you made an incorrect response, repeat Frames 19-24.)

positive

- - - - - - - - -

126. Neutron lifetime is the time it takes for a neutron to ____________________. (If you made an incorrect response, repeat Frame 38.)

control rods

- - - - - - - - -

Be born from fission, go through the slowing down process, and be either absorbed or lost by leakage.

- - - - - - - - -

127. The term "period" is considered to be ______________. (If you made an incorrect response, repeat Frames 41-46.)

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The time it takes for the neutron population to change by a factor of 2.72 (e).

\- - - - - - - - -

128. If the neutron population now is $n_o = 100$ neutrons/cm^3 and the reactor is on a 10-sec period, the neutron population 10 sec from now will be ________________. (If you made an incorrect response, repeat Frames 47-51.)

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$$n = n_o e^{t/\tau}, \text{ so } n = 100(e^{\frac{10 \text{ sec}}{10 \text{ sec}}}) \text{ or}$$
$$n = 100\, e^1 = 100(2.72) = 272 \text{ neutrons/cm}^3$$

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129. The power level of a reactor will increase more rapidly if the period is (5 sec, 20 sec). If the reactor has an infinite period, the power level is ______________. (If you made an incorrect response, repeat Frames 53-61.)

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130. The period a reactor has gives us an indication of what the neutron population ____________________ at any later time. (If you made an incorrect response, repeat Frame 74.)

5 sec, steady

\- - - - - - - - -

131. If the neutron flux increases from 1 to 100 (2 decades) in 23 sec, the period of the reactor is ______________. (If you made an incorrect response, repeat Frames 75-85.) — will be

- - - - - - - - - -

$$\tau = \frac{\text{time}}{2.3 \times \text{number of decades}} = \frac{23 \text{ sec}}{2.3 \times 2} = 5 \text{ sec}$$

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132. The startup rate can be expressed in decades per minute and in equation form is equal to:

$$\text{decades per minute} = \frac{26}{\tau(\text{in sec})}.$$

So if a reactor has a 13-sec period, in one minute the neutron flux will increase from 1 neutron/cm^2 • sec to ______________. (If you made an incorrect response, repeat Frames 84-90.)

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133. The difference between a transient and stable period is that a transient period exists only for a (short, long) interval of time. (If you made an incorrect response, repeat Frames 97-100.) — 100 n/cm^2 • sec

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134. Prompt criticality means ________________________. (If you made an incorrect response, repeat Frame 109.) — short

- - - - - - - - - -

A reactor is critical on prompt neutrons.

- - - - - - - - - -

135. When a k_{eff} increase is equal to the delayed neutron fraction, β, a reactor will be ________________ critical. (If you made an incorrect response, repeat Frames 111-115.)

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136. For a reactor with β = 0.006, a dollar's worth of k_{excess} is equivalent to ________________. (If you made an incorrect response, repeat Frames 119-121.)

prompt

- - - - - - - - - -

0.006

SECTION III-4

FUEL BURNUP

The purpose of this section is to discuss the effects on reactivity and reactor operation due to fuel burnup in a reactor.

4.1. Fuel Requirements for Critical Mass

1. Fuel burnup is the decrease in the fuel (fissionable material) as a result of fission reactions destroying fuel atoms.

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2. You should know by now that there is a minimum amount of fissionable material which is required before a chain reaction can be sustained. This minimum mass of fuel is called the ________________ ____________.

- - - - - - - - - -

3. When fission reactions occur, atoms of the fissionable material are removed from the supply. Eventually the supply will become less than the critical mass. When this occurs, the reactor will become (subcritical, critical, supercritical) and will (shut down, operate, start up).

critical mass

- - - - - - - - - -

4. In order to maintain continued operation after a reactor is made critical, it is necessary to have some extra fuel (and control measures) in addition to the ____________________ ____________________.

subcritical,
shut down

- - - - - - - - - -

5. The reactivity effect of the extra fuel is offset by ____________________, the control rods. As this extra fuel is consumed (burned up), control rods are withdrawn so that criticality is maintained. — critical mass

\- - - - - - - - -

6. When the control rods have been withdrawn as far as possible, the continuing burnup of the fuel results in the reactor becoming __________________ and shutting down. A new supply of fuel must then be added so that operation can be resumed. — poison

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7. Now you might ask, "Why don't we load enough extra fuel into the core initially so that we would operate for very long periods of time?" This would be desirable, but the control rods can control only so much reactivity. If we were to place more fuel in the core than the control rods could handle, then k_{eff} would be greater than one; even with the rods inserted, the neutron population would start increasing; and there would be no way to stop the power-level increase so the reactor would melt down. — subcritical

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8. It is general practice to limit the amount of __________________ available to the core to one-half of the amount that the poisons in the control rods can balance. This practice is followed because of considerations for safety. A large error in a fuel loading could still be controlled, or failure of half the control rods would not prevent the reactor from being shut down.

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9. Limiting the amount of reactivity available to a core to one-half the control-rod reactivity control capability is generally referred to as a <u>shutdown factor</u> of 2--since the control-rod reactivity worth is ________________________ as much as the maximum reactivity which can be given to the core. — reactivity

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10. A shutdown factor of 3 would mean that the reactivity worth of the control rod is exactly ________ _______ the reactivity worth of the excess fuel loaded into the core. — two times or twice

- - - - - - - - -

11. At the ORR Reactor, for example, a shutdown factor of 2 implies that the reactor must not become critical until all of the control rods (6), when withdrawn together, are at least halfway out of the core. — three times

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12. After criticality is established in a reactor, withdrawing a control rod slightly, to make a positive reactivity change so that k becomes greater than one, causes the power level to _______________. When the power is at the desired level, the control rod is inserted just enough to stop the positive period and to reestablish criticality ($k = 1$ and $\tau = \infty$).

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4.2. Fuel Loading

13. As the reactor operates, many fission reactions occur. The fuel is consumed (-Δk/k effect) at a fairly uniform rate, and the control rods are gradually withdrawn to give a +Δk/k effect, which exactly balances the effect of the ______________ consumed. At the ORR, the control rods are withdrawn at a uniform rate of ∿0.5 in. per day to compensate for fuel burnup. — increase

- - - - - - - - -

14. In order for a reactor to operate at a 30-Mw heat-output power level, 95.5×10^{16} fissions must occur each second--this means that 955,000,000,000,000,000 atoms of ^{235}U are consumed every second. One pound of ^{235}U has about 12×10^{23} atoms. — fuel

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15. In the actual operation of the ORR Reactor, about 1.26 g of ^{235}U are lost for each megawatt-day (Mwd) of operation. Operation at 30 Mw for one day consumes $30 \times 1.26 = 37.8$ g of ^{235}U. Of the 1.26 g lost per Mwd, only 1.07 g/Mwd actually fission because only about 85% of the fuel atoms which absorb neutrons undergo ______________. The other 15% remain as ^{236}U.

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16. The ORR will generally operate for about 14 days before refueling is required. Therefore, 14 days × 37.8 g/day is a total of ∿529 g (a little over one pound) of fuel burnup for 14 days of operation at 30 Mw. (About 454 g = 1 lb.) — fission

- - - - - - - - -

When an atom of ^{235}U undergoes fission, about 200 Mev of energy is released to produce heat. If we had 1 g of ^{235}U, and if over a period of 24 hrs all of the atoms underwent fission at a constant rate, a power level of 1 Mw would result (1,000,000 watts). To give you a comparison, the energy release due to fission of all the atoms in 1 g of ^{235}U is equivalent to ten thousand 100-watt light bulbs burning for an entire day.

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17. The lifetime of a fuel element will obviously depend on the rate at which the fuel is being used--that is, the power level of operation. More fission reactions per second are required for a higher power level, resulting in a faster fuel ______________ rate.

- - - - - - - - -

Another factor which affects the useful lifetime of a fuel element is the maximum burnup allowable. It may be 10% or 40%, etc. Obviously, it could not be 100% because of the critical mass requirement.

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18. In the ORR, when about 35% of the ^{235}U in a fuel element has been consumed, the element is considered to be "depleted". It is then replaced. In the HFIR the fuel depletion or ____________ is about 31%. burnup

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19. There are several other factors which affect the lifetime of a fuel element. One of the more important is the accumulation of fission products. Some of the fission products are strong neutron absorbers such as ^{135}Xe and ^{149}Sm. As the chain reaction proceeds, some of these products accumulate in the fuel element, thus tending to (lengthen, shorten) the lifetime. (Xenon-135 decays away but ^{149}Sm and others do not.) burnup

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20. When a fuel element is finally considered to be depleted, that is, when it is considered uneconomical to use it further, the element is stored for a "cooling" period. shorten

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21. This cooling period (usually 90 days) allows the shorter half-lived radioactive isotopes to decay away so that the radiation through the shielding of a shipping container is as low as is practical. The element is then shipped to a processing plant and the unused ^{235}U is reclaimed for reuse.

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22. The effect on the reactivity when a fuel element replacement is made can be estimated from the equation,

$$\frac{\Delta k}{k} = C \frac{\Delta M}{M} \frac{\overline{\phi}_i}{\overline{\phi}_C}$$

where $\Delta k/k$ is the reactivity, ΔM is the difference in the fuel mass of the two elements exchanged, M is the total fuel mass, $\overline{\phi}_i/\overline{\phi}_C$ is the ratio of the neutron flux at that position to the average flux in the entire core, and C is a constant found by experiment. (For the ORR, $C \approx 0.35$.) The flux may vary considerably from the center of the core to the outer regions of the core.

- - - - - - - - - -

23. Let us assume that the flux at a particular position in the core is the same as the average flux in the core. This would mean that $\overline{\phi}_i/\overline{\phi}_C = 1$. Now suppose a fuel element containing 180 g of ^{235}U were removed from that core position and replaced with an element containing 200 g of ^{235}U. The mass of ^{235}U in the core before the change was 5,000 g (about 10 lbs). The reactivity addition would be:

$$\frac{\Delta k}{k} = 0.35 \times \frac{200 - 180}{5{,}000} \times 1 = \_\_\_\_\_\_.$$

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24. Now suppose that for the same core and position, that is, M = 5,000 g, $\overline{\phi}_i/\overline{\phi}_C = 1$, a new fuel element containing 200 g of ^{235}U was allowed to accumulate a burnup of 30 g. The loss of reactivity due to the burnup of this element would be minus ________. 0.0014

- - - - - - - - -

$$\frac{\Delta k}{k} = 0.35 \times \frac{170 - 200}{5{,}000} = 0.35 \times \frac{-30}{5{,}000} = -0.0021$$

- - - - - - - - -

25. Suppose an ORR-type reactor containing 4000 g of ^{235}U had a 5% reactivity decrease due to fuel burnup. How many grams of ^{235}U would have to be added to the core to compensate for this burnup? Assume $\overline{\phi}_i/\overline{\phi}_C = 1$ and M = 4,000.

- - - - - - - - -

$$\frac{\Delta k}{k} = 0.05 = 0.35 \times \frac{M}{4{,}000}$$

$$M = \frac{4{,}000 \times 0.05}{0.35} \simeq 570 \text{ grams}$$

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4.3. Self Test

26. Fuel burnup is ____________. (If you made an incorrect response, repeat Frame 1.)

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The decrease in fuel as a result of fission reactions.

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27. To maintain operation after a reactor is made critical, extra fuel must be provided in the core in addition to the ______________ ___________. (If you made an incorrect response, repeat Frame 2.)

- - - - - - - - -

critical mass

28. Continued fuel burnup in a reactor eventually results in a shutdown because ______________. (If you made an incorrect response, repeat Frames 5-8.)

- - - - - - - - -

The amount of fuel becomes less than the critical mass.

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29. A shutdown factor of 2 means ________________. (If you made an incorrect response, repeat Frame 9.)

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The control-rod reactivity worth is twice as much as the available reactivity provided in the core.

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30. In normal reactor operation, control rods are withdrawn gradually (at a fairly uniform rate) to compensate for __________ ___________. (If you made an incorrect response, repeat Frames 12-14.)

\- - - - - - - - -

31. The fuel burnup rate is faster for a (high, low) power level. A fast fuel burnup rate results in a (short, long) fuel-element lifetime. (If you made an incorrect response, repeat Frame 17.)

fuel burnup

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32. The purpose of a cooling period for a depleted fuel element is to ____________________________. (If you made an incorrect response, repeat Frame 21.)

high, short

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Allow the short-half-life radioisotopes to decay so the radiation through the shipping container shielding is as low as practical.

\- - - - - - - - -

33. If the neutron flux at a particular position in an ORR core is the same as the average flux of the core and a 190-g element is replaced with a 200-g element, what is the positive reactivity effect? Assume M = 5,000 grams. (If you made an incorrect response, repeat Frames 22-25.)

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$$\frac{\Delta k}{k} = 0.35 \times \frac{200 - 190}{5{,}000} = 0.35 \times \frac{10}{5{,}000} = 0.0007$$

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SECTION III-5

XENON AND SAMARIUM POISONING EFFECTS

The purpose of this section is to discuss the accumulation of neutron-absorbing fission products in a reactor and the resulting effect on reactor operation.

5.1. Fission-Product Poisons

1. When ^{235}U atoms undergo fission, fission fragments (two or three smaller atoms per fission--usually two) are formed which stay in the fuel element. Most of these fission-fragment atoms are radioactive and decay to form more stable atoms.

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2. Many of the fission fragments are so unstable that they must emit several beta particles in succession before becoming stable atoms. You will recall that each emission of a beta particle from the nucleus of an atom changes the atom to a different element.

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3. The atoms produced by the fission process, whether they have already decayed to stable forms or not, are referred to as "fission products".

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4. The accumulation of neutron-absorbing fission products in the core has a negative reactivity effect. Therefore, reactor operation is affected by the accumulation of neutron-absorbing ________________ ____________________.

- - - - - - - - - -

5. Two of the fission products which very seriously affect the operation of a reactor are ^{135}Xe and ^{149}Sm. — fission products

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6. Xenon-135 and ^{149}Sm are very strong neutron absorbers; therefore, the accumulation of these fission products in the fuel region of a reactor will have a large ________________ reactivity effect.

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7. The ability to absorb neutrons and to cause a negative reactivity effect should be apparent after looking at the values of the neutron absorption cross sections. Xenon-135 has a microscopic neutron-absorption cross section of about 3 million "barns". Samarium-149 has a neutron absorption cross section of ∿40,800 "barns". As a comparison, the neutron-absorption cross section of hydrogen (moderator) is about 0.3 barns. You will recall that a "barn" is a unit which represents 10^{-24} cm^2. — negative

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8. The strongest poison of the two fission products, ^{135}Xe and ^{149}Sm, is ________________________.

- - - - - - - - -

5.2. Buildup and Removal

9. Let us first consider ^{149}Sm. This poison is formed from the radiative decay of the fission product ^{149}Pm. Promethium-149 is a β^- emitter. You will recall that for the nucleus of an atom to emit a β^-, a ______________ in the nucleus must change to a proton and a negative electron (β^-) which is emitted. The proton left in the nucleus changes the element to the next higher element in the periodic chart of the elements, which is ________________. ^{135}Xe

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10. About 1.4% of all the fission reactions result in the formation of ^{149}Pm which is radioactive and emits a ________________ particle to decay to ^{149}Sm. The half-life of ^{149}Pm is 53 hrs, but ^{149}Sm is stable; it does not decay. The equation which says the same thing is: neutron, samarium

$$1.4\% \text{ of fissions} \longrightarrow {}^{149}Pm \xrightarrow{53\text{ hrs}} {}^{149}Sm \text{ (stable)}$$

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11. Some ^{135}Xe is formed directly from fission in about 0.3% of the fissions, but most of it is formed from the radiative decay of the fission product ^{135}I. beta or β^-

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12. Iodine is element 53 and xenon is element 54. In order to change from element 53 to element 54, a ________________ must be added to the nucleus. In this case a neutron must change to a ______________ and an ______________ which is emitted in a decay process called beta decay.

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13. Xenon-135 is formed primarily from the ____________ ________________ of iodine-____.

proton, proton, electron or β^-

- - - - - - - - -

14. About 5.6% of the total fission reactions result in the formation of ^{135}I, which is radioactive and has a half life of 6.7 hrs. Iodine-135 emits a ________ particle to decay to ^{135}Xe.

beta decay, 135

- - - - - - - - -

15. You will recall that protons and neutrons have very nearly the same mass. The mass number in the above illustration is __________ for xenon as well as for iodine.

beta

- - - - - - - - -

16. Xenon-135 is also radioactive and has a half life of 9.2 hrs. It emits a beta particle to decay to cesium-____.

135

- - - - - - - - -

17. So you can see that at the same time that fission products are being formed, they are also undergoing "loss" or "removal" processes by either radiative decay or by neutron absorption.

135

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18. These processes do not actually physically remove atoms, but they do change them to other types of atoms. For our purposes, then, we can consider the original atoms to have been lost or removed.

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19. Obviously, since both of the poisons have large neutron absorption cross sections, they both will readily ____________ neutrons and thus be transmuted (transformed) to become different types of atoms, usually with a lower neutron-absorption cross section.

