Lectures on Applied Reactor Technology and Nuclear Power Safety

Lecture No 5

Title:

Reactor Kinetics and Reactor Operation

Henryk Anglart

Nuclear Reactor Technology Division

Department of Energy Technology

KTH

Spring 2005

Outline of the Lecture (1)

- **Reactor Kinetics**
  - Reactor Period
  - Effective Delayed Neutron Fraction
  - Effective Delayed Neutron Precursor Decay Constant
  - Prompt Criticality
  - Stable Period Equation
  - Reactor Startup Rate (SUR)
  - Doubling Time

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  - Operation
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  - Decay heat

Reactor Period (1)

- The **reactor period** is defined as the time required for reactor power to change by a factor of "e," where "e" is the base of the natural logarithm and is equal to about 2.718

- The reactor period is usually expressed in units of seconds

- From the definition of reactor period, it is possible to develop the relationship between reactor power and reactor period that is expressed by the following Equation: $P = P_0 e^{t/\tau}$, here τ is the reactor period

Reactor Period (2)

- The smaller the value of τ, the more rapid the change in reactor power

- If the reactor period is positive, reactor power is increasing

- If the reactor period is negative, reactor power is decreasing

Reactor Period (3)

- There are numerous equations used to express reactor period, but Equation shown below, or portions of it, will be useful in most situations

$$\tau = \frac{l^*}{\rho} + \frac{\overline{\beta}_{eff} - \rho}{\lambda_{eff}\rho + \dot{\rho}}$$

l^*	=	prompt generation lifetime
$\overline{\beta}_{eff}$	=	effective delayed neutron fraction
ρ	=	reactivity
λ_{eff}	=	effective deleyed neutron precursor decay constant
$\dot{\rho}$	=	rate of change of reactivity

- The first term in Equation is the prompt term and the second term is the delayed term

Effective Delayed Neutron Fraction (1)

- Recall that , the *delayed neutron fraction*, is the fraction of all fission neutrons that are born as delayed neutrons

- The value of β depends upon the actual nuclear fuel used

- the delayed neutron precursors for a given type of fuel are grouped on the basis of half-life

- The table on the next slide lists the fractional neutron yields for each delayed neutron group of three common types of fuel

Effective Delayed Neutron Fraction (2)

Group	Half-Life (sec)	Uranium-235	Uranium-238	Plutonium-239
1	55.6	0.00021	0.0002	0.00021
2	22.7	0.00141	0.0022	0.00182
3	6.22	0.00127	0.0025	0.00129
4	2.30	0.00255	0.0061	0.00199
5	0.61	0.00074	0.0035	0.00052
6	0.23	0.00027	0.0012	0.00027
TOTAL	-	0.00650	0.0157	0.00200

Effective Delayed Neutron Fraction (3)

- The term $\bar{\beta}$ (beta-bar) is the **average delayed neutron fraction**

- The value of $\bar{\beta}$ is the weighted average of the total delayed neutron fractions of the individual types of fuel

- Each total delayed neutron fraction value for each type of fuel is weighted by the percent of total neutrons that the fuel contributes through fission

- If the percentage of fissions occurring in the different types of fuel in a reactor changes over the life of the core, the average delayed neutron fraction will also change

- For a light water reactor using low enriched fuel, the average delayed neutron fraction can change from 0.0070 to 0.0055 as uranium-235 is burned out and plutonium-239 is produced from uranium-238

Effective Delayed Neutron Fraction (4)

- Delayed neutrons do not have the same properties as prompt neutrons released directly from fission

- The average energy of prompt neutrons is about 2 MeV. This is much greater than the average energy of delayed neutrons (about 0.5 MeV)

- The fact that delayed neutrons are born at lower energies has two significant impacts on the way they proceed through the neutron life cycle

- First, delayed neutrons have a much lower probability of causing fast fissions than prompt neutrons because their average energy is less than the minimum required for fast fission to occur

- Second, delayed neutrons have a lower probability of leaking out of the core while they are at fast energies, because they are born at lower energies and subsequently travel a shorter distance as fast neutrons

Effective Delayed Neutron Fraction (5)

- These two considerations (lower fast fission factor and higher fast non-leakage probability for delayed neutrons) are taken into account by a term called the *importance factor* (I)

- The importance factor relates the average delayed neutron fraction to the effective delayed neutron fraction

- The effective delayed neutron fraction $\overline{\beta}_{eff}$ is defined as the fraction of neutrons at thermal energies which were born delayed

$$\overline{\beta}_{eff} = \overline{\beta} \cdot I$$

Effective Delayed Neutron Fraction (6)

- In a small reactor with highly enriched fuel, the increase in fast non-leakage probability will dominate the decrease in the fast fission factor, and the importance factor will be greater than one

- In a large reactor with low enriched fuel, the decrease in the fast fission factor will dominate the increase in the fast non-leakage probability and the importance factor will be less than one (about 0.97 for a commercial PWR).

Effective Delayed Neutron Precursor Decay Constant (1)

- Another new term has been introduced in the reactor period (τ) equation

- That term is λ_{eff} (pronounced lambda effective), the **effective delayed neutron precursor decay constant**

- The decay rate for a given delayed neutron precursor can be expressed as the product of precursor concentration and the decay constant (λ) of that precursor

- The decay constant of a precursor is simply the fraction of an initial number of the precursor atoms that decays in a given unit time

Effective Delayed Neutron Precursor Decay Constant (2)

- A decay constant of 0.1 sec^{-1}, for example, implies that one-tenth, or ten percent, of a sample of precursor atoms decays within one second

- The value for the effective delayed neutron precursor decay constant, λ_{eff} , varies depending upon the balance existing between the concentrations of the precursor groups and the nuclide(s) being used as the fuel

Effective Delayed Neutron Precursor Decay Constant (3)

- If the reactor is operating at a constant power, all the precursor groups reach an equilibrium value

- During an up-power transient, however, the shorter-lived precursors decaying at any given instant were born at a higher power level (or flux level) than the longer-lived precursors decaying at the same instant

- There is, therefore, proportionately more of the shorter-lived and fewer of the longer-lived precursors decaying at that given instant than there are at constant power

- The value of λ_{eff} is closer to that of the shorter-lived precursors

Effective Delayed Neutron Precursor Decay Constant (4)

