Introduction to the Dynamics of Power Reactors

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Summary:

Dynamic Characteristics of neutron chain reactors, with time scales ranging from prompt-neutron lifetime (10^{-9} s to 10^{-3} s) through temperature-induced feedback, delayed neutron precursor production and decay, control systems response up to the time scale of fuel burnup and irradiation damage structures (~10^{+8} s).

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Introduction to the Dynamics of Power Reactors

This document ("gulp") deals in a mostly qualitative manner with the broad range of topics that must be considered in the course of fission reactor design. The main physical and functional aspects are introduced as a lead-in to the more precise and quantitative treatment described elsewhere.

1. Qualitative Comparison with a Coal Furnace

Figure 1 shows a sketch of these two processes. The left side of the Figure represents a coal station. Here we see that process inputs are fuel and air; the flow of each of these is controlled to match demand for the primary output, which is heat for boiling water. A relatively small amount of heat is needed to raise the fuel-air mixture up to the furnace temperature.

Fuel flows directly into the furnace and is burned within a few seconds to produce the secondary outputs, combustion gases and fly ash. Combustion gases transfer heat to water and steam is produced. There is only a small amount of fuel in the furnace at any time.

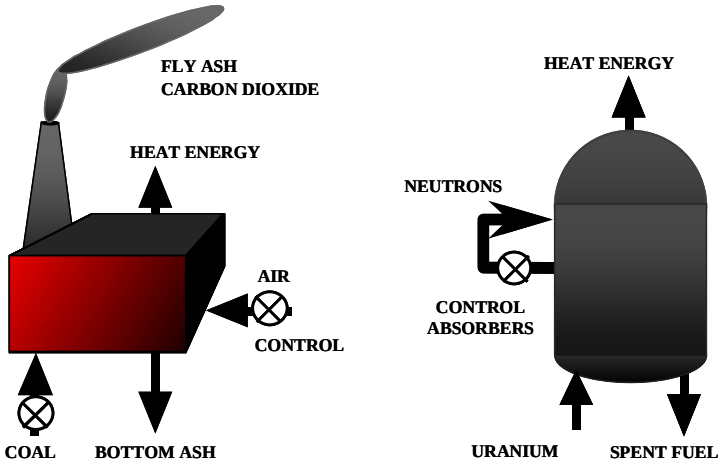

Figure 1 – Comparison of Coal and Nuclear Plants

The highest possible temperature in a coal furnace is equal to the flame temperature of the fuel. This temperature is near, but still below, the melting temperature of furnace materials. Combustion gases (containing trace amounts of several toxic elements) have a very large volume that makes purification expensive, though still possible. The unavoidable waste product is carbon dioxide. Tertiary output called bottom ash has a very large volume and contains toxic materials. No effective method has yet been found for long-term isolation of this waste from people.

A flow diagram for a nuclear plant is shown in the right-hand side of Figure 1. The first notable characteristic is that the process uses no air. Also, there is no secondary waste output. Fuel is added in batches, daily in some designs and yearly in other designs. The mass of fuel used is very small compared with the mass needed for a coal plant because its specific potential energy is large. Tertiary output (fission product material) is sealed inside the used fuel bundles.

The largest environmental advantage of nuclear technology is that it is possible to design a plant with zero waste output during normal operation. Used fuel is highly radioactive but is easy to manage safely. It decays to a very low level of toxicity in about five hundred years. This low level is then maintained, effectively forever. At the same time the fuel must be carefully protected from overheating during operation, to ensure that no radioactive materials are released accidentally.

In most designs the primary output, heat, is carried away from the reactor by water coolant under pressure. This coolant then is used to produce steam.

The most important unique feature of this process is that an intermediate product (neutrons) is essential to keep the fission process going. These neutrons are necessary to cause further fission. The neutrons "flow" through the reactor, slow down, and are absorbed. Control of the process is through increasing or decreasing the neutron capture rate within this flow so that the fission rate (energy released) matches the demand for steam to drive the turbine. Control materials are moved into, or out of, the neutron flow as required to achieve this goal.

Three characteristics of the process must be remembered. First, the chain reaction can be stopped very quickly by capturing a few more neutrons of the neutron flow. When this is done the neutron flow stops in a few seconds. Second, if control is lost for any reason it is possible for the neutron flow to increase very quickly and to release large amounts of heat from the reactor fuel. This is possible because a large amount of fuel (in terms of its potential energy) is located inside the reactor core at all times.

The fission rate has no intrinsic upper limit. As a result there is no effective limit to the fuel temperature. Fuel temperature can rise far above the melting temperature of reactor materials. Furthermore, coolant that normally contacts the fuel sheath can itself be vaporized at high temperature. Vapour is much less effective than water in removing fuel heat. Volume increases on vaporization and can lead to overpressure of containment barriers. Continued cooling of the fuel is required so that fuel temperatures remain low. Control and safety systems are required to prevent the fission rate from exceeding safe limits.