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20. Since ^{149}Sm is not radioactive and does not decay, the only removal process is the transmutation due to ________________ ____________________.

absorb

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21. When ^{149}Sm absorbs a neutron, it is transformed into ^{150}Sm, which does not readily absorb neutrons; so the ^{149}Sm can be considered as having been removed. By absorbing a neutron, ^{149}Sm is transformed to a less absorbing atom and may be considered as being ________________ from the fuel region.

neutron absorption

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22. When ^{149}Sm absorbs a neutron, it remains samarium because the number of ____________ in the nucleus has not changed. However, its __________ has increased by one; and while it is not a different element, it is a different ____________ of samarium and thus has different characteristics, including neutron absorption cross section.

removed

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23. Xenon-135 is radioactive and decays to a less absorbing atom (^{135}Cs) or can absorb a neutron and become a different, less absorbing xenon atom. Thus ^{135}Xe is removed both by radiative __________ and by ____________ ____________________.

protons, mass, isotope or atom

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24. The radiative decay of ^{135}Xe results in the formation of ______________.

decay, neutron absorption

- - - - - - - - -

25. The neutron-absorption cross section of ^{135}Cs is so small that it can be neglected. So, the neutron-absorbing ability of the ^{135}Xe atom is removed when it is transformed into ^{135}Cs by ________ ________.

^{135}Cs

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26. The absorption of a neutron by ^{135}Xe transforms it into ^{136}Xe, which also has such a small neutron-absorption cross section that it can be ignored. Therefore, ^{135}Xe is removed by __________________ ____________ and by ____________ ____________.

beta decay or radiative decay

- - - - - - - - -

27. Because there are removal processes, the accumulation of these poisons during operation continues until the removal rate equals the formation rate. When this occurs, there will be no further change in the amount of these poisons present because the __________ rate equals the ____________ rate and the poisons are being removed as fast as they are being formed.

neutron absorption, radiative decay

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28. When the poison formation rate equals the removal rate, the poison is said to be in "equilibrium".

formation, removal

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29. The equilibrium concentration of xenon or samarium occurs when ____________________.

- - - - - - - - -

The removal rate is the same as the formation or "buildup" rate.

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30. Equilibrium xenon or samarium results in a constant negative reactivity effect (poisoning).

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31. The amounts of reserve reactivity or k_{excess} lost due to equilibrium xenon and equilibrium samarium are different, primarily because of the difference in the formation and removal processes and the neutron-absorption cross sections.

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32. The equilibrium poisoning effect of ^{149}Sm will reach essentially a constant value for a given reactor fuel, -0.01 $\Delta k/k$, regardless of the neutron flux (power level of operation) if the fuel concentration does not change.

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33. The equilibrium ________________ effect due to ^{135}Xe, however, is greatly affected by the neutron flux.

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34. The poisoning effect of equilibrium Xe and Sm must be compensated for, as is done for fuel burnup, by loading ____________ fuel into the core in addition to the critical mass. poisoning

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35. Equilibrium Sm is reached in a high-flux reactor ($\phi \geq 10^{14}$ n/cm^2 • sec) after about 7 days of operation, whereas equilibrium Xe is reached after about 1 day of operation.

extra or excess

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36. Figure III-26 shows the rate of buildup to equilibrium Xe as compared to the buildup of Sm for a reactor operating at a neutron flux level of $\sim 10^{14}$ neutrons cm^{-2} • sec^{-1}.

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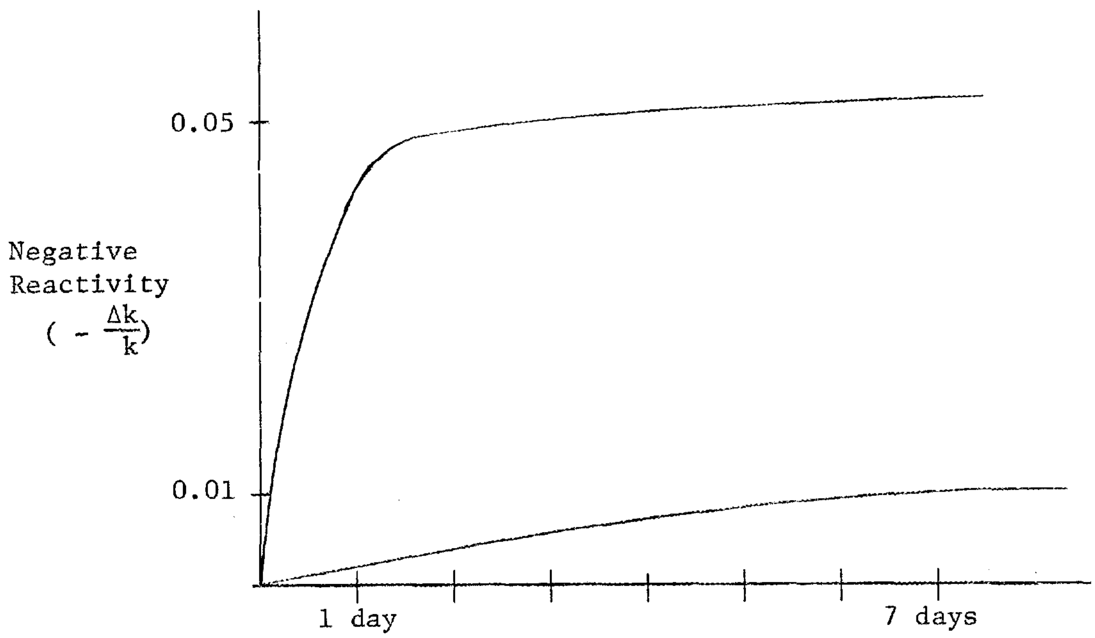

Fig. III-26. Xe and Sm Buildup

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37. Figure III-27 shows, roughly, the relationship between the equilibrium Xe poisoning and the neutron flux of reactors. This is an indication of the amount of fuel that has to be added to compensate for the equilibrium Xe.

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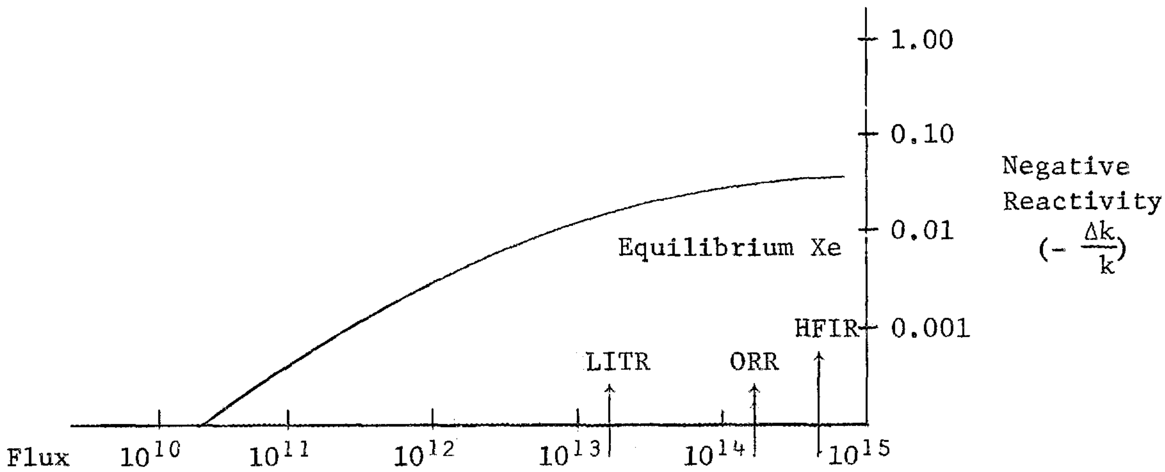

Fig. III-27. Equilibrium Xenon for Different Power Levels

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38. The initial buildup of xenon to the equilibrium value can be observed indirectly quite easily in reactors operating at neutron fluxes of 10^{13} neutrons cm^{-2} sec^{-1} or greater. In the ORR, for example, after the operating power level has been reached, there is a fairly rapid withdrawal of the control rods for about 24 hrs to compensate for the xenon buildup to the equilibrium level. The rod withdrawal rate to compensate for this buildup is about 3 in. the first day. After xenon equilibrium is reached, the control rods are withdrawn at the rate of about 1/2 in. per day to compensate for fuel burnup. This is shown in Fig. III-28.

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39. Once the equilibrium xenon concentration has been reached, it will remain approximately constant unless the reactor power level is changed.

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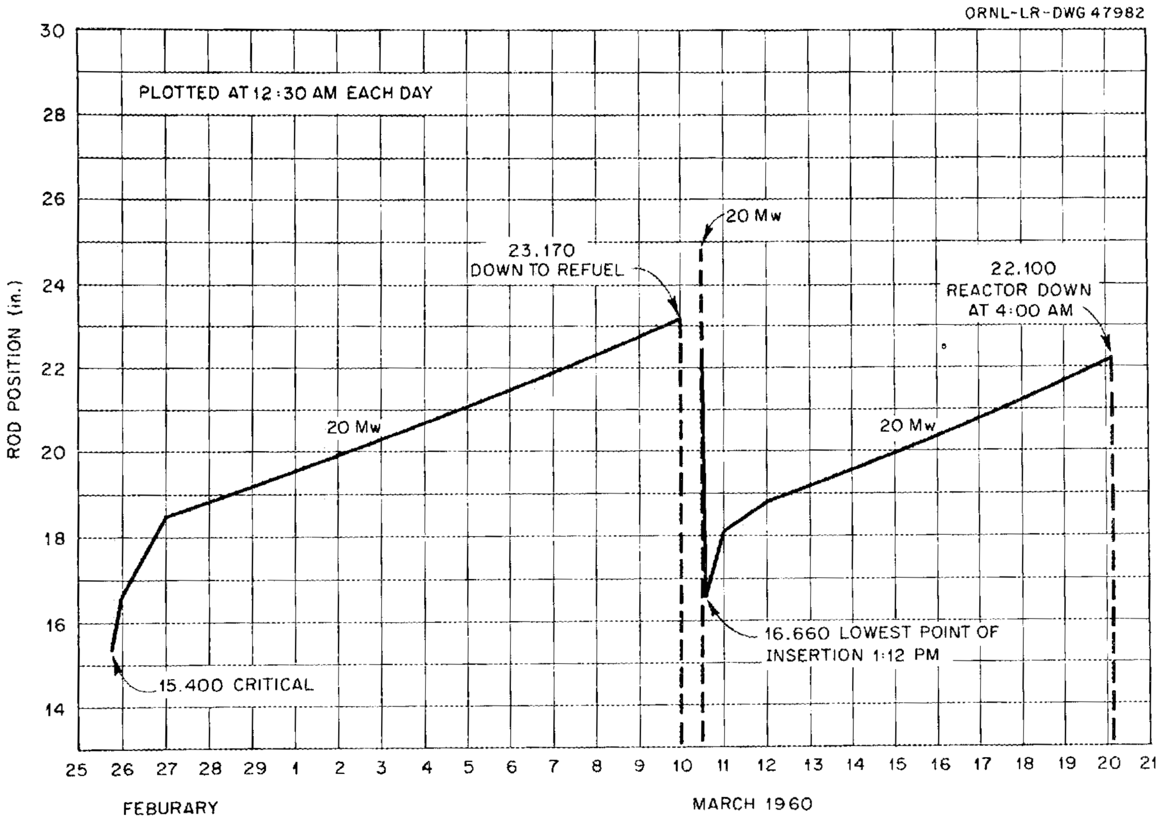

Fig. III-28. Cycle XXII; Rod Position vs Time

5.3. Effect of Shutdown on Poison Equilibrium

40. When the reactor is shut down, a peculiar thing occurs. Instead of the amount of xenon and samarium decreasing when fission-fragment production stops, it increases. Can you guess why?

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41. Let us first consider samarium. Samarium-149 is not radioactive, so it is not removed by the decay process. When the reactor is shut down, there are no more neutrons to remove the samarium. There is, however, quite a bit of promethium which has already been produced and is still undergoing radiative decay to form samarium.

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42. Since the ^{149}Sm is not being removed by radiative decay or neutron absorption, the decay of promethium will ____________________ the amount of Sm in the reactor.

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43. If the amount of ^{149}Sm was at an equilibrium value just prior to shutdown and after shutdown there are no removal processes but there is still a formation process, the amount of samarium must ______________. increase

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44. The negative reactivity value of equilibrium Sm is about $-0.01\ \Delta k/k$. After the reactor is shut down, the negative reactivity effect (a measure of the amount of Sm) increases to a value which depends upon what the operating neutron flux was. For a neutron flux of 2×10^{14} neutrons $cm^{-2} \cdot sec^{-1}$, the Sm effect after shutdown will increase to $-0.042\ \Delta k/k$. increase

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45. Figure III-29 is a graph showing the buildup of samarium to equilibrium value and then the final increase to the maximum in proportion to the number of days of operation of a reactor operating at a flux of 2×10^{14} neutrons $cm^{-2} \cdot sec^{-1}$.

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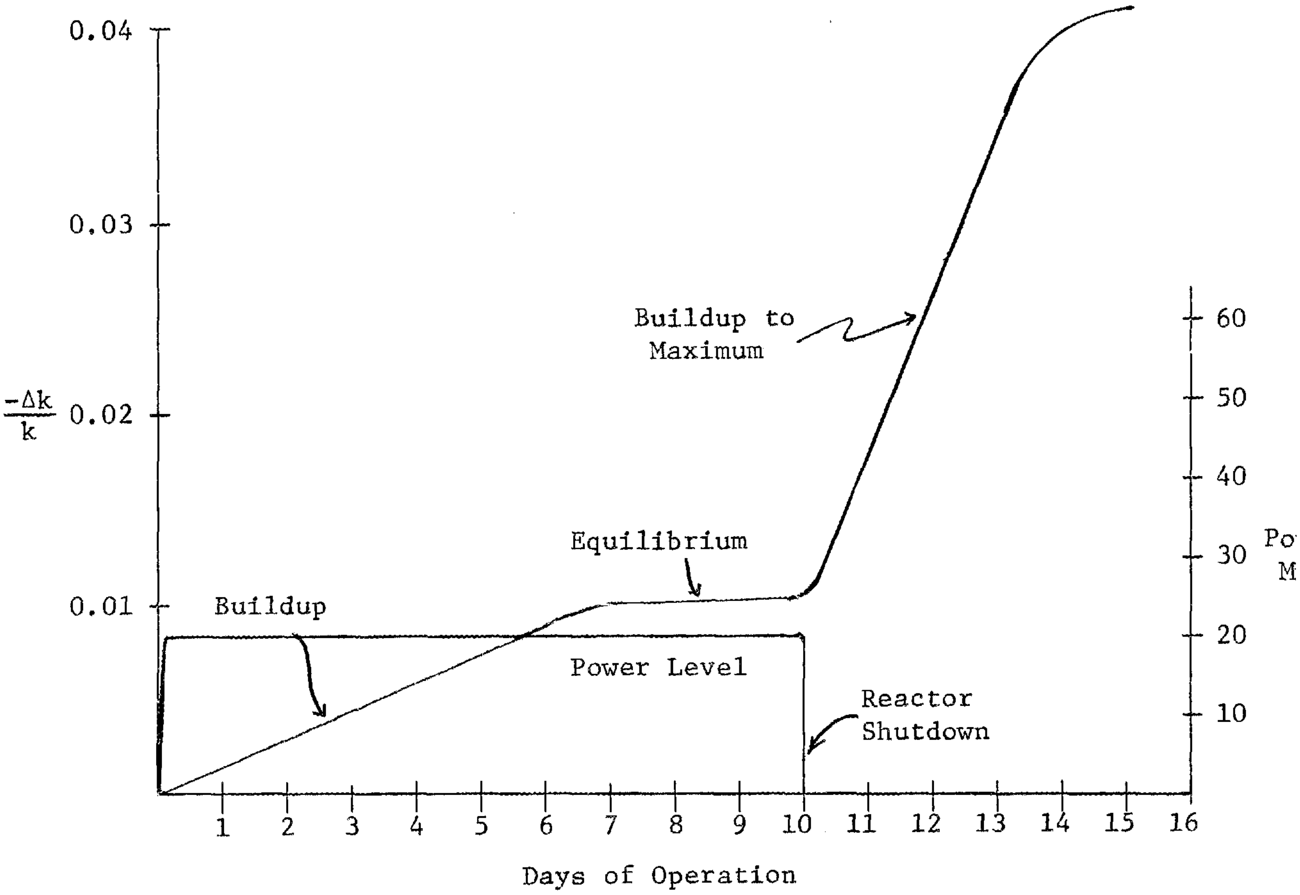

Fig. III-29. Samarium Poisoning

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46. The behavior of ^{135}Xe is different from that of ^{149}Sm. In the first place, Xe is removed by two processes: ________ ____________ and ____________ ____________.

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47. If equilibrium Xe has been reached and the reactor is then shut down, the removal of Xe by absorption of neutrons is essentially terminated; but the removal of ^{135}Xe by ____________ ________ continues.

neutron absorption, radiative decay

- - - - - - - - -

48. As you may recall, 5.6% of the fission reactions result in the formation of ^{135}I which decays to ^{135}Xe, which, in turn, decays to ^{135}Cs. The process can be expressed as follows with the numbers above the arrows representing the half lives of the decay processes.

radiative decay

$$^{135}I \xrightarrow{6.7\ hrs} {}^{135}Xe \xrightarrow{9.2\ hrs} {}^{135}Cs$$

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49. You can see that the ^{135}I which is formed directly from fission decays with a half life of 6.7 hrs, which is shorter than the half life of ^{135}Xe ($T_{1/2}$ = 9.2 hrs). This means that the iodine will form xenon (faster, slower) than the xenon can decay to cesium, and so we get a buildup of xenon poison after the reactor is shut down.

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50. After the reactor is shut down, there will be practically no ^{135}I formed because there are essentially no fission reactions. Eventually, all of the iodine will decay so that no more xenon is formed, and so also will all of the xenon eventually ________________. faster

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51. When enough of the iodine has decayed so that less xenon is being formed than is decaying each second, the concentration of xenon will start to decline since the decay rate will be greater than the ____________ ________. decay

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52. The maximum amount of xenon poisoning which occurs when the decay rate just equals the formation rate after shutdown is called peak xenon. formation rate

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53. Figure III-30 shows how the relative concentrations of xenon and samarium vary with time.