- During a down-power transient the longer-lived precursors become more significant

- The longer-lived precursors decaying at a given instant were born at a higher power level (or flux level) than the shorter-lived precursors decaying at that instant

- Therefore, proportionately more of the longer-lived precursors are decaying at that instant, and the value of λ_{eff} approaches the values of the longer-lived precursors

Effective Delayed Neutron Precursor Decay Constant (5)

- Approximate values for λ_{eff} are 0.08 sec^{-1} for steady-state operation, 0.1 sec^{-1} for a power increase, and 0.05 sec^{-1} for a power decrease

- The exact values will depend upon the materials used for fuel and the value of the reactivity of the reactor core

Effective Delayed Neutron Precursor Decay Constant (6)

- Let us recall the equation for reactor period:

$$\tau = \frac{l^*}{\rho} + \frac{\overline{\beta}_{eff} - \rho}{\lambda_{eff}\rho + \dot{\rho}}$$
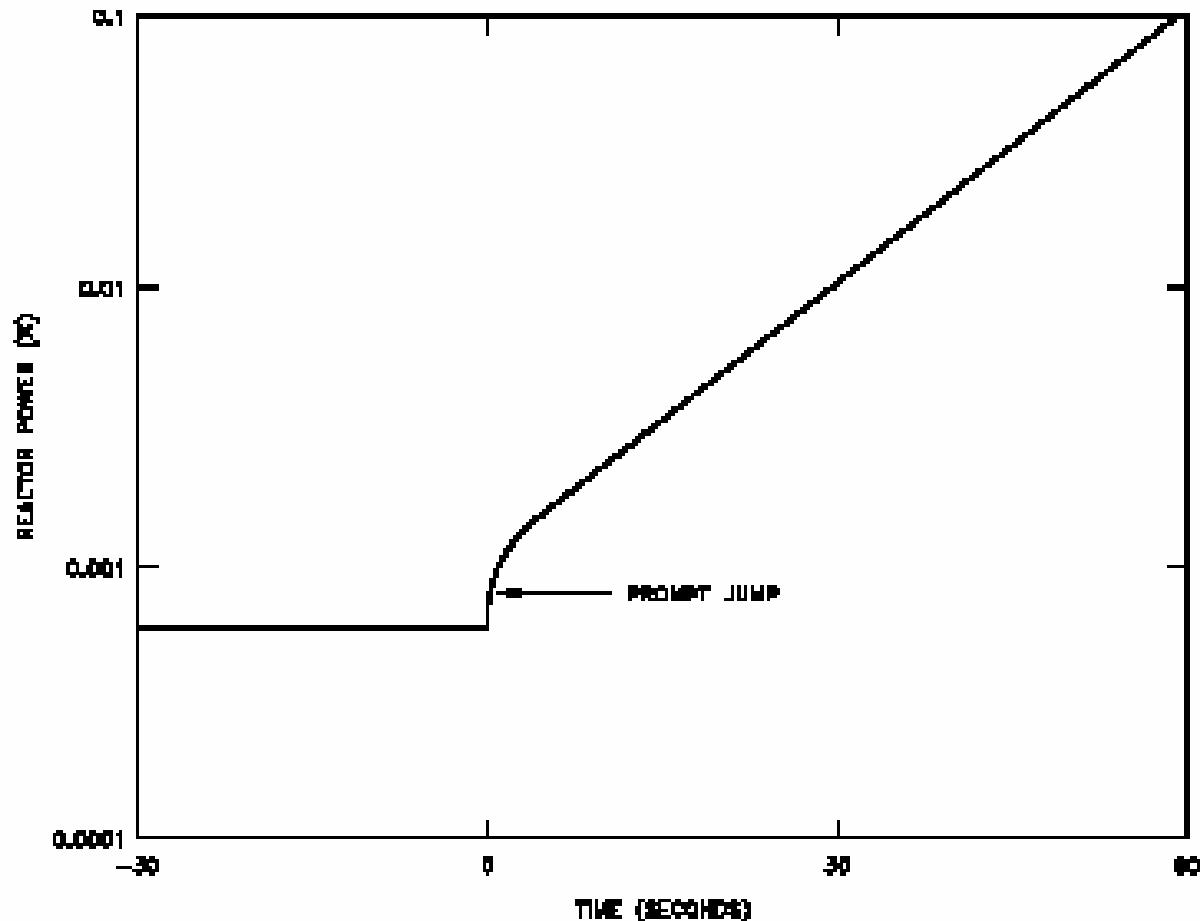
$$\text{prompt} \qquad \text{delayed}$$

$$\text{term} \qquad \text{term}$$

- If the positive reactivity added is less than the value of $\overline{\beta}_{eff}$, the emission of prompt fission neutrons alone is not sufficient to overcome losses to non-fission absorption and leakage

- If delayed neutrons were not being produced, the neutron population would decrease as long as the reactivity of the core has a value less than the effective delayed neutron fraction

Effective Delayed Neutron Precursor Decay Constant (7)

- The positive reactivity insertion is followed immediately by a small immediate power increase called the **prompt jump**

- This power increase occurs because the rate of production of prompt neutrons changes abruptly as the reactivity is added

- Recall that the generation time for prompt neutrons is on the order of 10^{-13} seconds