Reviewing this scenario, structural materials and coolant will degrade at very high temperatures. The radioactive fission products are located inside the fuel, in exactly the same place where most of the fission heat is released. If the fuel is not cooled these radioactive materials eventually will be released.

2. Reactor design

Providing equipment and systems to maintain the correct balance of heat production processes (neutron dynamics) and heat removal processes (coolant dynamics) at all times is one major task of the reactor core designer. Materials selection and structural design is the other major task. This course deals with the heat production part of the process design task.

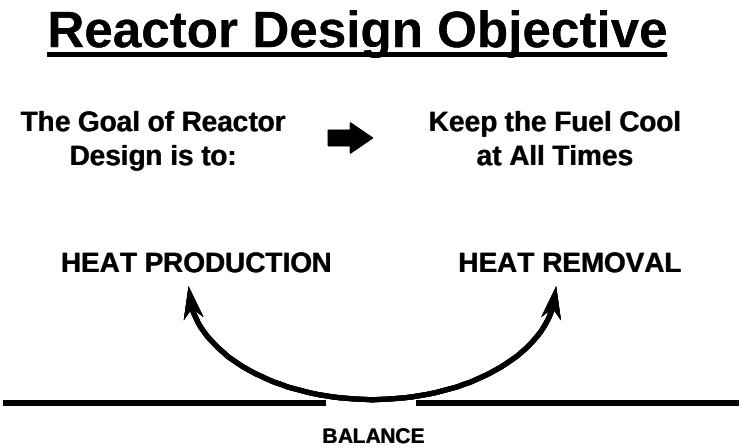

Figure 2 – The first principle of power reactor design

As illustrated in Figure 2, keeping the fuel cool (or, more precisely, "at the correct temperature") demands that a balance be maintained between heat production (from fission) and heat removal (to the steam turbine). The energy is transferred, in the form of electricity, to transmission lines and eventually to the load. Variation of this electrical load is the most fundamental source of perturbation in reactor steady state operation. There are many other sources of perturbation, each of which acts on a typical time scale. We will examine each of these in increasing order, starting with those acting on a nanosecond timescale.

3. Short time scales

Fission reactions occur in the order of one-hundredth of a picosecond – so short that the time of interaction between neutrons and nuclei can be considered instantaneous.

The next time scale of interest is the time-of-flight of a neutron from its production in fission to its first collision with another nucleus. We can calculate this time approximately from knowledge of the energy of fission neutrons and the mean distance of travel of neutrons in the reactor at that energy. In a typical uranium dioxide lattice the mean first-track length is about 4 centimetres. Calculating the neutron velocity from the equation $E=1/2\ m\ V^2$, the time taken for a fission neutron to travel this distance is about 2 nanoseconds.

The first neutron collision seldom results in fission (as necessary for continuation of the fission chain) the most probable interaction is neutron scattering. Several collisions normally occur before the neutron finally is absorbed by a nucleus. The designer is interested in the time taken between fission and absorption, because this time determines many of the dynamic characteristics of the reactor. This time is known as the prompt neutron lifetime or generation time. [Note: We are interested only in the ensemble average time interval because the neutron population is very large.] In thermal reactors this time includes the time to slow down from fission energy plus the time elapsed during diffusion in the lattice at thermal energies.

Of course, not all neutrons are emitted at the time of fission. About twenty fission product isotopes decay through neutron emission with half-life from about one-tenth of a second up to 60 seconds. These isotopes are important to control via their first-order delay on neutron population changes. They also are very important to space-time dependence of the neutron population; the so-called **point** model of reactor kinetics often fails because of its failure to account for the time delay in adjustment of the neutron density distribution following local perturbations. The more sophisticated **adiabatic** model often fails in the other extreme through its assumption that delayed neutrons always are emitted with the same spatial distribution as are prompt neutrons.

In special cases we find yet another source of delayed neutron emission (delayed, that is, relative to the original fission event) that must be accounted for in high-precision calculations. One of these special cases appears in reactors employing heavy water as moderator or coolant. Gamma rays emitted in the process of fission induce decay of deuterium and emission of a neutron. Strictly, these delayed reactions depend on the history of gamma ray distribution rather than neutron distribution; but most models simply add these reactions to the equations for delayed neutron production and decay from fission. The resultant error is small.

The neutron-absorbing properties of nuclear fuels change with temperature as a result of (a) density changes, and (b) changes in absorption properties of the nuclear resonances that occur in the few-kilovolt range of neutron energy. All temperature changes depend on the integral over time of the instantaneous reaction rate; including heat losses leads to the local temperature following a temporal convolution integral of the instantaneous reaction rate. The effect of fuel temperature on the chain reaction depends on the particular reactor characteristics; it may be positive (increasing fission rate) or negative (decreasing fission rate.)