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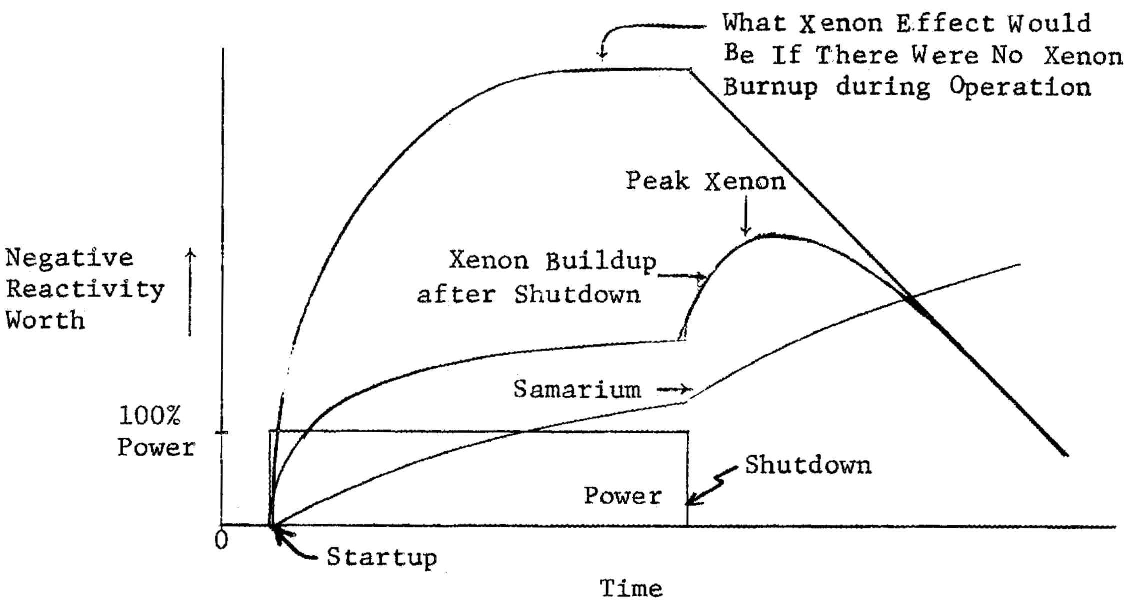

Fig. III-30. How the Relative Concentrations of Xenon and Samarium Vary with Time

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54. Note that in Fig. III-30 the xenon concentration starts to ______________ after peak xenon is reached. This is because there is now more xenon decaying than is being formed by the decay of iodine.

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55. These changing concentrations of xenon--that is, the buildup to equilibrium, the buildup from equilibrium to peak xenon, and the decay after peak xenon--are referred to as xenon transients. — decrease

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56. At the start of operation, there is a xenon transient which affects the operation of a reactor by causing the necessary withdrawal of the control rods until equilibrium xenon is reached; this was discussed earlier. The xenon transient following reactor shutdown (buildup to peak and the final decay) also has considerable effect on the operation of a reactor.

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57. A xenon transient is a change in the xenon ___________.

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58. The negative reactivity value of equilibrium xenon may be as much as $-0.05\ \Delta k/k$, but that due to the peak xenon may be as high as $-0.51\ \Delta k/k$ for a thermal neutron flux of 2×10^{14} neutrons $cm^{-2} \cdot sec^{-1}$. The negative reactivity value of peak xenon, then, may be _________ times as great as equilibrium xenon at this flux level. — concentration

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59. Since this negative reactivity value of peak xenon may be as much as 10 times the equilibrium value, it is difficult to load enough fuel into the reactor to overcome the negative reactivity effect of ________________ ____________ because of the limited control ability of the control rods. Usually enough fuel is loaded into a reactor to compensate only for a little more than equilibrium xenon and samarium plus some for fuel burnup. — ten

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60. The maximum negative reactivity value which occurs at peak xenon is usually reached in about 11 hrs after shutdown. — peak xenon

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61. For high-flux reactors, this fast buildup to the extremely large negative reactivity value at peak xenon following shutdown has the effect of making startup impossible if attempted after a period of 30 or 40 minutes following shutdown. However, by waiting a period of about 2 days, the concentration of xenon will have decayed to a value less than equilibrium xenon; and startup may then be possible.

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62. Generally, it is better to replace some fuel elements containing these fission products than to wait 2 days.

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63. The replacement of fuel elements following a shutdown is the general practice for the ORR and the HFIR when the shutdown is long enough for xenon poisoning to become too great to allow restarting of the reactor. The elements removed are allowed to ____________ at least two days. Thus, when a replacement is needed again, these elements may be reused.

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64. Figure III-31 illustrates some tests conducted at the Sodium Reactor Experiment (SRE). Note that for the smaller neutron fluxes (power levels) the ____________ ________________ worth of peak xenon after a power decrease is much less than at higher power levels. — decay

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65. Also, at shutdown from a low power level, peaking of xenon is (high, medium, almost none) shortly after shutdown. — negative reactivity

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66. Figure III-32 illustrates the long-term transient effect of xenon and samarium--that xenon dies off to equilibrium at about 2 1/2 days and that samarium is just reaching its final value after a week. — almost none

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67. According to this figure, equilibrium xenon had a negative reactivity effect of about ________%.

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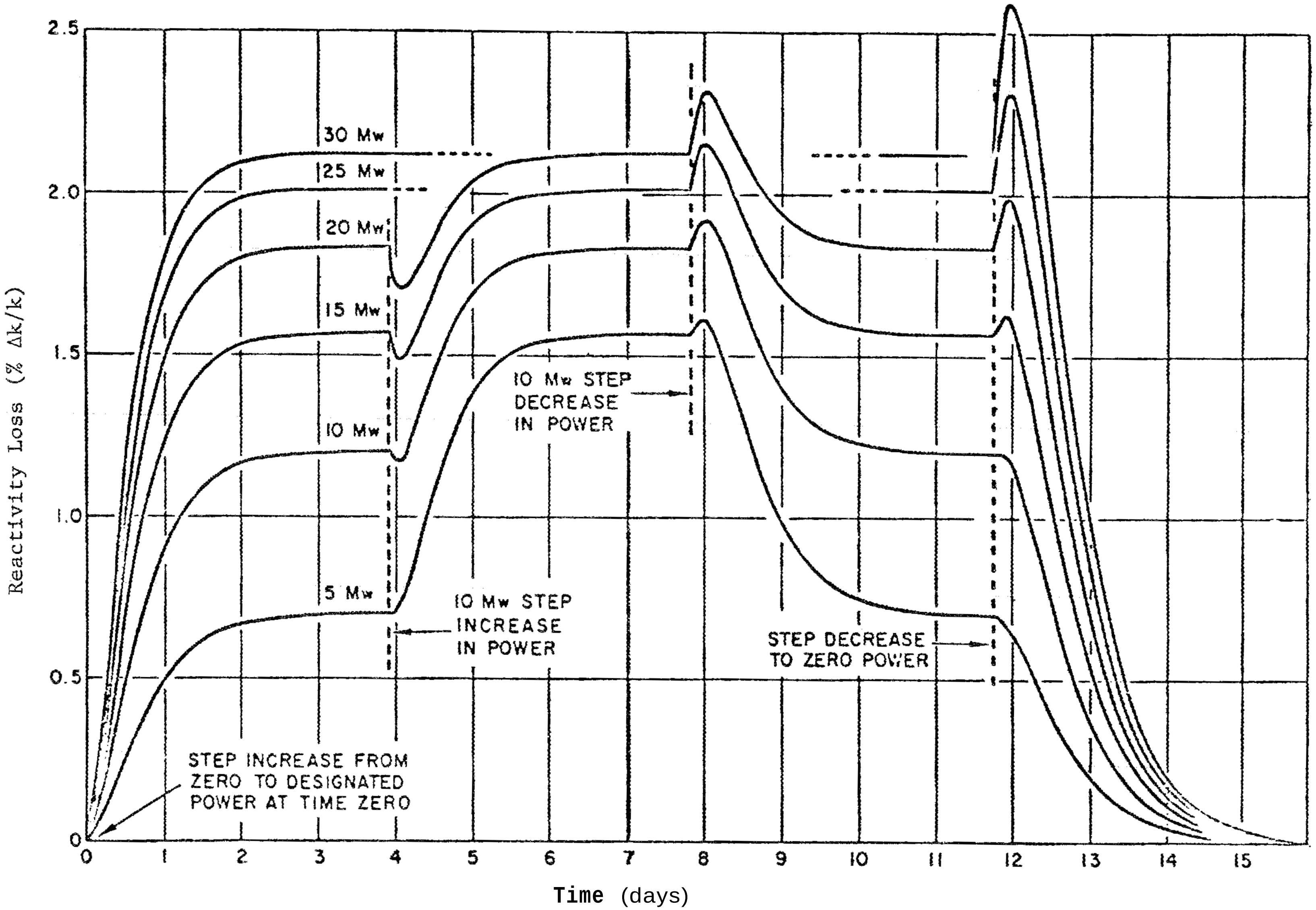
68. After shutdown, about _____ hrs are required for the total effect of both the ^{135}Xe and ^{129}Sm to decline to equilibrium. — 5

- - - - - - - - -

ORNL DWG. 68-4400



Fig, III-31. Reactivity Loss due to Xenon for Various Power Operations at SRE

ORNL DWG. 68-4401

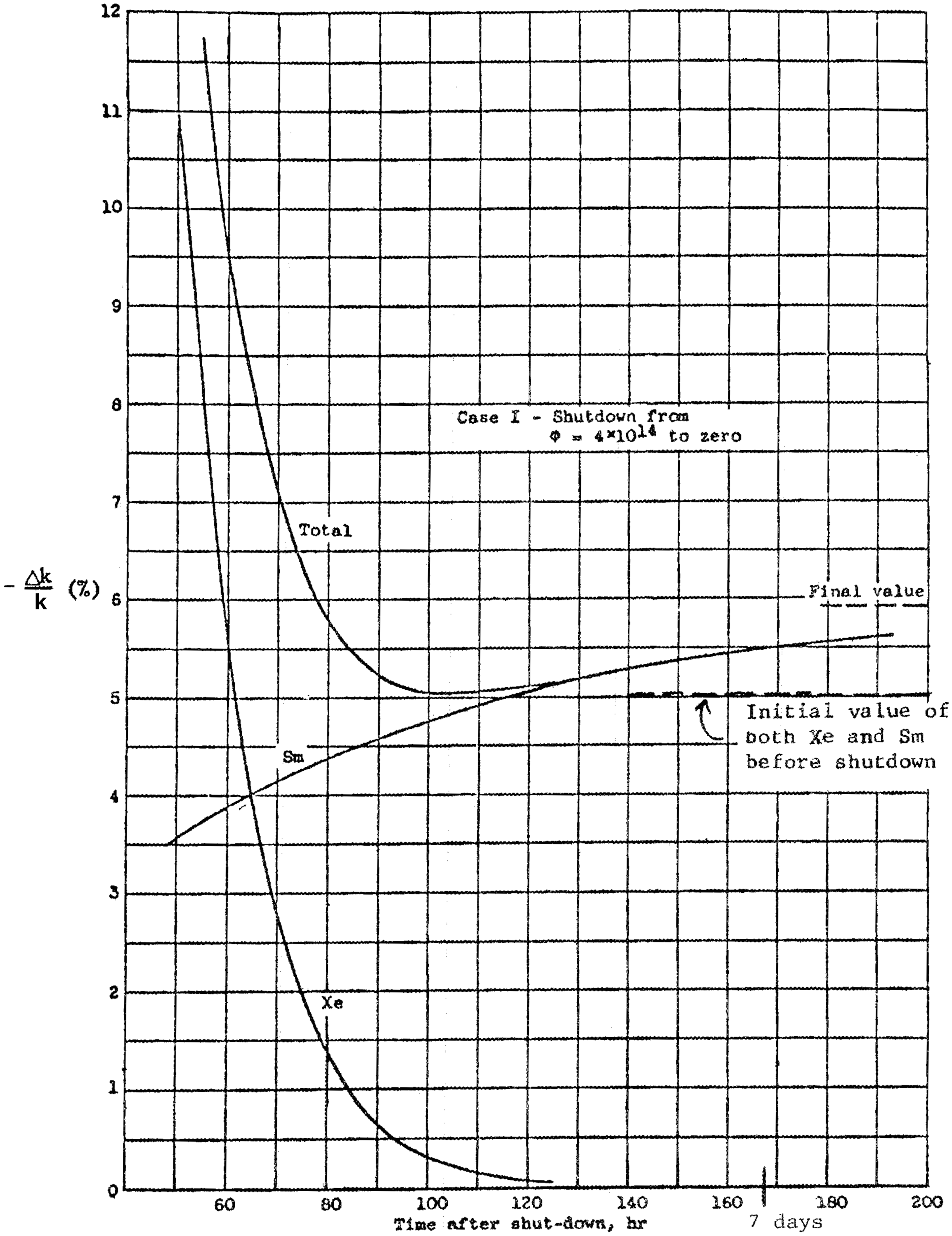


Fig. III-32. Xenon and **Samarium** Long-Term Transients

69. After about 65 hrs _______ has a much greater negative reactivity effect than _______________. 100

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70. Figure III-33 shows the xenon effect due to power changes. Note that the decrease in power results in a temporary increase in xenon because there are less neutrons to remove the xenon formed from the iodine already present. Remember that the iodine already present was produced by a higher neutron flux. ^{149}Sm, ^{135}Xe

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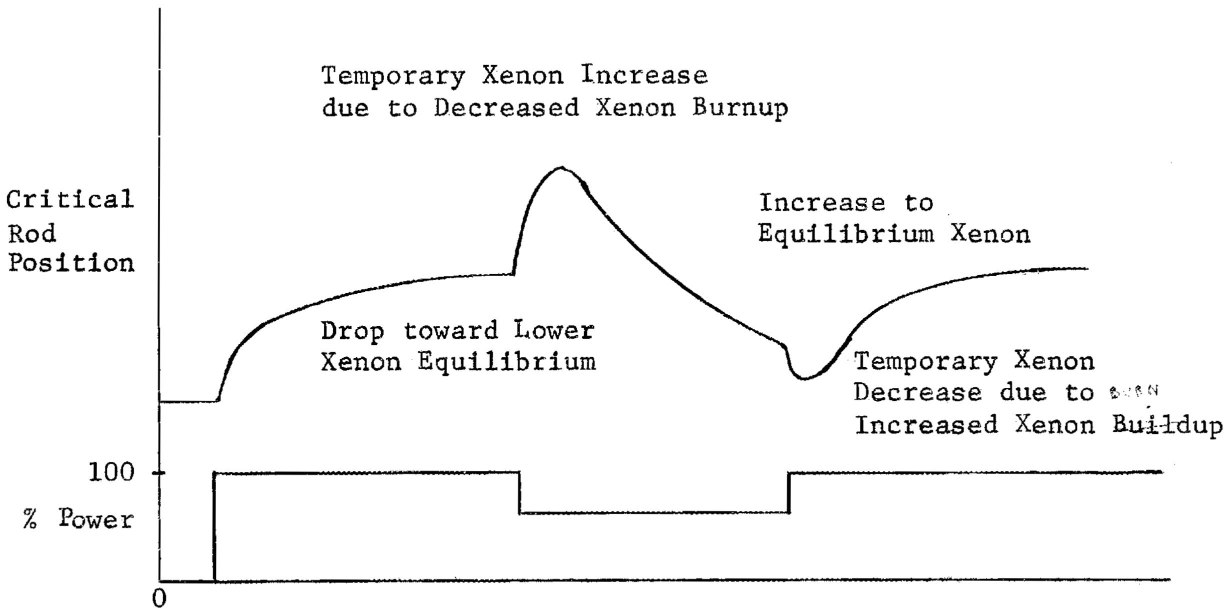

Fig. III-33. Xenon Response to Power Changes

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71. A reduction of the reactor power level, after equilibrium xenon is established, may also result in a shutdown because ______________________________.

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There will be less neutrons to remove the xenon, so a buildup occurs which may exceed the available reactivity.

- - - - - - - - -

5.4. Self Test

72. Xenon-135 and ^{149}Sm are strong neutron-absorbing __________ ____________. The reactivity effect of these isotopes is __________. (If you made an incorrect response, repeat Frame 6.)

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73. Samarium-149 is a (stronger, weaker) neutron poison than ^{135}Xe. (If you made an incorrect response, repeat Frames 7-8.)

fission products, negative

- - - - - - - - -

74. Most of the fission-product poison ^{135}Xe is formed by the radiative decay of ____________. (If you made an incorrect response, repeat Frame 11.)

weaker

- - - - - - - - -

75. Xenon-135 is removed by two processes, ____________ ____________ and neutron ____________. Samarium-149 is not radioactive, so it is removed only by ____________ ____________. (If you made an incorrect response, repeat Frames 20-26.)

^{135}I

- - - - - - - - -

76. When the ^{135}Xe and ^{149}Sm removal rate equals the formation rate, we say the concentrations are in __________. (If you made an incorrect response, repeat Frame 29.)

radiative decay, absorption, neutron absorption

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77. The negative reactivity effect of equilibrium xenon and samarium has to be compensated for, as was done for fuel burnup, by ________________. (If you made an incorrect response, repeat Frame 34.) equilibrium

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Loading extra fuel into the core in addition to the critical mass.

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78. Once equilibrium xenon has been reached, it is maintained until the power level is changed. When the reactor is shut down, the amounts of both xenon and samarium (decrease, increase) because ________________________. (If you made an incorrect response, repeat Frames 38-53.)