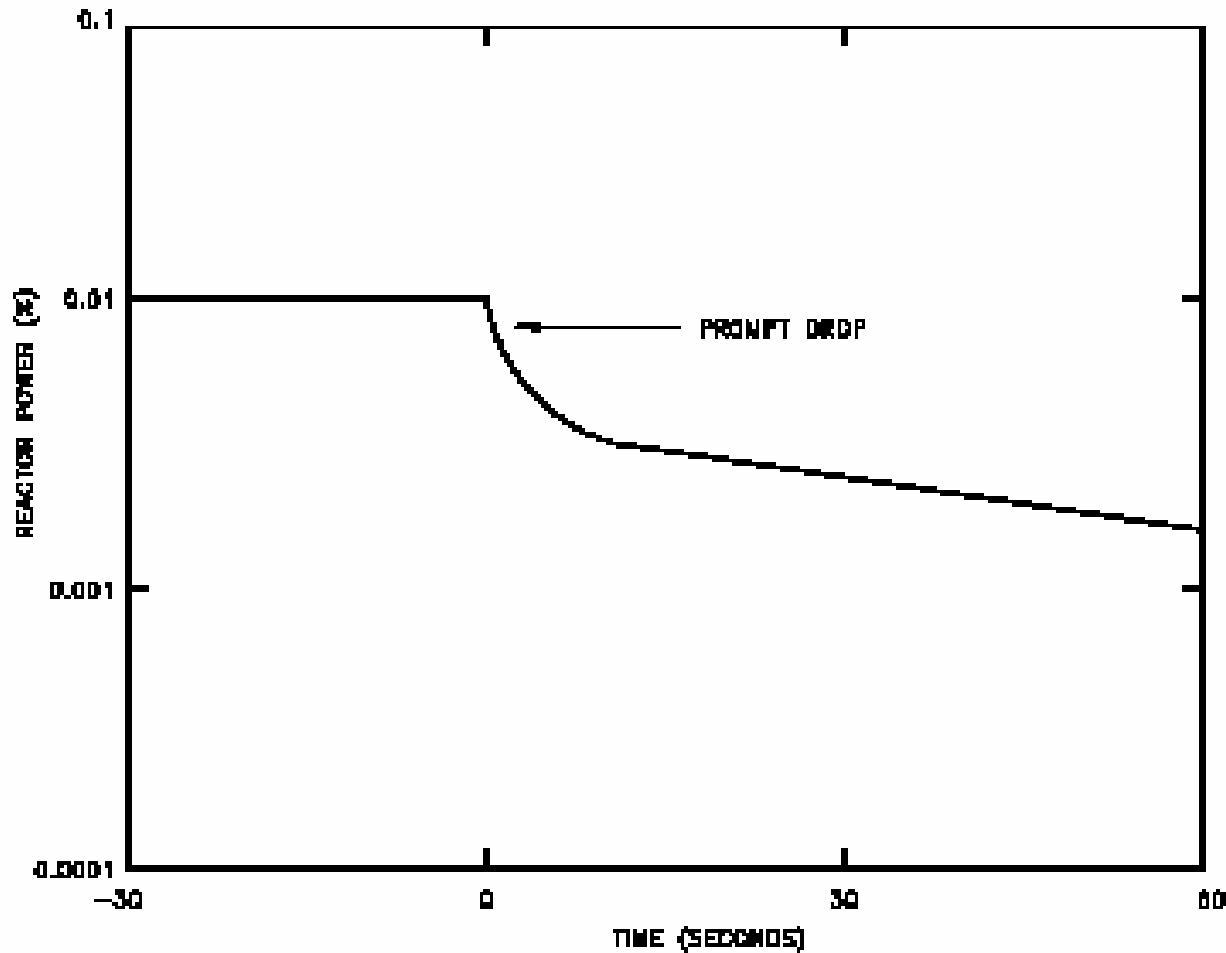- The effect can be seen in Figure on the next slide

Effective Delayed Neutron Precursor Decay Constant (8)

Effective Delayed Neutron Precursor Decay Constant (9)

- After the prompt jump, the rate of change of power cannot increase any more rapidly than the built-in time delay the precursor half-lives allow

- Therefore, the power rise is controllable, and the reactor can be operated safely

- Conversely, in the case where negative reactivity is added to the core there will be a prompt drop in reactor power

- The *prompt drop* is the small immediate decrease in reactor power caused by the negative reactivity addition. The prompt drop is illustrated in Figure on the next slide

Effective Delayed Neutron Precursor Decay Constant (10)

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Henryk Anglart
Nuclear Reactor Technology Division
Department of Energy Technology, KTH

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Prompt Criticality (1)

- It can be readily seen from Equation for the reactor period that if the amount of positive reactivity added equals the value of $\overline{\beta}_{eff}$, the reactor period equation becomes the following

$$\tau = \frac{l^*}{\rho} + \frac{\overline{\beta}_{eff} - \rho}{\lambda_{eff}\rho + \dot{\rho}} \underset{\overline{\beta}_{eff} = \rho}{\Longrightarrow} \tau = \frac{l^*}{\rho}$$

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Prompt Criticality (2)

- In this case, the production of prompt neutrons alone is enough to balance neutron losses and increase the neutron population

- The condition where the reactor is critical on prompt neutrons, and the neutron population increases as rapidly as the prompt neutron generation lifetime allows is known as **prompt critical**

- The prompt critical condition does not signal a dramatic change in neutron behavior

Prompt Criticality (3)

- The reactor period changes in a regular manner between reactivities above and below this reference

- Prompt critical is, however, a convenient condition for marking the transition from delayed neutron to prompt neutron time scales

- A reactor whose reactivity even approaches prompt critical is likely to suffer damage due to the rapid rise in power to a very high level

- For example, a reactor which has gone prompt critical could experience a several thousand percent power increase in less than one second

Prompt Criticality (4)

- Because the prompt critical condition is so important, a specific unit of reactivity has been defined that relates to it

- The unit of reactivity is the dollar ($), where one dollar of reactivity is equivalent to the effective delayed neutron fraction $\overline{\beta}_{eff}$

- A reactivity unit related to the dollar is the cent, where one cent is one-hundredth of a dollar

- If the reactivity of the core is one dollar, the reactor is prompt critical

- Because the effective delayed neutron fraction is dependent upon the nuclides used as fuel, the value of the dollar is also dependent on the nuclides used as fuel

Stable Period Equation (1)

- For normal reactor operating conditions, the value of positive reactivity in the reactor is never permitted to approach the effective delayed neutron fraction, and the reactor period equation is normally written as follows

$$\tau = \frac{\overline{\beta}_{eff} - \rho}{\lambda_{eff}\,\rho + \dot{\rho}}$$

- The above Equation is referred to as the **transient period equation** since it incorporates the $\dot{\rho}$ term to account for the changing amount of reactivity in the core

- The l^*/ρ term (prompt period) is normally negligible with respect to the remainder of the equation and is often not included

Stable Period Equation (2)

- For conditions when the amount of reactivity in the core is constant ($\dot{\rho} = 0$), and the reactor period is unchanging, the reactor period Equation can be simplified further to Equation shown below which is known as the **stable period equation**

$$\tau = \frac{\overline{\beta}_{eff} - \rho}{\lambda_{eff}\,\rho}$$

Reactor Startup Rate - SUR (1)