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Increase--the formation by radioactive decay of the parent fission products continues, but the removal by neutron absorption stops.

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79. Xenon transients are ______________________. (If you made an incorrect response, repeat Frame 55.)

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Changes in the concentration of xenon which occur when reactor power levels are changed.

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80. The negative reactivity effect due to peak xenon may be as much as 10 times that due to ________________ xenon. (If you made an incorrect response, repeat Frame 58.)

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equilibrium

SECTION III-6

TEMPERATURE EFFECTS

The purpose of this section is to discuss the reactivity effects due to temperature changes in a reactor.

6.1. Reactivity and Temperature

1. The effects of temperature changes are noticed every day in our day-to-day routine. For example, the density and size of a quantity of water changes when it becomes an ice cube or steam.

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2. Temperature changes in a reactor may also result in density and ________ changes.

- - - - - - - - - -

3. The density and size of reactor materials such as fuel, moderator, coolant, etc., are affected when ________ changes occur. — size

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4. An increase in ________________ produces an increase in the actual size of a reactor, although it probably is not visible to the naked eye. — temperature

- - - - - - - - - -

5. Any change in the density or size of the materials (fuel, etc.) in a reactor will affect the neutron multiplication factor, k_{eff}, because of effects on Σ_a, Σ_s, etc. — temperature

- - - - - - - - - -

6. Since a temperature change will affect the size and density of reactor materials, it will have an effect on the _________________________.

- - - - - - - - -

Neutron multiplication factor, or k_{eff}.

- - - - - - - - -

7. The effect of temperature changes in a reactor is expressed in terms of reactivity; that is, $\Delta k/k$, which is equal to

$$\frac{k_{eff} - 1}{k_{eff}}$$

- - - - - - - - -

6.2. Temperature Coefficients

8. The reactivity change for a 1°F change in temperature is represented by the symbols $\frac{\Delta k}{k}/°F$. This representation is called the temperature coefficient.

- - - - - - - - -

Many people of the world do not use the Fahrenheit temperature scale. The temperature scale used by most scientists and, actually, by most of the people of the world is the Celsius or Centigrade scale. This scale, usually abbreviated C, has 100 degrees between the freezing point of water (at 0°C) and the boiling point (at 100°C). The Fahrenheit scale has 180 degrees between the same two points (32°F at the freezing point and 212°F at the boiling point of water). Thus, the degree Celsius is 1.8 times (9/5) as large a temperature change as the degree Fahrenheit.

The temperature coefficients of reactors in countries other than the U. S. would probably always be calculated in the units $\frac{\Delta k}{k}/°C$. Since 1°C is a temperature change 1.8 times the change of 1°F, we would expect that the reactivity change $\frac{\Delta k}{k}/°C$ would be $1.8 \times \frac{\Delta k}{k}/°F$. Thus we can write the conversion: $\frac{\Delta k}{k}/°C = 1.8 \frac{\Delta k}{k}/°F$.

- - - - - - - - -

9. The temperature coefficient $\frac{\Delta k}{k}/°F$ represents the amount of ____________________ change when the temperature changes _______ °F.

- - - - - - - - - -

10. The total reactivity change due to a temperature change can be calculated by the equation

reactivity, one

$$\frac{\Delta k}{k} = (\frac{\Delta k}{k}/°F) \times (\Delta T)$$

where ΔT is the temperature change $T_2 - T_1$ (the temperature after the change minus the temperature before the change).

- - - - - - - - - -

11. If the temperature changes 5°F, the reactivity change will be found by multiplying __________ times the temperature coefficient.

- - - - - - - - - -

12. If $\frac{\Delta k}{k}/°F = 0.001\%$ ($\frac{\Delta k}{k}/°C = 0.0018\%$), as the temperature changes from 100°F to 150°F there is a reactivity change of ______________.

5°F

- - - - - - - - - -

13. If the temperature coefficient is negative, a rise in temperature will have a negative reactivity effect; a decrease in temperature will have a ______________ reactivity effect.

$0.05\% \frac{\Delta k}{k}$

- - - - - - - - - -

14. Let us assume that a reactor has a temperature coefficient of $-0.002\% \frac{\Delta k}{k}/°F$ and the operating temperature is increased from 100°F to 140°F, which is equivalent to a ΔT of ______. The total reactivity (loss, gain) will then be equal to ________.

positive

- - - - - - - - - -

15. If the temperature coefficient of a reactor is $-0.001\% \frac{\Delta k}{k}/°F$ and the average temperature is reduced from 135°F to 90°F, we expect that the reactivity will (decrease, increase).

+40°F, loss, $0.08\% \frac{\Delta k}{k}$

\- - - - - - - - - -

16. A calculation of the change in reactivity, from information in the above frame, shows it to be a (plus, minus) ________% $\frac{\Delta k}{k}$ because:

increase

$$\frac{\Delta k}{k} = (-0.001\% \frac{\Delta k}{k} \cdot °F)(90°F - 135°F) = ?$$

\- - - - - - - - - -

17. The temperature coefficient (of reactivity) of a reactor is the result of a combination of several different temperature effects. For example, an increase in temperature may decrease the density of the material in the reactor, which may result in a decrease in the macroscopic absorption cross section, Σ_a. A decrease in the absorption cross section means that there will be increased neutron leakage resulting in a negative effect on ________________.

plus, 0.045%

\- - - - - - - - - -

18. An increase in temperature may cause an increase in the actual size of a reactor. This results in less neutron leakage and consequently has a _____________ effect on reactivity.

reactivity

\- - - - - - - - - -

19. The average energy (or velocity) of a thermal neutron increases with increasing temperature. Since the cross section Σ_a decreases as the neutron velocity increases, this results in more neutron leakage and a ________________ effect on reactivity.

positive

\- - - - - - - - - -

20. The combined effect on reactivity due to the density changes, cross sections, etc., as the temperature changes, is expressed as the temperature coefficient which represents the amount of ______________ change for each ________________ change.

negative

- - - - - - - - -

21. In order to calculate the value of the temperature coefficient, the usual procedure is to determine $k_{eff,1}$ at a temperature T_1 and then determine $k_{eff,2}$ at a higher temperature, T_2. The temperature coefficient is found by the equation

reactivity, degree F or degree C

$$\frac{k_2 - k_1}{k_2 \, (T_2 - T_1)} = \frac{\Delta k}{k} / {}^\circ F$$

- - - - - - - - -

22. The temperature coefficient at the ORR was determined by first calibrating the control rods for their reactivity worth. Criticality was then established and the water was heated gradually from 70°F to 120°F. The amount of rod withdrawal to compensate for this temperature increase and maintain criticality was a measure of the negative effect on reactivity due to the ______________________ _______________. Figure III-34. shows the results of these measurements and the values obtained for the temperature coefficient.

- - - - - - - - -

23. The term negative temperature coefficient means the negative effect on ______________ which occurs when the temperature increases ____________________.

temperature rise or temperature increase

- - - - - - - - -

ORNL-LR-DWG 35188

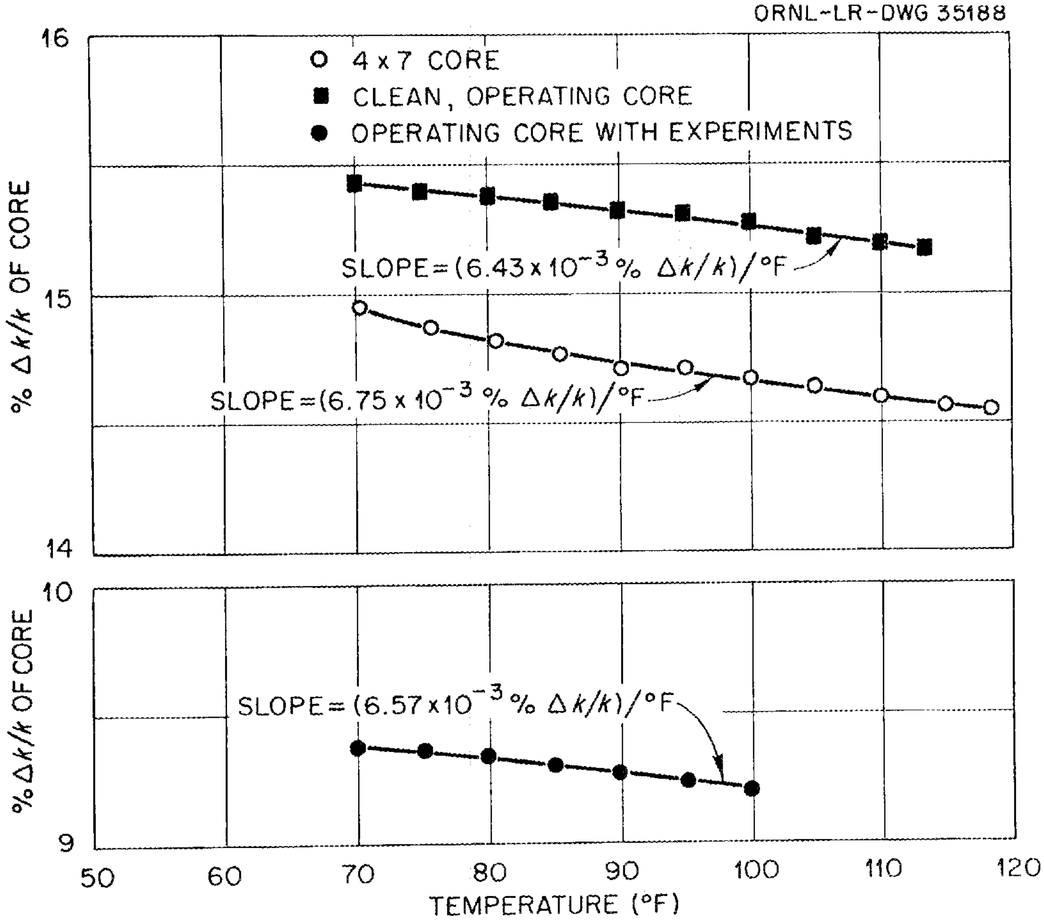

Fig. III-34. Temperature Coefficients

- - - - - - - - - -

24. What happens to the loss in reactivity due to a temperature increase when the temperature is returned to its former value?

reactivity, 1°F

- - - - - - - - - -

It is regained or returned to the system.

- - - - - - - - - -

25. The reactivity loss due to a temperature increase is not permanent and is regained when the temperature is ______________________.

- - - - - - - - - -

26. In 1962, the core lifetime of a power reactor (YANKEE) was extended several months by lowering the average core operating temperature when the reactor was about to be shut down due to fuel burnup. — lowered

- - - - - - - - -

6.3. Reactor Control

27. A reactor which has a negative temperature coefficient is considered to be much safer to operate than one which has a positive temperature coefficient.

- - - - - - - - -

28. If a reactor is critical at some temperature and the control rods are then withdrawn ($+\Delta k/k$), the fission rate and temperature will (increase, decrease).

- - - - - - - - -

29. If a reactor has a positive temperature coefficient, an increased temperature will result in a (positive, negative) effect on reactivity. — increase

- - - - - - - - -

30. A positive effect on reactivity in a reactor as a result of a temperature increase means that when the temperature increases, the fission rate will increase, which results in a further temperature increase that tends to further increase the fission rate, and so on. — positive

- - - - - - - - -

31. Control of a reactor with an appreciable positive temperature coefficient would be like starting a car down a mountain road with very poor brakes. How do you control it?

- - - - - - - - -

32. If the reactor has a negative temperature coefficient, a temperature increase will cause a negative effect on reactivity. This tends to (slow down, speed up) the increase in the fission rate and makes it easier to control.

- - - - - - - - -

33. Obviously, a positive temperature coefficient (is, is not) desirable, since it stimulates increased fission rate. A negative temperature coefficient is preferred, since it has a stabilizing effect on the fission rate increase so that the increase is not self-perpetuating. — slow down

- - - - - - - - -

34. Control of a reactor is more difficult if the reactor has a (positive, negative) temperature coefficient. — is not

- - - - - - - - -

35. When a reactor goes from initial criticality to the normal operating power level, large temperature changes may occur. The negative reactivity effect of these large temperature changes is usually compensated for by having loaded extra fuel into the core in addition to the critical mass (as is done for fuel burnup effects). Thus, when reactivity changes occur during operation due to temperature changes, they can be compensated for by adjusting the ____________ ____________________. — positive

- - - - - - - - -

36. A single temperature coefficient to describe the reactivity effect of temperature changes is useful as long as the temperatures are <u>uniform</u> throughout the reactor. — control rods

- - - - - - - - -

37. A uniform temperature throughout a reactor occurs only from initial criticality up to very low power levels. When power operation is established, temperatures throughout the core may vary in the different regions by a large amount.

\- - - - - - - - -

38. Figure III-35 is a graphical representation of how temperatures might vary in the fuel and coolant of one type of reactor from initial criticality to full power. Note that the average coolant temperature from T_2 to T_3 increased from 440°F to 455°F while the fuel temperature increased from 440°F to ________.

\- - - - - - - - -

39. The reason that the fuel temperature increased so much should be obvious because the heat being generated is caused by ________________ reactions in the fuel. 2000°F

\- - - - - - - - -

40. Another factor which causes large variations between fuel and coolant temperatures is air gaps, left between fuel rods and their cladding, to contain fission-product gases and to allow for expansion and contraction. These air gaps cause the fuel to be hotter because it is harder for heat to pass through air than through metal. Also, some fuels are in the form of oxides such as UO_2 rather than metallic compounds such as UAl_3 or dispersions such as U_3O_8 + Al. Oxides generally have poorer heat-transfer characteristics and thus have higher operating ____________________. fission

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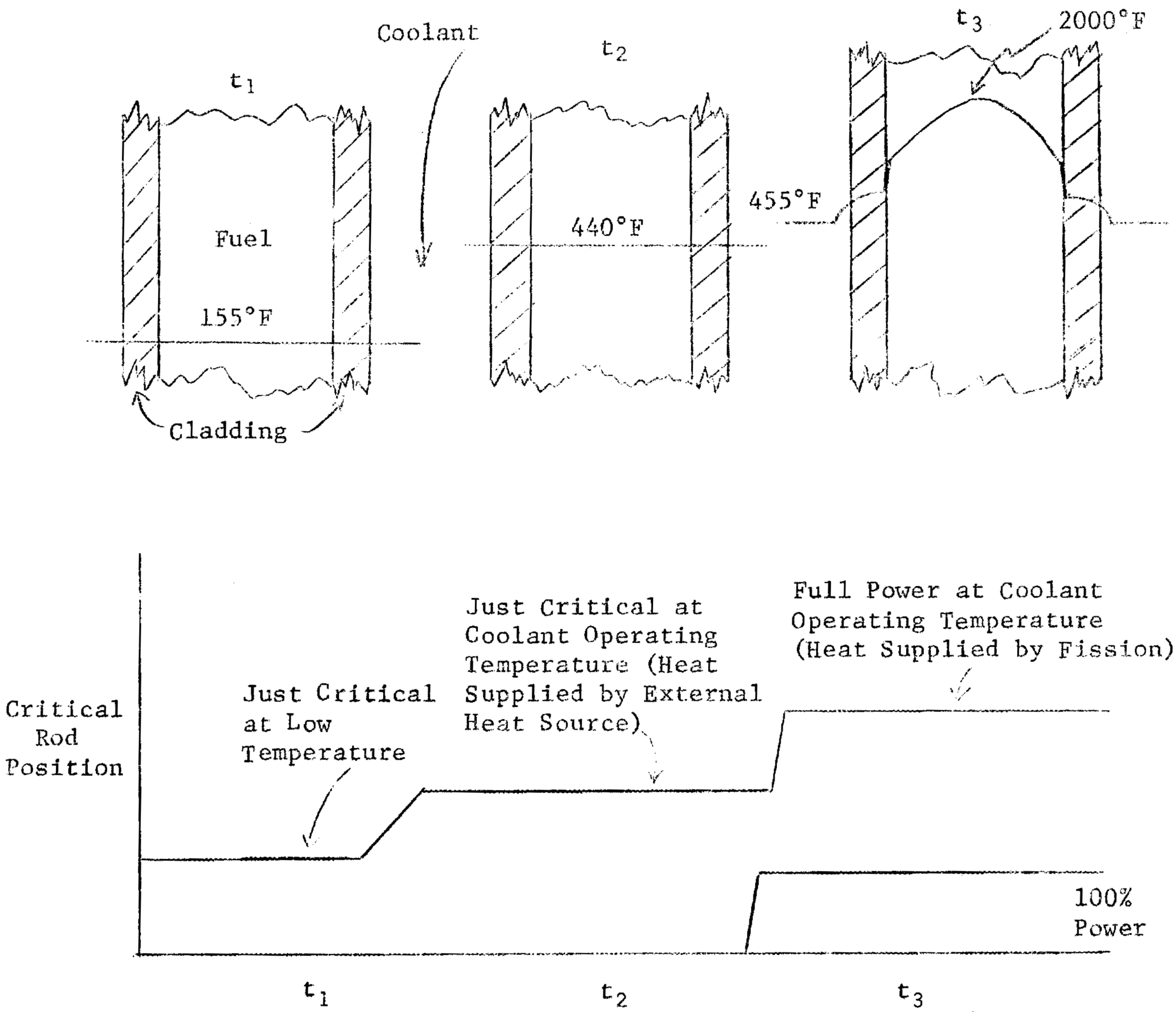

Fig. III-35. Temperatures in Rod-Type Fuel during Startup of a Reactor

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41. The point is that at normal operating power levels the temperatures in the fuel region will be (much less, greater) than in the moderator or reflector region. Also, these regions are composed of different materials. Therefore, to determine the overall effect on reactivity, the temperatures and temperature coefficients of each region must be considered. temperatures

- - - - - - - - -

42. Temperatures in the fuel will be greater than in other regions because this is where most of the heat is ______________. | greater

- - - - - - - - -

43. To determine the overall effect on reactivity of temperature changes in a reactor, we should consider (one, all) temperature coefficients. | produced or generated

- - - - - - - - -

44. If the temperature coefficients and temperatures of each region of the core are known, then the total effect on reactivity can be determined by the equation | all

$$\text{total } \frac{\Delta k}{k} = \left[(\frac{\Delta k}{k}/°F)_r \times \Delta T_r\right] + \left[(\frac{\Delta k}{k}/°F)_m \times \Delta T_m\right] + \left[(\frac{\Delta k}{k}/°F)_f \times \Delta T_f\right]$$

where the subscript r is for reflector, m for moderator, and f for fuel.

- - - - - - - - -

45. Let us consider again the temperature coefficient which was determined for a water-reflected reactor, like the ORR, at criticality by heating the water from 70°F to 120°F. The coefficient determined in this manner would not be applicable to high-power operating conditions because then the reflector, moderator, and fuel would no longer be at the same temperature and they have different coefficients.

- - - - - - - - -

46. Suppose the reflector coefficient was +0.008% $\frac{\Delta k}{k}$/°F, the moderator coefficient was 0, and the fuel coefficient was -0.01% $\frac{\Delta k}{k}$/°F. The resultant reactivity change for a 50°F change would be ______________.

- - - - - - - - -

$$(+0.008\% \frac{\Delta k}{k}/^{\circ}F) \times 50^{\circ}F + (-0.01\% \frac{\Delta k}{k}/^{\circ}F) \times 50^{\circ}F =$$
$$(+0.4\% \frac{\Delta k}{k}) + (-0.5\% \frac{\Delta k}{k}) = -0.1\% \frac{\Delta k}{k}$$

\- - - - - - - - -

47. Using the information in Frame 46, the reactivity change, if the fuel changed an average of 250°F while the reflector changed 50°F, would be _______________.

\- - - - - - - - -

48. The result of Frame 46 shows that if the fuel and reflector both increased from 70°F to 120°F, the total reactivity change would be $-0.1\% \frac{\Delta k}{k}$. These conditions occur, however, only at low power levels. When the power is raised to the normal operating level, the reflector temperature will likely stay at about 120°F; but the fuel temperature may increase considerably. So, when the power level is raised, the reactivity change from the reflector will be the same, but there will be a large negative reactivity effect from the fuel. $-2.1\% \frac{\Delta k}{k}$

\- - - - - - - - -

49. One additional point is that, for the case we are discussing, after the normal power level has been established, a reduction in the coolant flow rate would cause the fuel, moderator, and reflector temperatures to increase so there would be a change in reactivity due to both the reflector and fuel. On the other hand, a reduction in power level would result in an appreciable decrease only in the fuel temperature; and only the fuel would cause an appreciable reactivity change.

\- - - - - - - - -

50. Let us consider further the fuel temperature coefficient, since this is the region where the largest temperature changes occur.

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6.4. Doppler Effect

51. An important effect in the determination of the fuel temperature coefficient is the "Doppler Effect".

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52. The Doppler effect is the apparent broadening of the resonance-absorption cross-section peaks; in other words, the resonance absorption peaks respond to a wider range of neutron energies. Figure III-36 shows how the peak becomes wider as the temperature is increased, and neutrons which have both more and less energy than that of the peak become more easily absorbed.

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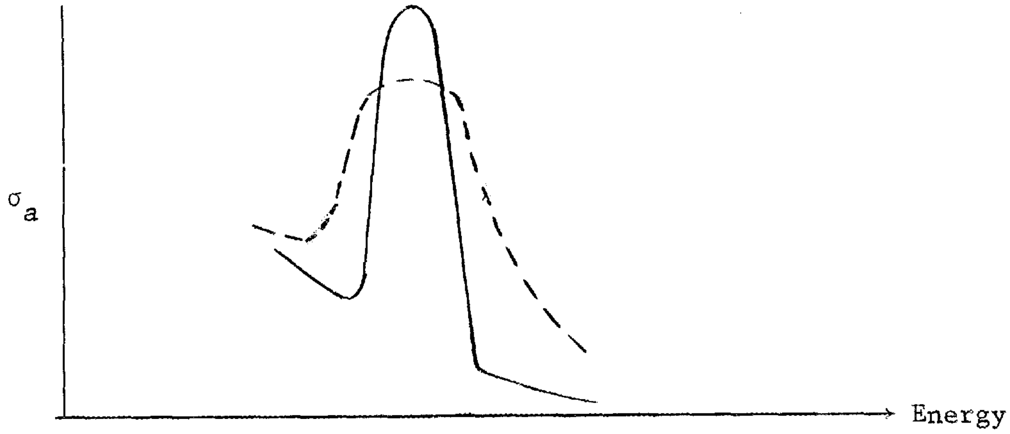

The change in the shape of a neutron resonance peak as the temperature of the resonance absorber is increased.

Fig. III-36. Doppler Temperature Effect

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53. This broadening effect, therefore, results in neutron absorption over a wider range of neutron velocities--consequently, (fewer, more) neutrons are absorbed in nonfission reactions, increasing the negative temperature coefficient.

- - - - - - - - -

54. The broadening effect is due to the fact that a temperature increase increases the vibration of the individual atoms. When a neutron collides with this vibrating atom, the collision speed may be greater than the speed of the neutron, so the effective speed of the neutron has been ____________________.

more

- - - - - - - - -

55. If its actual speed was a little too slow for it to be easily absorbed, the speed of the atom moving toward it would make its collision speed relatively faster; and it would be _________________.

increased

- - - - - - - - -

56. If it were too fast to be absorbed and struck an atom moving away from it, the relatively ___________ speed of impact would allow it to be absorbed.

absorbed

- - - - - - - - -

57. This effect may be compared to the collision speed of two cars. If two cars are going in the same direction and the car behind collides with the one in front, the collision speed is not nearly as great as it would be if the struck car were sitting still. The collision speed would be far greater if both cars were in motion and collided "head on".

slower

- - - - - - - - -

58. One of the resonance peaks of ^{238}U appears just above the room temperature thermal-energy range. The collision speed of the thermal neutrons in a heated medium may, however, become high enough to have enough speed to be influenced by this peak. If this occurs, the absorption of neutrons is (much less, greater) than it would be at a reduced temperature. This will be even more likely if the peak has been broadened due to the ^{238}U also being heated.

- - - - - - - - -

59. Figure III-37 is a pictorial representation of the Doppler effect. As was discussed, this effect may be compared to the collision of two automobiles. greater

- - - - - - - - -

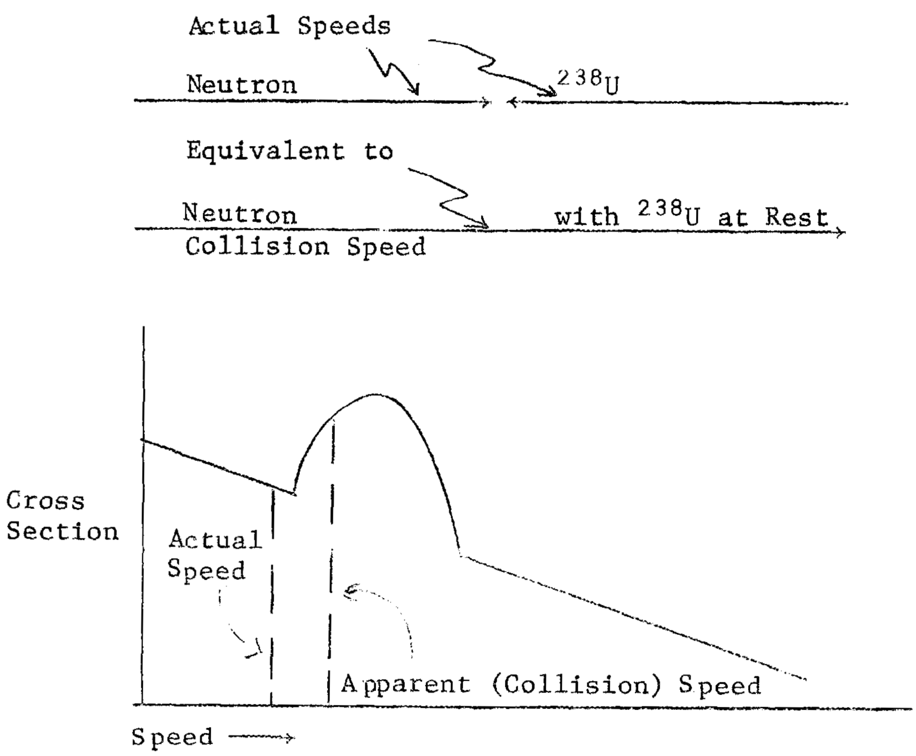

Fig. III-37. Doppler Effect

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61. To summarize what has been said:

a. A temperature change in a reactor results in changes in material density, sizes of components, cross sections, neutron speeds, and, consequently, affects the neutron multiplication factor.

b. The temperature changes in the various regions of the core of a reactor can be very different.

c. Since each region of the core is composed of different materials, each region will have a different temperature coefficient.

d. The fuel temperature coefficient is primarily a result of the Doppler effect which is a broadening of the resonance absorption cross section as a result of the increased vibration of the uranium atoms.

- - - - - - - - -

6.5. Self Test

62. Changes in sizes and densities occur in a reactor as a result of ________________ changes. (If you made an incorrect response, repeat Frame 2.)

- - - - - - - - -

63. The neutron multiplication factor, k_{eff}, is affected by size and density changes; therefore, temperature changes will affect the ________ ______________ ____________. (If you made an incorrect response, repeat Frame 6.)

temperature

- - - - - - - - -

64. The reactivity change for a 1° temperature change is represented by $\frac{\Delta k}{k}/°F$, which is called the ____________ ______________. (If you made an incorrect response, repeat Frame 8.)

neutron multiplication factor

- - - - - - - - -

65. If ΔT is the temperature change, the reactivity change due to this temperature change is equal to __________. (If you made an incorrect response, repeat Frame 10.)

temperature coefficient

- - - - - - - - -

$$\boxed{\frac{\Delta k}{k}/°F \times \Delta T}$$

- - - - - - - - -

66. A temperature increase may result in an increase in the size of a reactor; thus, less neutron leakage would occur. Consequently, a ________________ reactivity change results. (If you made an incorrect response, repeat Frame 18.)

- - - - - - - - -

67. Reactivity which is lost as a result of a temperature increase (is, is not) lost permanently. (If you made an incorrect response, repeat Frame 25.)

positive

- - - - - - - - -

68. A positive temperature coefficient means that when the temperature increases, the fission rate will ______________. An increase in the fission rate results in a further temperature ______________. A reactor is safer to operate if it has a (negative, positive) temperature coefficient. (If you made an incorrect response, repeat Frames 27-34.)

is not

- - - - - - - - -

69. During normal reactor operation, reactivity changes due to temperature changes can be compensated for by adjusting the ____________ ____________, if extra fuel has been provided in addition to the ____________ ____________. (If you made an incorrect response, repeat Frame 35.)

increase,
increase,
negative

- - - - - - - - -

70. A uniform temperature distribution occurs throughout a reactor only at (low, high) power levels. (If you made an incorrect response, repeat Frames 36-37.)

control rods,
critical mass

- - - - - - - - -

71. During normal reactor operation, temperatures are higher in the fuel region than in other regions because this is where the ____________ is being generated. (If you made an incorrect response, repeat Frames 38-39.)

low

- - - - - - - - -

72. To determine the overall effect of temperature changes in a reactor, we should consider (one, all) temperature coefficients. (If you made an incorrect response, repeat Frame 43.) heat

- - - - - - - - -

73. If the reflector temperature coefficient is $+0.008\% \frac{\Delta k}{k}/°F$ and the moderator temperature coefficient is $-0.01\% \frac{\Delta k}{k}/°F$, the resultant reactivity change due to these two for a 50°F change would be _______________. (If you made an incorrect response, repeat Frame 46.) all

- - - - - - - - -

$-0.1\% \frac{\Delta k}{k}$ because $0.008\% \times 50°F + -0.01\% \times 50°F =$

$$+0.4\% \frac{\Delta k}{k} + -0.5\% \frac{\Delta k}{k} = -0.1\% \frac{\Delta k}{k}$$

- - - - - - - - -

74. The principal effect which determines the fuel temperature coefficient is the ____________ effect. (If you made an incorrect response, repeat Frame 51.)

- - - - - - - - -

75. The Doppler effect is the apparent broadening of the resonance absorption cross-section peaks as a result of increased ____________ of uranium atoms. (If you made an incorrect response, repeat Frames 52-60.) Doppler

- - - - - - - - -

vibration or motion

SECTION III-7

NEUTRON FLUX DISTRIBUTION

The purpose of this section is to discuss the manner in which the neutrons are distributed throughout the core of a reactor.

7.1. Basic Information

1. Before we get started, let us be sure we understand what the term "neutron flux distribution" means. You may wish to review Frames 108-110 of Section III-1 where the neutron flux has been defined as the product of the neutron density times the neutron velocity. That is,

$$\phi = n \times v = \frac{\text{neutrons}}{\text{cm}^3} \times \frac{\text{cm}}{\text{sec}}$$

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2. Now let us consider the term "distribution". For example, we shall assume that you have four quarters and four pockets. If you placed one quarter in each pocket, then your money would be evenly ______________ among the pockets.

\- - - - - - - - -

> Distributed--divided, spread, separated, etc., are good synonyms, but let us use distributed.

\- - - - - - - - -

3. Like the money was distributed among the pockets, so also are neutrons __________________ throughout a reactor.

\- - - - - - - - -

4. The distribution of neutrons throughout a reactor is a little more uniform than the pocket distribution of coins; that is, there are no "pockets" where a large number of neutrons can be found or "pockets" where there are no neutrons. It is true, however, that some parts contain more neutrons than others.

distributed

\- - - - - - - - -

5. Figure III-38 illustrates how the neutrons might be distributed through the fuel region (core) of a reactor.

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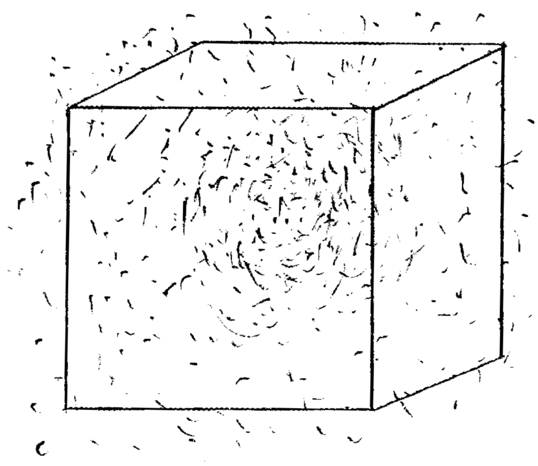

Fig. III-38. Neutron Distribution

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6. The manner in which the neutron flux varies throughout the core of a reactor is generally referred to as the neutron ____________ ____________________.

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7. Although the distribution of neutrons in a reactor depends, to a large degree, on the shape of the reactor and to a lesser degree on the individual components, a uniform loading of fuel in the core will result in a higher neutron flux in the central region. — flux distribution

- - - - - - - - - -

8. A reactor which has a uniform fuel distribution will generally have more neutrons in the (outer, central) region.

- - - - - - - - - -

9. The reason the neutron density is greater in the center of the core is because neutrons tend to leak out from the sides. — central

- - - - - - - - - -

10. Figure III-39 shows how the neutron flux is distributed about the vertical centerline of a reactor and illustrates the gradual decrease in neutron density, due to neutron leakage, as the sides of the core are approached.

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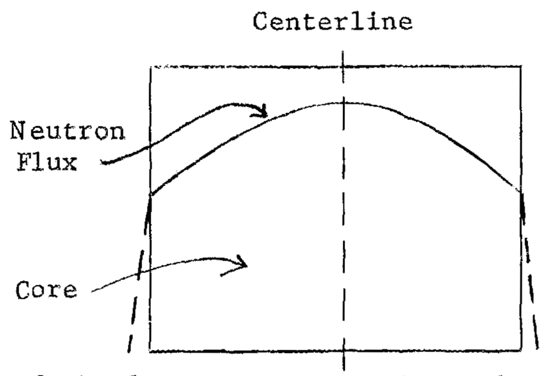

The height of the line represents the number of neutrons per cm^2 per sec. At the edges, the number of neutrons per cm^3 is low; and in the center it is high.

Fig. III-39. Neutron Distribution

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11. The neutron flux in the outer regions of the core is less than the central region because of ____________ ____________________.