- The **reactor startup rate** (SUR) is defined as the number of factors of ten that power changes in one minute

- The units of SUR are powers of ten per minute, or decades per minute (DPM)

- Equation below shows the relationship between reactor power and startup rate (*t* time in minutes)

$$P = P_0 \cdot 10^{SUR(t)}$$

Reactor Startup Rate - SUR (2)

- The relationship between reactor period and sturtup rate can be developed by considering the following equations

$$P = P_0 \cdot 10^{SUR(t)} \qquad P = P_0 e^{t/\tau}$$

$$10^{SUR(t)} \equiv e^{2.303 \cdot SUR(t)} = e^{t/\tau} \Rightarrow \frac{t(\text{sec})}{\tau} = 2.303 \cdot SUR[t(\text{min})]$$

$$SUR = \frac{60}{\tau} \Big/ 2.303 = \frac{26.06}{\tau}$$

Doubling Time (1)

- Sometimes it is useful to discuss the rate of change of reactor power in terms similar to those used in radioactive decay calculations

- **Doubling** or **halving time** are terms that relate to the amount of time it takes reactor power to double or be reduced to one-half the initial power level

- If the stable reactor period is known, doubling time can be determined as follows:

- Doubling time DT = τ ln 2, where τ is stable reactor period

Reactor Operation - Startup (1)

- When a reactor is started up with unirradiated fuel, or on those occasions when the reactor is restarted following a long shutdown period, the source neutron population will be very low

- In some reactors, the neutron population is frequently low enough that it cannot be detected by the nuclear instrumentation during the approach to criticality

- Installed neutron sources, such as those discussed in earlier parts of this course, are frequently used to provide a safe, easily monitored reactor startup

Reactor Operation - Startup (2)

- The neutron source, together with the subcritical multiplication process, provides a sufficiently large neutron population to allow monitoring by the nuclear instruments throughout the startup procedure

- Without the installed source, it may be possible to withdraw the control rods to the point of criticality, and then continue withdrawal without detecting criticality because the reactor goes critical below the indicating range

- Continued withdrawal of control rods at this point could cause reactor power to rise at an uncontrollable rate before neutron level first becomes visible on the nuclear instruments

Reactor Operation - Startup (3)

- An alternative to using a startup source is to limit the rate of rod withdrawal, or require waiting periods between rod withdrawal increments

- By waiting between rod withdrawal increments, the neutron population is allowed to increase through subcritical multiplication

- Subcritical multiplication is the process where source neutrons are used to sustain the chain reaction in a reactor with a multiplication factor (k_{eff}) of less than one

Reactor Operation - Startup (4)

- The chain reaction is not "self-sustaining," but if the neutron source is of sufficient magnitude, it compensates for the neutrons lost through absorption and leakage

- This process can result in a constant, or increasing, neutron population even though k_{eff} is less than one

Estimated Critical Position (1)

- In the previous lecture, 1/M plots were discussed

- These plots were useful for monitoring the approach to criticality and predicting when criticality will occur based on indications received while the startup is actually in progress

- Before the reactor startup is initiated, the operator calculates an estimate of the amount of rod withdrawal that will be necessary to achieve criticality

Estimated Critical Position (2)

- This process provides an added margin of safety because a large discrepancy between actual and estimated critical rod positions would indicate that the core was not performing as designed

- Depending upon a reactor's design or age, the buildup of xenon within the first several hours following a reactor shutdown may introduce enough negative reactivity to cause the reactor to remain shutdown even with the control rods fully withdrawn

- In this situation it is important to be able to predict whether criticality can be achieved, and if criticality cannot be achieved, the startup should not be attempted

Estimated Critical Position (3)

- For a given set of conditions (such as time since shutdown, temperature, pressure, fuel burnup, samarium and xenon poisoning) there is only one position of the control rods (and boron concentrations for a reactor with chemical shim) that results in criticality, using the normal rod withdrawal sequence

- Identification of these conditions allows accurate calculation of control rod position at criticality

- The calculation of an **estimated critical position** (ECP) is simply a mathematical procedure that takes into account all of the changes in factors that significantly affect reactivity that have occurred between the time of reactor shutdown and the time that the reactor is brought critical again

Estimated Critical Position (4)

- For most reactor designs, the only factors that change significantly after the reactor is shut down are the average reactor temperature and the concentration of fission product poisons

- The reactivities normally considered when calculating an ECP include the following
  - Basic reactivity of the core
  - Direct xenon reactivity
  - Indirect xenon reactivity
  - Temperature reactivity

Estimated Critical Position (5)

- Basic Reactivity of the Core:
  - The reactivity associated with the critical control rod position for a xenon-free core at normal operating temperature. This reactivity varies with the age of the core (amount of fuel burnup)

- Direct Xenon Reactivity:
  - The reactivity related to the xenon that was actually present in the core at the time it was shutdown. This reactivity is corrected to allow for xenon decay

Estimated Critical Position (6)

- Indirect Xenon Reactivity:
  - The reactivity related to the xenon produced by the decay of iodine that was present in the core at the time of shutdown

- Temperature Reactivity:
  - The reactivity related to the difference between the actual reactor temperature during startup and the normal operating temperature

Estimated Critical Position (7)

- To arrive at an ECP of the control rods, the basic reactivity, direct and indirect xenon reactivity, and temperature reactivity are combined algebraically to determine the amount of positive control rod reactivity that must be added by withdrawing control rods to attain criticality

- A graph of control rod worth versus rod position is used to determine the estimated critical position

Core Power Distribution (1)

- In order to ensure predictable temperatures and uniform depletion of the fuel installed in a reactor, numerous measures are taken to provide an even distribution of flux throughout the power producing section of the reactor

- This shaping, or flattening, of the neutron flux is normally achieved through the use of *reflectors* that affect the flux profile across the core, or by the installation of poisons to suppress the neutron flux where desired

- The last method, although effective at shaping the flux, is the least desirable since it reduces neutron economy by absorbing the neutrons

Core Power Distribution (2)

- A reactor core is frequently surrounded by a "reflecting" material to reduce the ratio of peak flux to the flux at the edge of the core fuel area

- Reflector materials are normally not fissionable, have a high scattering cross section, and have a low absorption cross section

- Essentially, for thermal reactors a good moderator is a good reflector
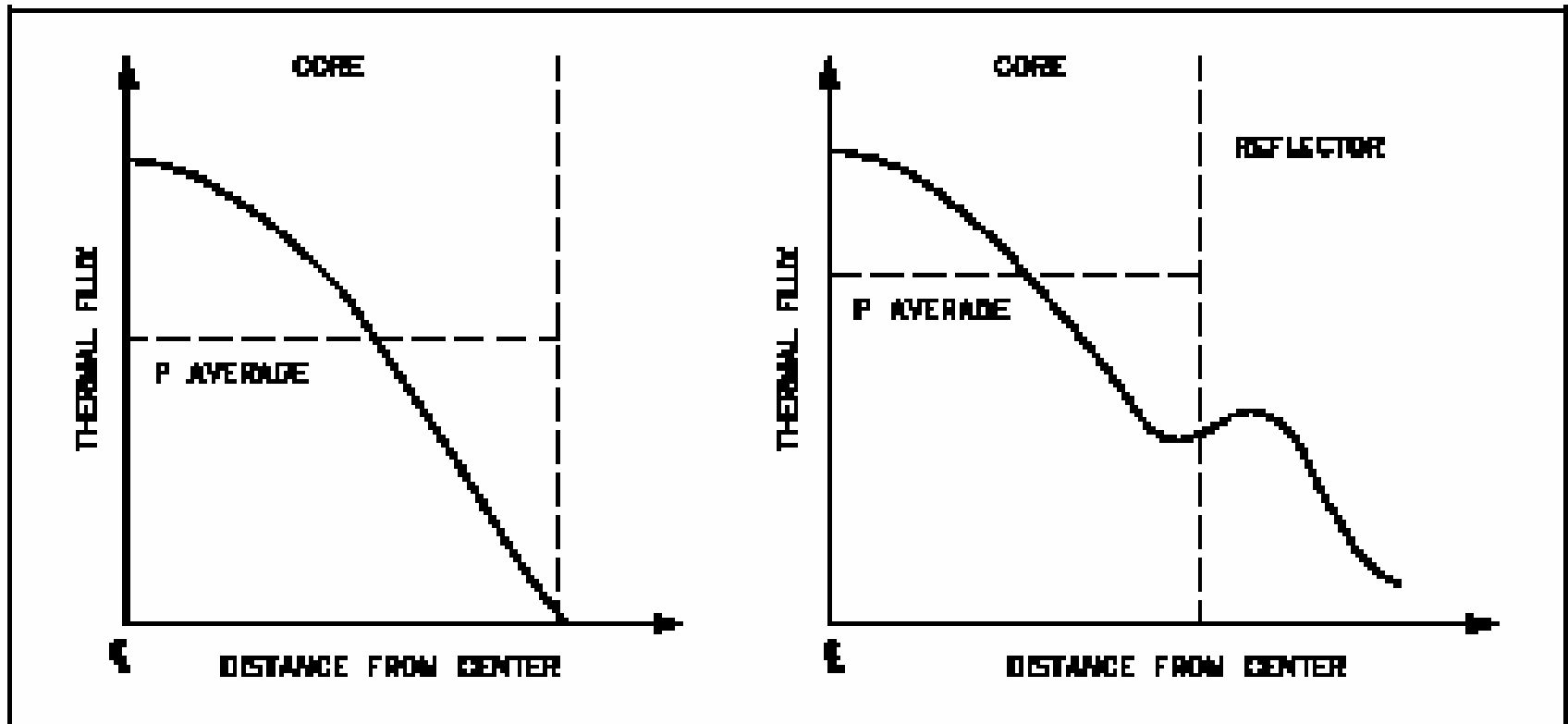
Core Power Distribution (3)

- Water, heavy water, beryllium, zirconium, or graphite are commonly used as reflectors

- In fast reactor systems, reflectors are not composed of moderating materials because it is desired to keep neutron energy high

- The reflector functions by scattering some of the neutrons, which would have leaked from a bare (unreflected) core, back into the fuel to produce additional fissions

Core Power Distribution (4)

- Figure on the next slide shows the general effect of reflection in the thermal reactor system where core power is proportional to the thermal flux

- Notice that a reflector can raise the power density of the core periphery and thus increase the core average power level without changing the peak power

- As illustrated in the Figure, the thermal flux in the reflector may actually be higher than that in the outermost fuel since there are very few absorptions in the reflector
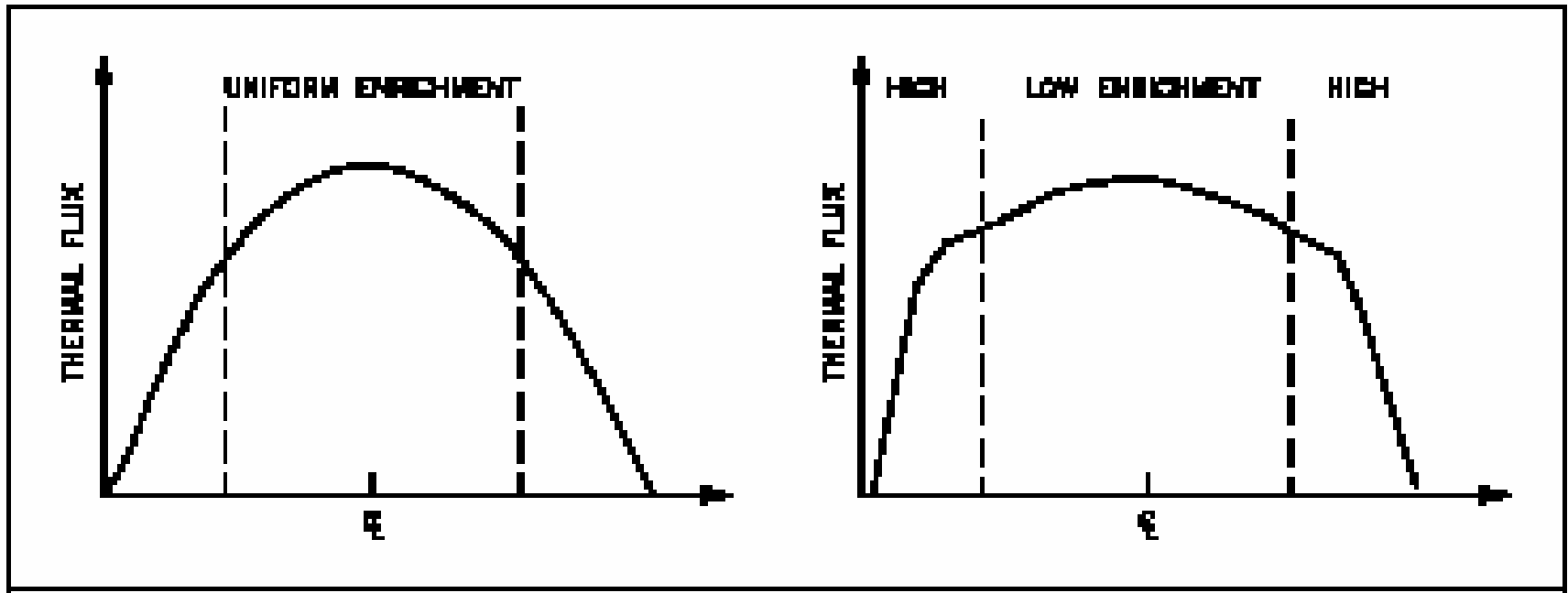
Core Power Distribution (5)