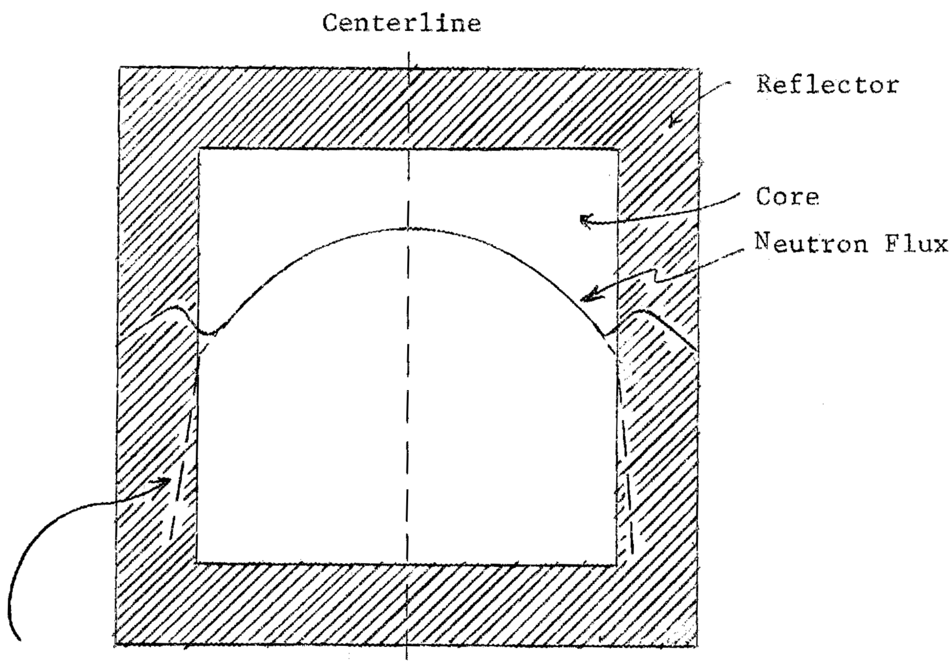
- - - - - - - - -

7.2. Reflector Effects

12. If a neutron reflecting material is placed around the core so that neutrons are reflected back into the fuel region, the neutron flux assumes a flatter distribution as shown in Fig. III-40.

neutron leakage

- - - - - - - - -



The dotted line represents what the neutron flux would have been without the reflector.

Fig. III-40. Reflector Effects on Neutron Flux (and Density)

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13. The placement of reflector material around the core of a reactor decreases neutron leakage; therefore, k_{eff} will ________________ and a (negative, positive) effect on reactivity results.

- - - - - - - - -

14.	A reflector material placed around the core reflects neutrons back into the fuel region. The neutron flux distribution is, therefore, altered by the reflector and becomes (more peaked, flatter).	increase, positive

- - - - - - - - -

15.	A flat neutron flux distribution occurs when the neutron density (varies, is the same) throughout the core.	flatter

- - - - - - - - -

16.	Usually a flat neutron flux distribution is preferred because then the same amount of fuel will undergo fission in each cm^3 throughout the core, resulting in uniform heat generation. If heat is generated uniformly throughout the core, the temperature distribution will also tend to be ________________.	is the same

- - - - - - - - -

7.3. Temperature Effects

17.	A uniform temperature distribution throughout the core is desirable because the maximum power output will then be possible, limited only by the capacity of the cooling system.	uniform

- - - - - - - - -

18.	The operating power level in a reactor is limited by the high-temperature regions sometimes called "hot spots". If the power level were raised, melting might occur in some of these ________ ________.	

- - - - - - - - -

19. Let us suppose that the maximum temperature which can be allowed in a reactor is 210°F because temperatures greater than this might cause boiling of the water. This means that the power level of the reactor can be raised only until this temperature is reached in <u>any</u> region of the core. If the left side of the core reaches this temperature and the right side is only 150°F, then the maximum power level of the reactor has been reached because the left side of the core is now at the limiting temperature. Obviously, a greater power level could be reached if the right side of the core could be raised from 150°F to 210°F so that a uniform temperature distribution was obtained. hot spots

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20. Because of the limitations caused by the high-temperature regions, the maximum power output of the low-temperature regions will be much less than they could be; consequently, the overall power output of the reactor will be __________ than if the temperatures were uniform.

\- - - - - - - - -

21. A higher power level can be obtained from a reactor which has a (nonuniform, flat) power distribution. less

\- - - - - - - - -

22. In all reactors, the power level is equal to the average neutron flux times the mass of fuel times some constant. In equation form, this is: $P = \bar{\phi} \times M \times C$; where P is the power, $\bar{\phi}$ is average neutron flux, M is mass of fuel, and C is a constant number which must be determined for the particular reactor. flat

\- - - - - - - - -

23. According to this equation (remembering that the value of C does not change), if the mass of fuel (M) decreases, the neutron flux will have to increase in order to maintain a constant power level.

$$\underset{\text{constant}}{P} = \overset{\uparrow}{\bar{\phi}} \times \overset{\downarrow}{M} \times \underset{\text{constant}}{C}$$

- - - - - - - - -

7.4. Fuel Burnup Effects

24. The operation of a reactor involves a gradual burnup of fuel. Consequently, continued operation will result in the average neutron flux gradually (increasing, decreasing).

- - - - - - - - -

25. Since the central region initially has a higher neutron flux, more fuel will be burned up there during operation than in the outer regions; so, a distortion of the fuel distribution will develop as operation continues. increasing

- - - - - - - - -

26. Figure III-41 illustrates how the fuel and neutron flux distributions in a reactor would be at the start of operation as compared to the distributions at the end of operation.

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27. As the fuel is burned up, the neutron flux ____________.

- - - - - - - - -

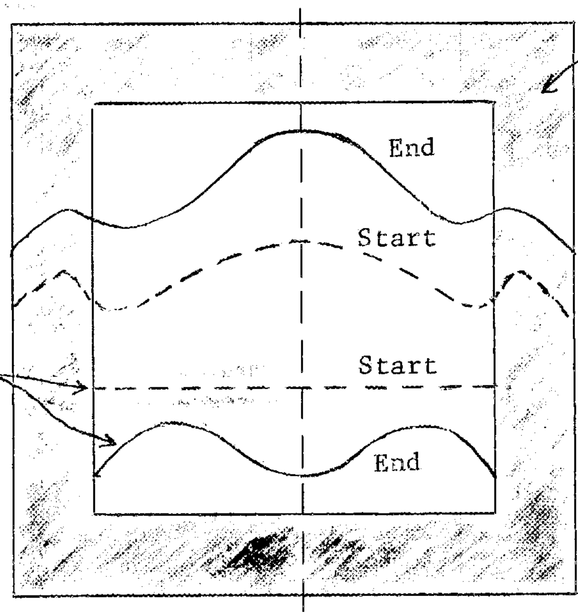


Fig. III-41. Flux Changes during Operation

- - - - - - - - - -

28. The fuel is burned up at a faster rate in the high neutron-flux regions until finally the amount of fuel has decreased so much that the power production in this region starts to decrease because of the lack of fuel to cause fission. increases

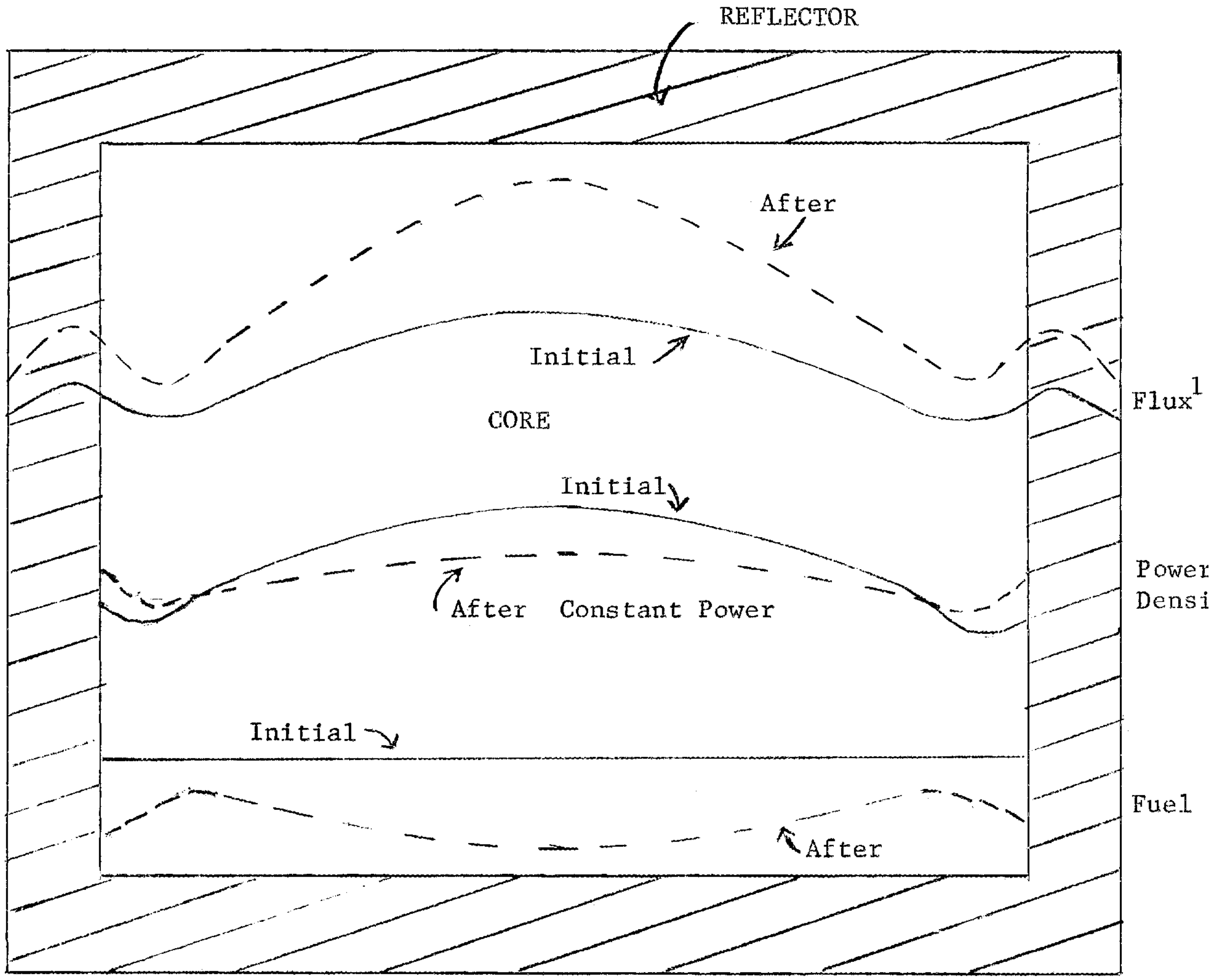
- - - - - - - - - -

29. Figure III-42 shows how the power distribution in the core varies compared to the flux and fuel distributions. Note that the power distribution becomes flatter as the operation continues.

- - - - - - - - - -

30. A flat power distribution is more desirable because the heat production and temperatures are distributed ____________________ over the entire core.

- - - - - - - - - -



[1]To maintain the same power output, the average flux must rise because the average Σ_f is falling. (Review Section III-1, Frames 111 to 114.)

[2]To maintain the same power output (Mw), the average power density must be constant. As the power density in the central region falls, it must rise in the outer region. This is done by increasing the neutron flux level. (Note that the central power density drops more than the outer power density is raised. This is because there is more volume in the outer regions to make up for the smaller power-density change.

Fig. III-42. Idealized Neutron Flux, Power, and Fuel Distribution--before and after Power Operation

- - - - - - - - -

31. To obtain a flat power distribution, some reactors start with a lower fuel density in the center of the core to compensate for the naturally (low, high) neutron flux in that area.

uniformly or evenly

- - - - - - - - -

32. In a research reactor, the fuel may be unevenly loaded into the core in order to enhance the neutron flux near experiment rigs. This also results in distortions of the neutron-flux ____________.

high

- - - - - - - - -

33. Figure III-43 shows a typical ORR core loading which illustrates the distribution of fuel in order to satisfy the neutron flux requirements of experimenters.

distribution

- - - - - - - - -

7.5. Control-Rod Effects

34. The neutron flux distribution in a reactor is affected by almost any change in the core. Thus far we have discussed fuel burnup effects and reflector effects. Control rods also affect the neutron flux--probably more drastically than anything else.

- - - - - - - - -

35. Let us look at Fig. III-44 for just a minute. This illustrates how the neutron flux distribution might appear when a control rod containing poison is inserted into the reactor.

- - - - - - - - -

ORNL DWG. 68-4422

POOL
W

Fuel Weight

S — N

A-1 E	A-2 E	A-3 I	A-4 190.13	A-5 201.19	A-6 182.17	A-7 I	A-8 Be	A-9 Be
B-1 E	B-2 Be	B-3 201.74	B-4 CR 74.29	B-5 184.03	B-6 CR 83.93	B-7 201.97	B-8 E	B-9 Be
C-1 E	C-2 Be	C-3 154.83	C-4 150.92	C-5 157.49	C-6 157.39	C-7 151.67	C-8 174.34	C-9 Be
D-1 131.80	D-2 201.23	D-3 176.37	D-4 CR 114.21	D-5 157.40	D-6 CR 115.12	D-7 158.03	D-8 I	D-9 Be
E-1 195.93	E-2 187.20	E-3 201.35	E-4 185.16	E-5 201.07	E-6 188.50	E-7 201.21	E-8 137.17	E-9 Be
F-1 Be	F-2 Be	F-3 Be	F-4 CR-Al	F-5 Be	F-6 CR-Al	F-7 Be	F-8 I	F-9 E
G-1 Be	G-2 Be	G-3 Be	G-4 Be	G-5 Be	G-6 Be	G-7 Be	G-8 Be	G-9 Be

E

Be--------Beryllium Reflector Piece

CR--------Control Rod of Part Cadmium, Part Fuel

E---------Experiment Rig

CR-Al----Control Rod of Part Cadmium, Part Aluminum

I---------Radioisotope Production Facility

Total Mass = 4867.85 grams of ^{235}U

Control-Rod Positions at Critical = 17.25 inches

Fig. III-43. Core Fuel Loading

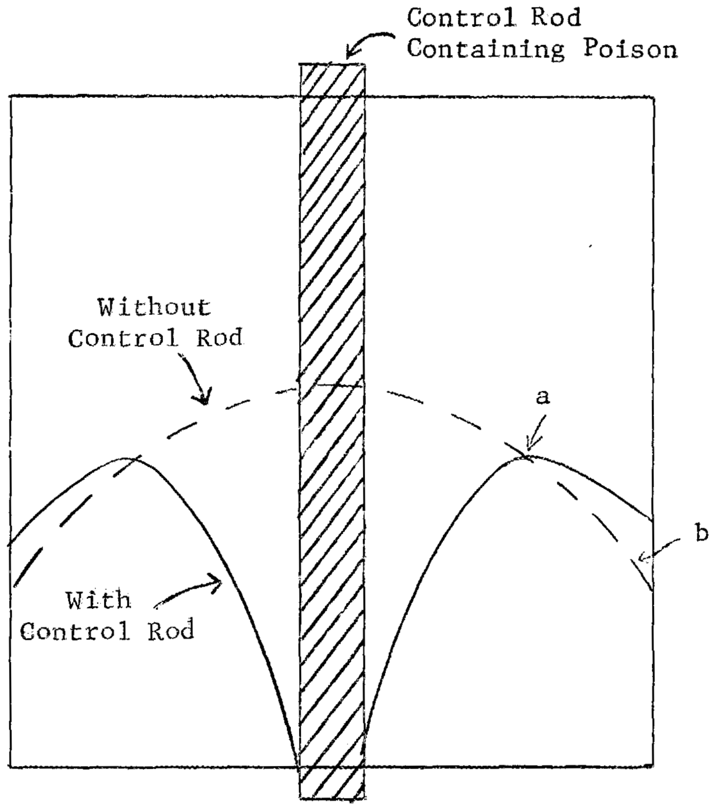


Fig. III-44. Neutron Flux Distortion

- - - - - - - - -

36. This control rod was inserted into the center of the core where the neutron flux was maximum. The reason for this is that at the point where the neutron flux peaks, a control rod will have the most effect. It would have been less effective if it had been inserted near the edge of the core, such as point b, because here there are (more, fewer) neutrons for the control rod to absorb.

- - - - - - - - -

37. If an additional rod is to be inserted, the most effective place would be point (a, b). fewer

- - - - - - - - -

38. This explains why the control-rod worths are different in a reactor which has several control rods. a

- - - - - - - - -

39. As the control rod is withdrawn, we will note that the neutron flux distribution approaches that which would occur if there were no poison in the reactor. See Fig. III-45.

- - - - - - - - -

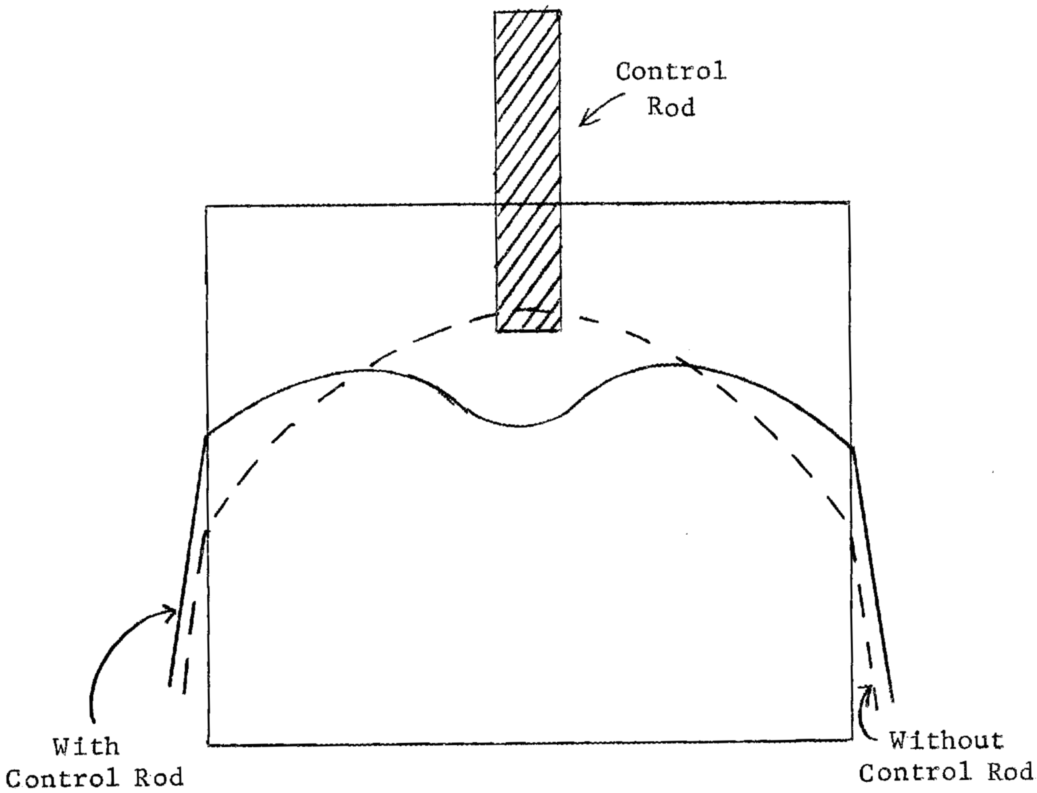


Fig. III-45. Neutron Flux Distortion

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40. Similar depressions in the neutron flux distribution occur whenever any neutron poison (neutron absorber) is inserted into the core of a reactor.