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Department of Energy Technology, KTH

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Core Power Distribution (6)

- Varying the fuel enrichment or fuel concentrations in the core radially, axially, or both, can readily be used to control power distribution

- The simplified example illustrated in Figure on the next slide shows the effect of using a higher enrichment in the outer regions of the core

- Varying fuel concentrations or poison loading for flux shaping is frequently referred to as zoning

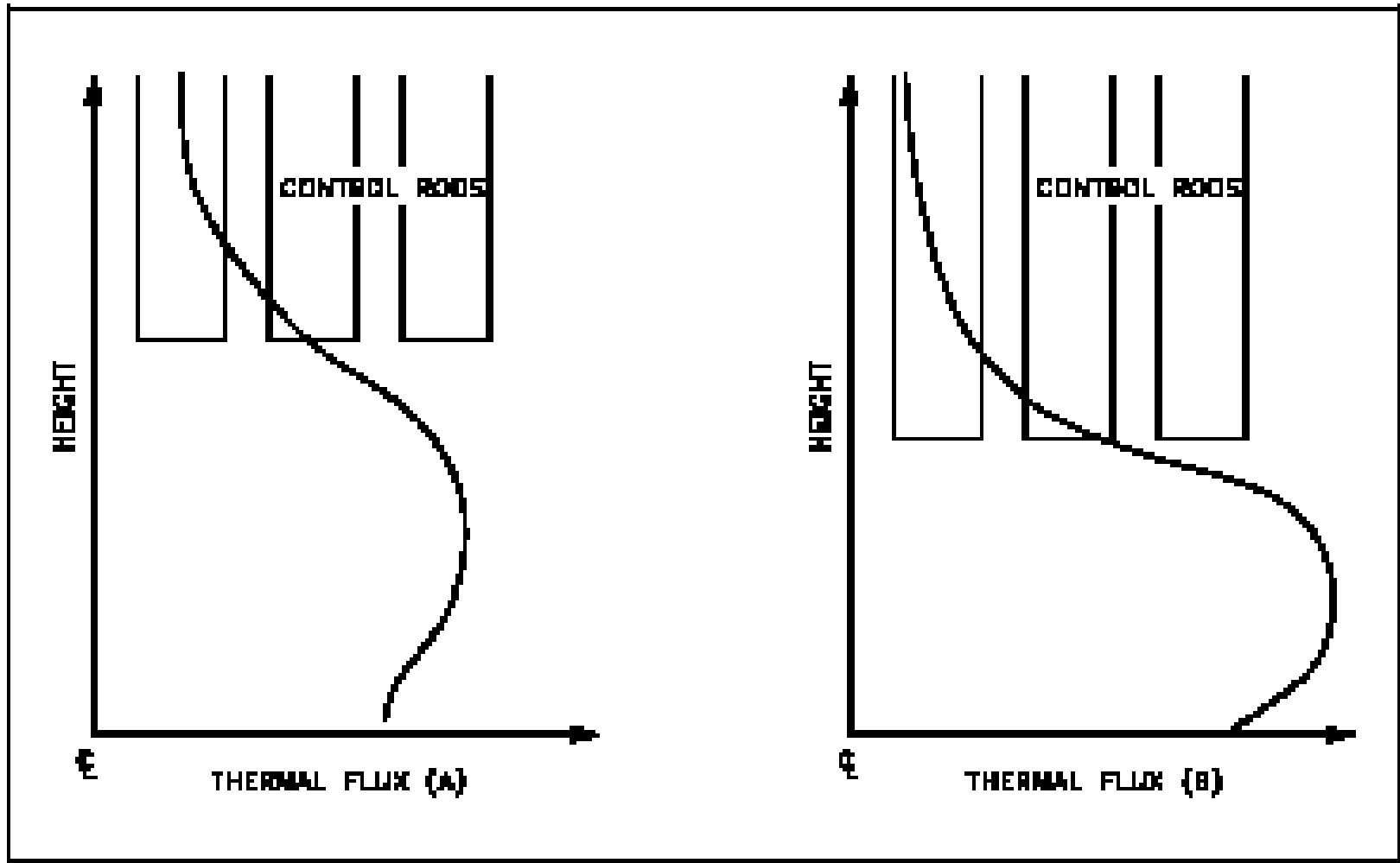- In the example illustrated the large central peak is reduced, but the average power level remains the same

Core Power Distribution (7)

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Department of Energy Technology, KTH

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Core Power Distribution (8)

- The previous examples discuss changes in radial power distribution

- Large variations also exist in axial power distribution

- Figure (A) on the next slide illustrates the power distribution that may exist for a reactor with a cylindrical geometry

- The control rods in this reactor are inserted from the top, and the effect of inserting control rods further is shown in Figure (B)

- The thermal flux is largely suppressed in the vicinity of the control rods, and the majority of the power is generated low in the core

- This flux profile can be flattened by the use of axial fuel and/or poison zoning

Core Power Distribution (9)

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Nuclear Reactor Technology Division
Department of Energy Technology, KTH*

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Power Tilt (1)

- A **power tilt**, or flux tilt, is a specific type of core power distribution problem