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41. The location of control rods in reactors is generally at positions where the neutron flux is (small, large) because here they will be more effective.

- - - - - - - - - -

42. Thus far we have been looking at what is called the radial neutron flux distribution. Radial implies that it is parallel to the radius, whereas axial implies parallel to the axis. When discussing a reactor, the axis is considered to be the centerline which is parallel to the control-rod motion. — large

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43. Figure III-46 illustrates the difference in the neutron flux distribution in the axial and radial directions.

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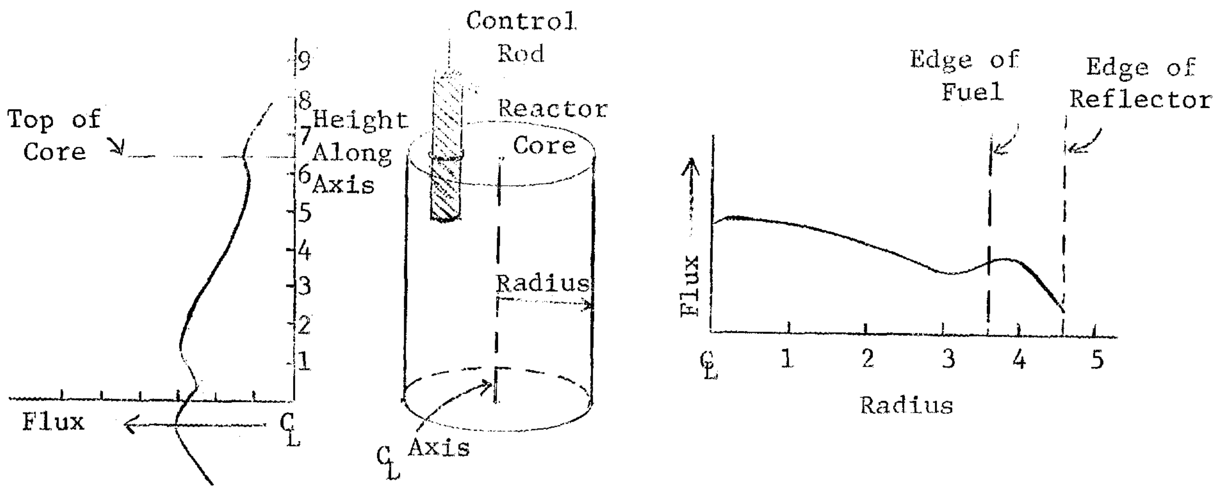

Plot of Flux along the Axis of the Core

Plot of Flux along the Radius of the Core

Fig. III-46. Radial versus Axial Flux Plots

- - - - - - - - - -

44. The effect of a control rod on the axial neutron flux distribution is shown in Fig. III-47.

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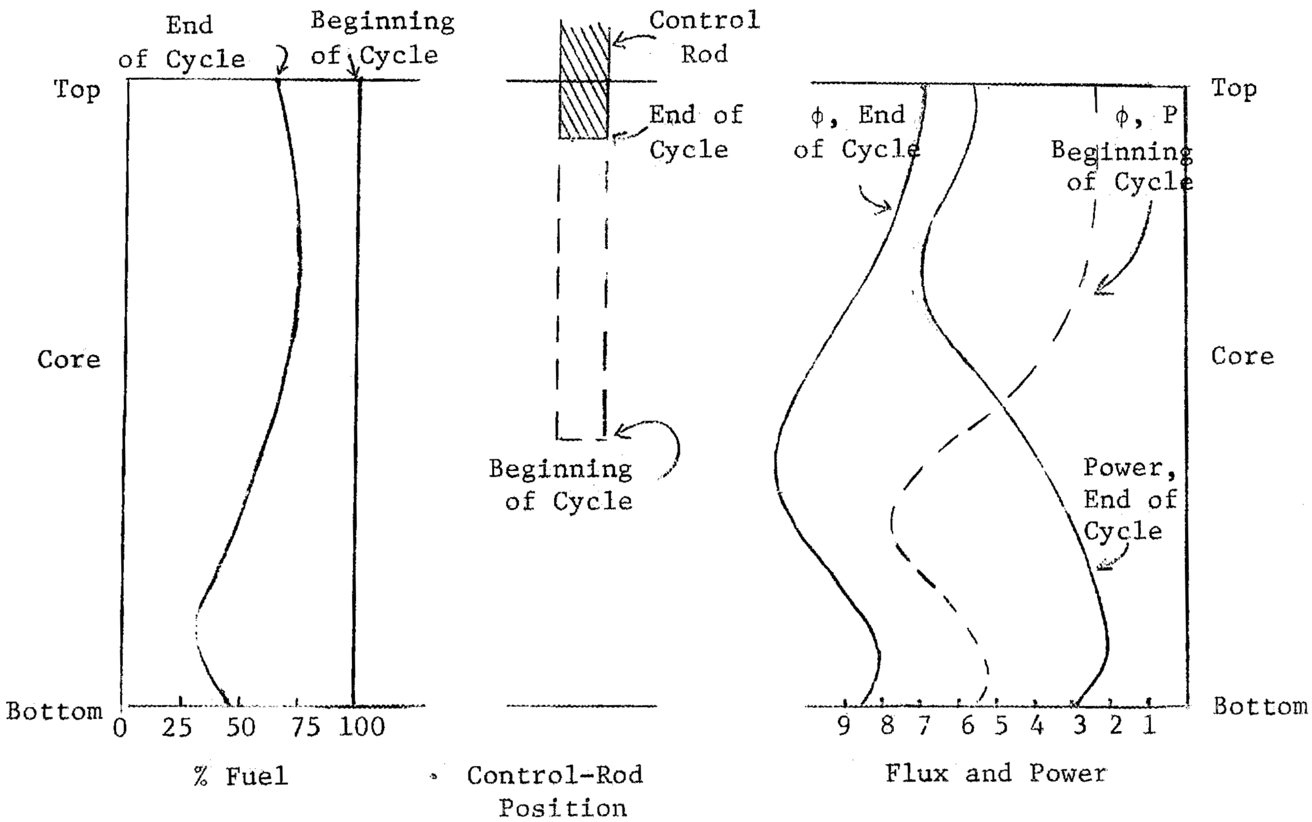

Fig. III-47. Idealized Axial Power and Neutron Flux Distributions around a Control Rod

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7.6. Control-Rod Worth

45. At the beginning of operation (at criticality), about one-half of the control-rod poison is in the core and the other half is out of the core (shutdown factor of 2). This means that the neutron flux is depressed at the top of the core and is __________ at the bottom of the core, as shown in Fig. III-47 (beginning of cycle).

- - - - - - - - - -

46. As the fuel is burned up, the control rod is withdrawn until finally all or almost all of the poison is removed from the core. As it is withdrawn, the neutron flux (and power) tends to flatten out. Figure III-47 shows also how the neutron flux and power distributions would appear at the end of operation. high

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47. Now, look at Fig. III-48, which shows the actual "fine structure" of the neutron flux distribution in a small segment of the core.

- - - - - - - - -

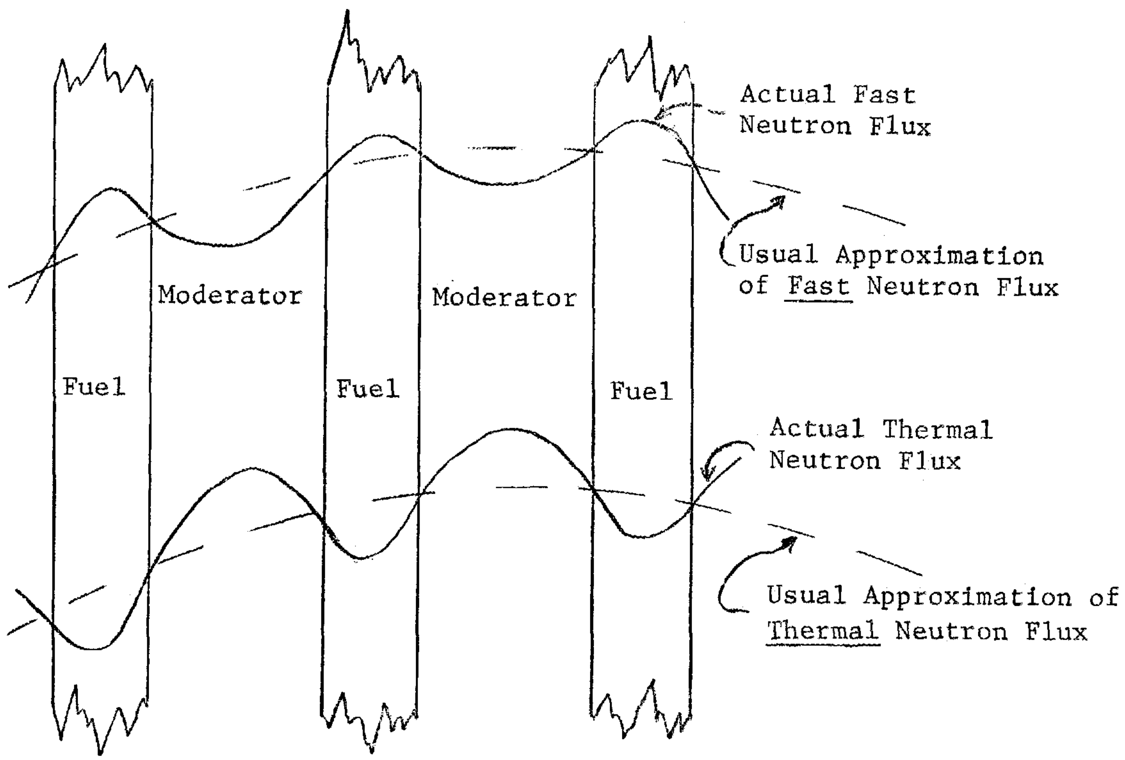

Fig. III-48. "Fine Structure" of Neutron Flux Distribution

- - - - - - - - -

48. Had the fuel and moderator been a homogeneous mixture (homogeneous mixture means uniform mixture like homogenized milk), the actual neutron flux would have been smooth as in the dotted lines of Fig. III-48. representing the usual approximation which averages out the small dips and peaks.

- - - - - - - - -

49. In a nonhomogeneous reactor, such as the ORR or HFIR, the fuel (plates) are separated by channels of water which act both as moderator and as coolant. This separation of fuel and water results in small peaks as shown. The fast neutron flux peaks in the __________________ because this is where the fast neutrons are born; as they move into the water, they become thermalized--thus causing the thermal neutron flux peaks there.

- - - - - - - - -

50. The depression in the <u>thermal</u> neutron flux in the fuel region occurs because <u>thermal</u> neutrons are absorbed in the fuel. As long as the fuel plates and water channels are kept thin, these variations in the neutron fluxes produce no important effects. fuel

- - - - - - - - -

51. The fact that the neutron density is less near the edges of the core than in the center causes the worth of control rods per inch of insertion to vary. The reactivity worth of a control rod might be as much as 10% $\Delta k/k$ or more for full travel of the entire rod. If the rod is 20 in. long, then you might think that each 1 in. of rod is worth 0.5% $\Delta k/k$. But this is not correct.

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52. It is generally true that the "end positions" of control-rod travel are not as effective as the "middle positions".

- - - - - - - - -

53. The reason the end positions are worth less in changing reactivity than the middle positions is because the first movements of a rod remove or insert poison at the edges of the core where the neutron flux is ________________.

- - - - - - - - -

54. Obviously, a poison material will be more effective (absorb more neutrons) at places where there are more ____________________. small

- - - - - - - - -

55. As the movement of the rod continues <u>into</u> the core, the poison material penetrates into the central region of the core where there are ___________ neutrons and the effect per inch on reactivity (increases, decreases). neutrons

- - - - - - - - -

56. As the control rod is inserted farther into the core so that penetration is made through to the outer regions of the other side, less and less effect per inch occurs with further insertion. more, increases

- - - - - - - - -

57. As the control rod approaches the end of its travel, it has (less, more) effect per inch of travel than when it is in the central region of the core.

- - - - - - - - -

58. Figure III-49 illustrates the relative effects of a small movement of a control rod. less

- - - - - - - - -

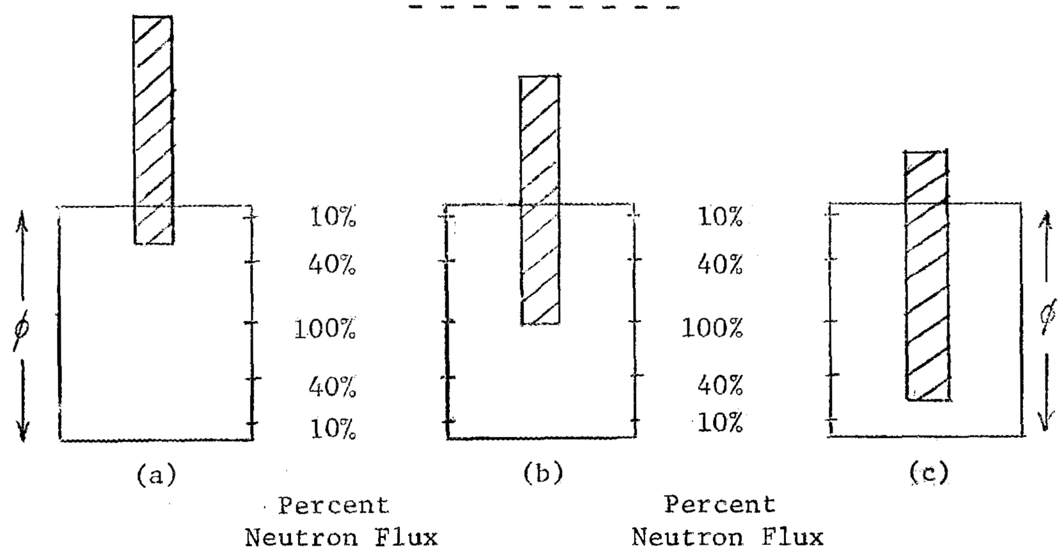

Fig. III-49. Control-Rod Effects

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59. In Fig. III-49a, the rod has just entered the low-flux region near the edge of the core. In Fig. III-49b the end of the rod enters the area where the neutron flux is maximum (100%). In Fig. III-49c the rod is again entering a low-flux region. At any time during the insertion, there is still the same amount of poison in the other regions just passed so the only new effect on reactivity is that produced as the end of the rod enters a new region.

- - - - - - - - -

60. The largest reactivity effect of a small movement is produced when the rod is in the position as shown in (a, b, c).

- - - - - - - - -

61. The reactivity worth of a control rod is generally determined for each inch of travel (or some such fraction of the length). Since the neutron flux is lower at the top and bottom of the core, it can be expected that the reactivity worth of the first few inches of control-rod movement will have (less, more) effect than when the end of the rod is in the center of the core. — b

- - - - - - - - -

62. It is true that in the "end positions" a control rod motion has less effect on reactivity than in the _____________ position of its travel. — less

- - - - - - - - -

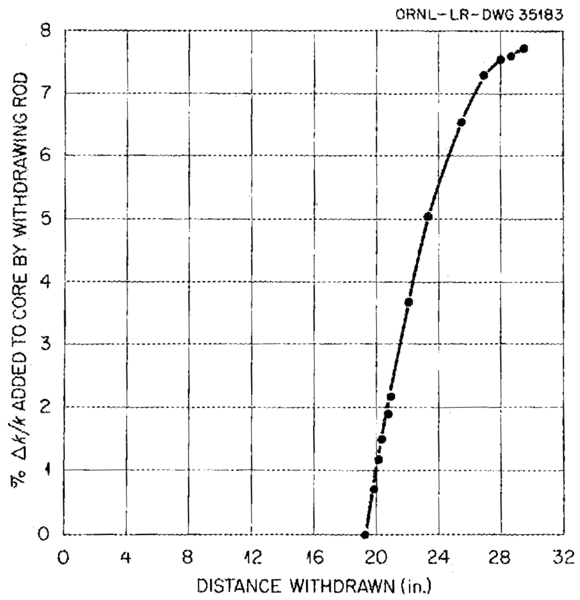
63. Control rods can be calibrated in reactivity worth per inch or for total worth of their full length by using any of several different methods. For example: — middle or center

    a. Cancelling out the effects of a rod movement with a small amount of neutron absorber of known (calculated) reactivity worth.
    b. Observing the period resulting from a rod movement.
    c. Observing the magnitude of the neutron flux increases and decreases while rapidly oscillating the rod over a small distance.
    d. Observing the decreasing neutron flux following a reactor scram.