- It is a non-symmetrical variation of core power in one quadrant of the core relative to the others

- The power in one portion might be suppressed by over-insertion of control rods in that portion of the core, which, for a constant overall power level, results in a relatively higher flux in the remainder of the core

- This situation can lead to xenon oscillations, which were previously discussed

Shutdown Margin (1)

- **Shutdown margin** is the instantaneous amount of reactivity by which a reactor is subcritical or would be subcritical from its present condition assuming all control rods are fully inserted except for the single rod with the highest integral worth, which is assumed to be fully withdrawn

- Shutdown margin is required to exist at all times, even when the reactor is critical

- It is important that there be enough negative reactivity capable of being inserted by the control rods to ensure complete shutdown at all times during the core lifetime

Shutdown Margin (2)

- A shutdown margin in the range of one to five percent reactivity is typically required

- The stuck rod criterion refers to the fact that the shutdown margin does not take credit for the insertion of the highest worth control rod

- The application of the stuck rod criterion ensures that the failure of a single control rod will not prevent the control rod system from shutting down the reactor

Reactor Operation (1)

- During reactor operation, numerous parameters such as temperature, pressure, power level, and flow are continuously monitored and controlled to ensure safe and stable operation of the reactor

- The specific effects of variations in these parameters vary greatly depending upon reactor design, but generally the effects for thermal reactors are as discussed in the following

Temperature Effects (1)

- The most significant effect of a variation in temperature upon reactor operation is the addition of positive or negative reactivity

- As previously discussed, reactors are generally designed with negative temperature coefficients of reactivity (moderator and fuel temperature coefficients) as a self-limiting safety feature

- A rise in reactor temperature results in the addition of negative reactivity

Temperature Effects (2)

- If the rise in temperature is caused by an increase in reactor power, the negative reactivity addition slows, and eventually turns the increase in reactor power

- This is a highly desirable effect because it provides a negative feedback in the event of an undesired power excursion

Temperature Effects (3)

- Negative temperature coefficients can also be utilized in water cooled and moderated power reactors to allow reactor power to automatically follow energy demands that are placed upon the system

- For example, consider a reactor operating at a stable power level with the heat produced being transferred to a heat exchanger for use in an external closed cycle system

- If the energy demand in the external system increases, more energy is removed from reactor system causing the temperature of the reactor coolant to decrease

- As the reactor temperature decreases, positive reactivity is added and a corresponding increase in reactor power level results

Temperature Effects (4)

- As reactor power increases to a level above the level of the new energy demand, the temperature of the moderator and fuel increases, adding negative reactivity and decreasing reactor power level to near the new level required to maintain system temperature

- Some slight oscillations above and below the new power level occur before steady state conditions are achieved

- The final result is that the average temperature of the reactor system is essentially the same as the initial temperature, and the reactor is operating at the new higher required power level

- The same inherent stability can be observed as the energy demand on the system is decreased

Temperature Effects (5)

- If the secondary system providing cooling to the reactor heat exchanger is operated as an open system with once-through cooling, the above discussion is not applicable

- In these reactors, the temperature of the reactor is proportional to the power level, and it is impossible for the reactor to be at a higher power level and the same temperature

Pressure Effects (1)

- The pressure applied to the reactor system can also affect reactor operation by causing changes in reactivity

- The reactivity changes result from changes in the density of the moderator in response to the pressure changes

- For example, as the system pressure rises, the moderator density increases and results in greater moderation, less neutron leakage, and therefore the insertion of positive reactivity

Pressure Effects (2)

- A reduction in system pressure results in the addition of negative reactivity

- Typically, in pressurized water reactors (PWR), the magnitude of this effect is considerably less than that of a change in temperature

- In two-phase systems such as boiling water reactors (BWR), however, the effects of pressure changes are more noticeable because there is a greater change in moderator density for a given change in system pressure

Power Level Effects (1)

- A change in reactor power level can result in a change in reactivity if the power level change results in a change in system temperature

- The power level at which the reactor is producing enough energy to make up for the energy lost to ambient is commonly referred to as the **point of adding heat**

Power Level Effects (2)

- If a reactor is operating well below the point of adding heat, then variations in power level produce no measurable variations in temperature

- At power levels above the point of adding heat, temperature varies with power level, and the reactivity changes will follow the convention previously described for temperature variations

Power Level Effects (3)

- The inherent stability and power turning ability of a negative temperature coefficient are ineffective below the point of adding heat

- If a power excursion is initiated from a very low power level, power will continue to rise unchecked until the point of adding heat is reached, and the subsequent temperature rise adds negative reactivity to slow, and turn, the rise of reactor power

- In this region, reactor safety is provided by automatic reactor shutdown systems and operator action

Flow Effects (1)

- At low reactor power levels, changing the flow rate of the coolant through the reactor does not result in a measurable reactivity change because fuel and moderator temperatures and the fraction of steam voids occurring in the core are not changed appreciably

- When the flow rate is varied, however, the change in temperature that occurs across the core (outlet versus inlet temperature) will vary inversely with the flow rate

- At higher power levels, on liquid cooled systems, increasing flow will lower fuel and coolant temperatures slightly, resulting in a small positive reactivity insertion

Flow Effects (2)

- A positive reactivity addition also occurs when flow is increased in a two-phase (steam-water) cooled system

- Increasing the flow rate decreases the fraction of steam voids in the coolant and results in a positive reactivity addition

- This property of the moderator in a two-phase system is used extensively in commercial BWRs

- Normal power variations required to follow load changes on BWRs are achieved by varying the coolant/moderator flow rate

Core Burnup (1)

- As a reactor is operated, atoms of fuel are constantly consumed, resulting in the slow depletion of the fuel frequently referred to as core burnup

- There are several major effects of this fuel depletion

- The first, and most obvious, effect of the fuel burnup is that the control rods must be withdrawn or chemical shim concentration reduced to compensate for the negative reactivity effect of this burnup

Core Burnup (2)

- Some reactor designs incorporate the use of supplemental burnable poisons in addition to the control rods to compensate for the reactivity associated with excess fuel in a new core

- These fixed burnable poisons burn out at a rate that approximates the burnout of the fuel and they reduce the amount of control rod movement necessary to compensate for fuel depletion early in core life

Core Burnup (3)

- As control rods are withdrawn to compensate for fuel depletion, the effective size of the reactor is increased

- By increasing the effective size of the reactor, the probability that a neutron slows down and is absorbed while it is still in the reactor is also increased

- Therefore, neutron leakage decreases as the effective reactor size is increased

Core Burnup (4)

- The magnitude of the moderator negative temperature coefficient is determined in part by the change in neutron leakage that occurs as the result of a change in moderator temperature

- Since the fraction of neutrons leaking out is less with the larger core, a given temperature change will have less of an effect on the leakage

- Therefore, the magnitude of the moderator negative temperature coefficient decreases with fuel burnup

Core Burnup (5)

- There is also another effect that is a consideration only on reactors that use dissolved boron in the moderator (chemical shim)

- As the fuel is burned up, the dissolved boron in the moderator is slowly removed (concentration diluted) to compensate for the negative reactivity effects of fuel burnup

- This action results in a larger (more negative) moderator temperature coefficient of reactivity in a reactor using chemical shim

Core Burnup (6)

- This is due to the fact that when water density is decreased by rising moderator temperature in a reactor with a negative temperature coefficient, it results in a negative reactivity addition because some moderator is forced out of the core

- With a coolant containing dissolved poison, this density decrease also results in some poison being forced out of the core, which is a positive reactivity addition, thereby reducing the magnitude of the negative reactivity added by the temperature increase

- Because as fuel burnup increases the concentration of boron is slowly lowered, the positive reactivity added by the above poison removal process is lessened, and this results in a larger negative temperature coefficient of reactivity

Core Burnup (7)

- The following effect of fuel burnup is most predominant in a reactor with a large concentration of uranium-238

- As the fission process occurs in a thermal reactor with low or medium enrichment, there is some conversion of uranium-238 into plutonium-239

- Near the end of core life in certain reactors, the power contribution from the fission of plutonium-239 may be comparable to that from the fission of uranium-235

Core Burnup (8)

- The value of the delayed neutron fraction (b) for uranium-235 is 0.0064 and for plutonium-239 is 0.0021

- Consequently, as core burnup progresses, the effective delayed neutron fraction for the fuel decreases appreciably

- It follows then that the amount of reactivity insertion needed to produce a given reactor period decreases with burnup of the fuel

Reactor Shutdown (1)

- A reactor is considered to be shut down when it is subcritical and sufficient shutdown reactivity exists so there is no immediate probability of regaining criticality

- Shutdown is normally accomplished by insertion of some (or all) of the control rods, or by introduction of soluble neutron poison into the reactor coolant

- The rate at which the reactor fission rate decays immediately following shutdown is similar for all reactors provided a large amount of negative reactivity is inserted

Reactor Shutdown (2)

- After a large negative reactivity addition the neutron level undergoes a rapid decrease of about two decades (prompt drop) until it is at the level of production of delayed neutrons

- Then the neutron level slowly drops off as the delayed neutron precursors decay, and in a short while only the longest-lived precursor remains in any significant amount

- This precursor determines the final rate of decrease in reactor power until the neutron flux reaches the steady state level corresponding to the subcritical multiplication of the neutron source

Reactor Shutdown (3)

- The half-life of the longest lived delayed neutron precursor results in a reactor period of around -80 seconds or a startup rate of -1/3 DPM for most reactors after a reactor shutdown

- One noticeable exception to this is a heavy water reactor

- In a heavy water reactor, the photo-neutron source is extremely large after shutdown due to the amount of deuterium in the moderator and the large number of high energy gammas from short-lived fission product decay

Reactor Shutdown (4)

- The photo-neutron source is large enough to have a significant impact on neutron population immediately after shutdown

- The photo-neutron source has the result of flux levels decreasing more slowly so that a heavy water reactor will have a significantly larger negative reactor period after a shutdown

Reactor Shutdown (5)

- Throughout the process of reactor shutdown the nuclear instrumentation is closely monitored to observe that reactor neutron population is decreasing as expected, and that the instrumentation is functioning properly to provide continuous indication of neutron population

- Instrumentation is observed for proper overlap between ranges, comparable indication between multiple instrument channels, and proper decay rate of neutron population

Reactor Shutdown (6)

- A distinction should be made between indicated reactor power level after shutdown and the actual thermal power level

- The indicated reactor power level is the power produced directly from fission in the reactor core, but the actual thermal power drops more slowly due to decay heat production as previously discussed

- Decay heat, although approximately 5 to 6% of the steady state reactor power prior to shutdown, diminishes to less than 1% of the pre-shutdown power level after about one hour

Reactor Shutdown (7)

- After a reactor is shutdown, provisions are provided for the removal of decay heat

- If the reactor is to be shut down for only a short time, operating temperature is normally maintained

- If the shutdown period will be lengthy or involves functions requiring cooldown of the reactor, the reactor temperature can be lowered by a number of methods

- The methods for actually conducting cooldown of the reactor vary depending on plant design, but in all cases limitations are imposed on the maximum rate at which the reactor systems may be cooled

Reactor Shutdown (8)

- These limits are provided to reduce the stress applied to system materials, thereby reducing the possibility of stress induced failure

- Although a reactor is shut down, it must be continuously monitored to ensure the safety of the reactor

- Automatic monitoring systems are employed to continuously collect and assess the data provided by remote sensors

- It is ultimately the operator who must ensure the safety of the reactor

Decay Heat (1)

- About 7% of the 200 MeV produced by an average fission is released at some time after the instant of fission

- This energy comes from the decay of the fission products

- When a reactor is shut down, fission essentially ceases, but decay energy is still being produced

- The energy produced after shutdown is referred to as decay heat

Decay Heat (2)

- The amount of decay heat production after shutdown is directly influenced by the power history of the reactor prior to shutdown

- A reactor operated at full power for 3 to 4 days prior to shutdown has much higher decay heat generation than a reactor operated at low power for the same period

- The decay heat produced by a reactor shutdown from full power is initially equivalent to about 5 to 6% of the thermal rating of the reactor

Decay Heat (3)

- This decay heat generation rate diminishes to less than 1% approximately one hour after shutdown

- However, even at these low levels, the amount of heat generated requires the continued removal of heat for an appreciable time after shutdown

- Decay heat is a long-term consideration and impacts spent fuel handling, reprocessing, waste management, and reactor safety