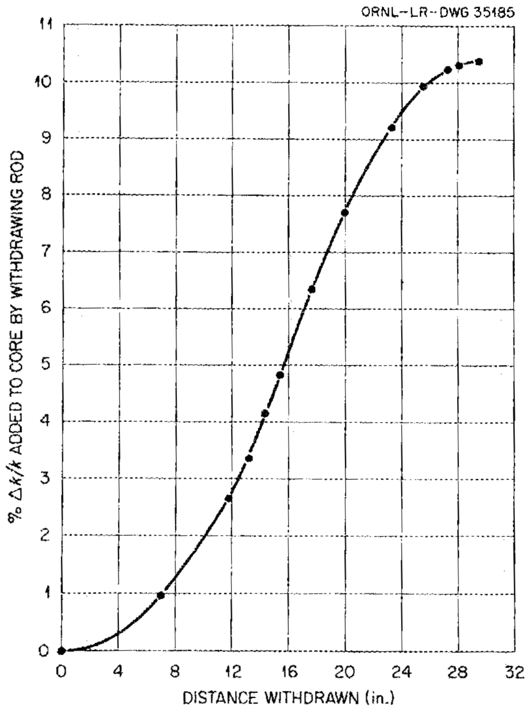
- - - - - - - - -

64. Figure III-50 is a graph of reactivity worth versus rod position. The S-shape is typical of rod calibration curves.

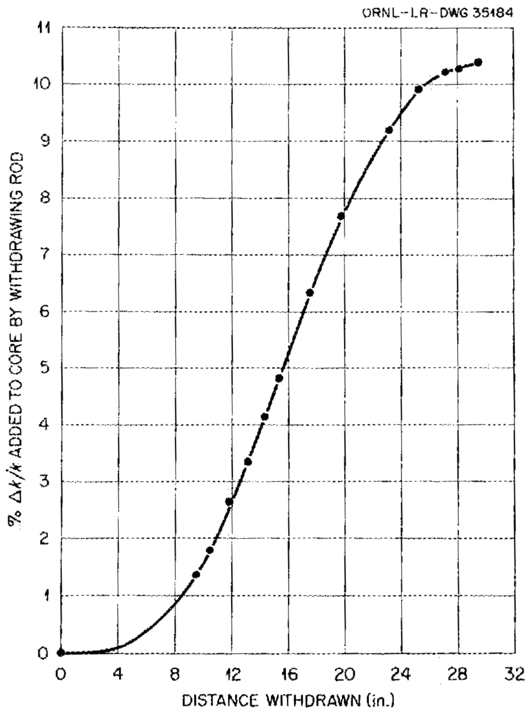
- - - - - - - - -



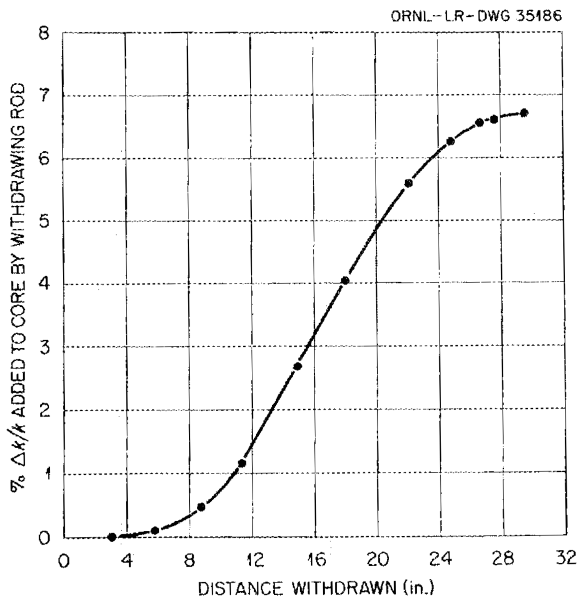
Gang Rod Calibration for Operating Core with Experiments. Core worth, 7.72% Δk/k; central slope, (1.30% Δk/k)/in.



Number 4 Rod Calibration for Operating Core with Experiments. Total Worth, 10.37% Δk/k; central slope, (0.63% Δk/k)/in.



Number 3 Rod Calibration for Operating Core with Experiments. Total worth, 10.35% Δk/k; central slope, (0.64% Δk/k)/in.



Number 5 Rod Calibration for Operating Core with Experiments. Total worth, 6.70% Δk/k; central slope, (0.43% Δk/k)/in.

Fig. III-50. Reactivity Worth vs Rod Position

65. Considering only single rods, No. 3 has the steepest slope with ________________ per inch and rod No. 5 has the least slope with ______________ per inch.

- - - - - - - - -

66. This means that if all rods are about half withdrawn, rod No. ___ will add the greatest amount of reactivity as it is withdrawn another inch.

0.64% $\Delta k/k$
0.43% $\Delta k/k$

- - - - - - - - -

67. Note that when withdrawal starts, the No. 4 rod must be withdrawn about 7 in. to cause the first 1% change in reactivity. However, the change from 5% to 6% $\Delta k/k$ (1% $\Delta k/k$ change) requires a rod movement of only about ______ inches.

3

- - - - - - - - -

68. Note that the reactivity worth per inch does not change much at the beginning nor at the end of travel. However, in the middle, the reactivity worth changes considerably more for each inch of movement; this results from the fact that

____

2

- - - - - - - - -

The neutron flux is greater in the center than at the outer edges of the core, and the rod is more effective in the high-flux regions.

- - - - - - - - -

69. Figure III-51 shows a graph of reactivity worth per inch versus rod position. The total worth for the accumulated rod movement is shown as curve A. Curve B shows the worth of each inch of rod travel.

- - - - - - - - -

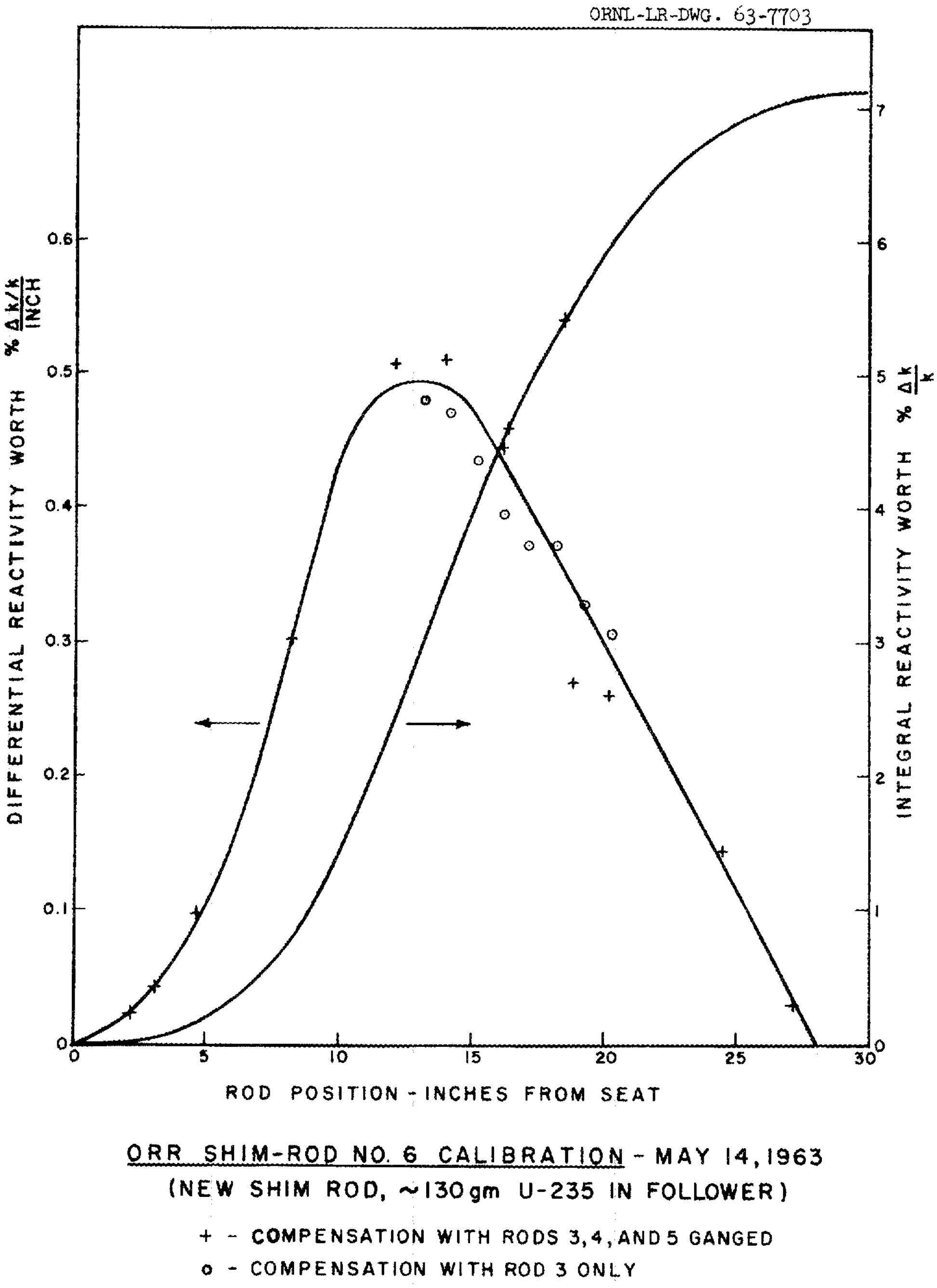


Fig. III-51. ORR Shim-Rod No. 6 Calibration - May 14, 1963 (New Shim Shim Rod, ~130 gm ^{235}U Follower)

70. The worth per inch increases up to about ____ or _____ inches, where an inch of rod movement is worth about 0.5% $\Delta k/k$.

- - - - - - - - -

71. Note also that at both 5 in. withdrawn and 25 in. withdrawn, an inch of rod movement is worth about ____________. 12, 13

- - - - - - - - -

72. These control-rod calibrations are used in many ways. They are used to analyze hazards, to set operational limits, and for other operational purposes. 0.1% $\Delta k/k$

- - - - - - - - -

73. Most reactors have automatic control systems called "servo systems". These servo systems are allowed to make only small reactivity changes. If they were allowed to make large changes, any failure of the system might result in a large reactivity change and a possible core meltdown. In order to limit the amount of reactivity used by the servo system to a safe amount, knowledge of control-rod reactivity worths is necessary.

- - - - - - - - -

74. It should be pointed out that while we have emphasized the desirability of a flat neutron-flux distribution, we do not want a flat distribution in some types of reactors. The HFIR is such a reactor. This reactor was designed so that a maximum flux would occur in a "flux trap" in the center of the core so that some special materials can be irradiated in the highest possible neutron flux.

- - - - - - - - -

75. Actually, a flux trap is not a trap at all. The word trap indicates that there is no way of escape; and a flux trap is <u>not</u> a region of no escape for neutrons.

\- - - - - - - - -

76. For an example, let us use a bird refuge, a sanctuary. We will assume that there are 100 ducks on a lake, and ducks alight on the lake at the rate of 25 per hour. Some fly away again; some die of old age; and some are killed by predators, but all have the opportunity to leave or stay as they see fit.

\- - - - - - - - -

77. If 25 ducks leave each hour by any of the methods listed in Frame 76, we would say that the average life of a duck on the lake is 1 hr. Some might fly off immediately, and others might stay for months; but the average lifetime on the lake is

______________.

\- - - - - - - - -

78. If there are no changes in the situation, the average duck population will remain constant at ______ ducks. 1 hr

\- - - - - - - - -

79. For the purposes of analysis, we keep a chart of duck movements and find that each hour, 100

10% of the population - 10 ducks - fly away

14% of the population - 14 ducks - eaten by predators (Σ_a)

<u>1%</u> of the population - <u>1 duck</u> - dies of old age

25% of the population - 25 ducks - lost each hour

\- - - - - - - - -

80. However, 25 ducks arrive each hour, so the duck population on the lake remains ______________.

- - - - - - - - -

81. If we let P represent the total duck population — the same or constant

$$10\%P + 14\%P + 1\%P = 25 \text{ ducks},$$

or

$$(0.10 + 0.14 + 0.01)P = 25 \text{ ducks}$$
$$0.25P = 25$$
$$P = 25/0.25$$
$$P = \_\_\_\_\_\_ \text{ ducks.}$$

- - - - - - - - -

82. Now let us remove some predators (reducing Σ_a). Our records now show: — 100

10% - 10 ducks - fly away
9% - 9 ducks - are eaten by predators
<u>1%</u> - <u>1 duck</u> - dies of old age
20% - 20 ducks - lost each hour.

- - - - - - - - -

83. It is rather obvious that if more ducks arrive than leave, the duck population will increase. It is not quite so obvious that the duck population will again become constant when the percent of loss of the <u>new</u> population equals 25 ducks.

- - - - - - - - -

84. When the percent of the population that is lost equals the number of ducks arriving, the duck population will remain ______________.

- - - - - - - - -

85. If we let D represent the new duck population, D will become stable when 20% of D equals _____ ducks. | constant

- - - - - - - - -

86. If | 25

$$10\%D + 9\%D + 1\%D = 25 \text{ ducks},$$

then

$$(0.10 + 0.09 + 0.01)D = 25 \text{ ducks}$$
$$D = 25/0.20$$

D = ________ (the new stable duck population).

- - - - - - - - -

87. If, in our hypothetical case, only 15 ducks leave per hour, the duck population will again ___________ until it reaches a point of stability when the 15% loss equals _______ ducks, the number arriving per hour. | 125 ducks

- - - - - - - - -

88. In an analagous situation, the stable neutron population in a flux trap is the average number of neutrons which remain when the percent of the population that is lost exactly equals the number of neutrons _______ the trap. | increase, 25

- - - - - - - - -

89. The neutron flux trap region in a reactor might be more correctly named if it were called a neutron sanctuary. Neutrons come and neutrons go, but the average life of a neutron in the region called flux trap is longer than it is in other parts of the core. Thus, the neutron density here is ________ than it is in other parts of the core. | entering

- - - - - - - - -

90. The trap (sanctuary) is usually in the central part of the core where a large volume of moderator is surrounded by fuel. Fast neutrons from the fuel are thermalized in the moderator and remain there for a (longer, shorter) time than they would in the fuel because the Σ_a of the moderator is lower than that of the fuel. — greater

\- - - - - - - - -

91. Since the thermal neutrons have a longer life in the trap, the thermal neutron density is (greater, less) in the trap than in the fuel. — longer

\- - - - - - - - -

92. Materials placed in the trap are in a (lower, higher) thermal neutron flux than if they were placed anywhere else in the core. — greater

\- - - - - - - - -

93. The thermal neutron flux is high because the probability of absorption is (greater, less) in the moderator than in the fuel. — higher

\- - - - - - - - -

less

7.7. Self Test

94. The neutron flux, ϕ, is the number of neutrons in a cubic centimeter multiplied by their ________. (If you made an incorrect response, repeat Frame 1.) | less

- - - - - - - - -

95. The number of thermal neutrons in a cubic centimeter multiplied by their speed is usually called the thermal ________ ________. (If you made an incorrect response, repeat Frame 1.) | velocity or speed

- - - - - - - - -

96. The manner in which neutrons are distributed throughout a reactor is called the neutron flux ________. (If you made an incorrect response, repeat Frames 2-6.) | neutron flux

- - - - - - - - -

97. A reactor which has a uniform fuel distribution will generally have more neutrons per cm^3 in the (outer, central) region because of neutron ________. (If you made an incorrect response, repeat Frames 7-10.) | distribution

- - - - - - - - -

98. The neutron flux distribution is changed when a reflector is placed around the core of a reactor because neutrons which would otherwise escape are ________ back into the core. (If you made an incorrect response, repeat Frames 11-14.) | central, leakage

- - - - - - - - -

99. A flux distribution which is uniform throughout the core is called a (peaked, flat) distribution. (If you made an incorrect response, repeat Frame 15.) | reflected or returned

- - - - - - - - -

100. If heat is generated uniformly throughout the core of a reactor, then the temperature distribution will be (peaked, flat). (If you made an incorrect response, repeat Frame 16.) flat

- - - - - - - - - -

101. The maximum power output of a reactor will be possible if the temperature distribution is (uniform, nonuniform). (If you made an incorrect response, repeat Frames 17-21.) flat

- - - - - - - - - -

102. To maintain a constant reactor power level as the mass of fuel decreases, the neutron flux must (increase, decrease). (If you made an incorrect response, repeat Frames 23-24.) uniform

- - - - - - - - - -

103. The fuel in a reactor which is loaded uniformly will be consumed at a faster rate in the region where the flux is (high, low). (If you made an incorrect response, repeat Frame 28.) increase

- - - - - - - - - -

104. The maximum effectiveness of a control rod per unit length is obtained if it is inserted where the neutron flux is (maximum, minimum). (If you made an incorrect response, repeat Frames 36-41.) high

- - - - - - - - - -

105. The first movements of a control rod remove or insert poison near the edges of the core where the neutron flux is (high, low) so the effect per inch will be (small, large). (If you made an incorrect response, repeat Frames 45-53.) maximum

- - - - - - - - - -

106. Movements of the control rod into or out of the center of the core cause (more, less) effect than at the edges of the core. (If you made an incorrect response, repeat Frames 50-52.) — low, small

\- - - - - - - - -

107. The thermal neutron density in a flux trap is greater than in other parts of the core because the thermal neutron lifetime is ______________ there. (If you made an incorrect response, repeat Frame 81.) — more

\- - - - - - - - -

longer

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