The local temperature of reactor coolant is determined mostly by the time-integral of fuel temperature, that itself depends, as discussed above, on the time-integral of the fission rate. And so, except when a coolant changes phase (liquid to gaseous) this density change has a second-order effect on fission rate.

In the case of boiling the relationship is more complicated, depending on the coolant flow rate and especially on transient pressure (that directly changes the saturation temperature). One of the most important accident events in a pressurized water reactor such as CANDU would be breaking of the heat-transport system boundary. Such an event would lead to fast depressurization of the coolant as well as sudden vaporization or 'flashing'. Boiling may have a direct influence on fission rate (either positive or negative) and an indirect influence via the resulting increase in fuel temperature. If the failed pipe were located inside the reactor, vaporization of the coolant can change the neutron moderator's geometry very rapidly. This change may have a direct effect on the chain reaction as well as on its spatial distribution.

All control actions are very slow compared with the time scales discussed here, and are discussed in a later section of this lecture. The exception is emergency shutdown following detection of an unsafe state. Shutdown action can be designed to significantly decrease the population of neutrons, and therefore the energy release rate, within one-tenth of a second (discounting the detection and initiation lag time that depends on particular design characteristics.)

A highly simplified view of reactor dynamic characteristics is shown in Figure 3. The 'effective' neutron lifetime was estimated by assuming a single half-life for delayed neutrons and using an arbitrary step increase in reactivity. It can be seen that all reactors behave the same when the step reactivity increase is less than about 0.5 times the delayed neutron fraction.

At higher values of reactivity, a reactor having a short prompt neutron lifetime responds very, very rapidly. On the other hand, when the prompt neutron lifetime is around

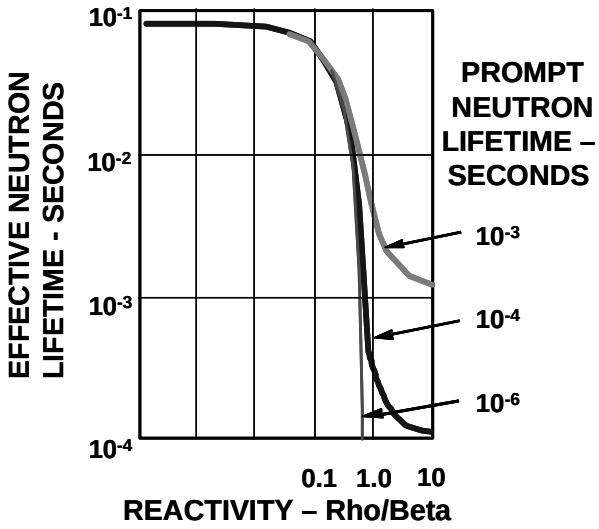

Figure 3 – Effect of prompt neutron lifetime on reactor dynamic behaviour

one millisecond (typical of the CANDU reactor) the effect of this "prompt-critical transition" effect is much smaller. In extreme circumstances, a power reactor with long prompt neutron lifetime is easier to control, and the consequences of a complete loss of control are less severe.

The Nuclear Engineering website http://epic.mcmaster.ca/~garlandw/index.htm includes download programs. One of these, EXKIN, is a simple point-kinetics model that can be run to look at the effects of different reactor parameters on dynamic reactor behaviour. This exercise is not intended as a precise model of reactor dynamics, but only as a device to assist you in understanding of the various parameters involved.

4. Medium Time Scales

Reactor control systems are used to (a) bring the reactor assembly to a self-sustaining (critical) state, (b) to raise power output, (c) to control power and spatial power distribution within prescribed limits, and (d) to shut down the reactor. Control changes are very slow during normal operation (typically seconds or minutes). These changes can be separated logically from safety-related control actions that always act to reduce local and global power when an abnormal condition is detected. (Most power reactor control systems actually act on the neutron flux through either increasing or decreasing local parasitic absorption. Such changes directly effect power production.

Further discussion of control systems is best reserved until we address the set of reactor flux equations in more detail.

Some of the fission products produced during operation have high neutron capture cross-sections. [Historical note: When the first high-power reactor was started in Hanford, Washington in the 1940's, staff were surprised when the reactor shut itself off shortly after the power was increased. It was then realized that the concentration of the isotope Xenon 135 slowly increases as the fission process continues at high power.] Added neutron absorption from this Xenon subsequently reduces the reactivity of any thermal reactor so it will shut itself down if no control action is taken. Most of this Xenon is produced indirectly via the decay of Iodine 135, with a half-life of 6.6 hours. The balance between production and capture of Xenon 135 leads to an equilibrium concentration at a given steady-state power and a rapid decrease in concentration as power is raised (reactivity increase), followed by a subsequent increase in concentration (reactivity decrease). The steady-state concentration of Xenon saturates at high power levels.

The reactivity introduced by Xe135 in a CANDU reactor at full power is about -28 mk; rapid buildup after shutdown prevents restart of the reactor for about 40 hours unless restart to a significant power level is achieved within about 30-40 minutes. Even at the stable level of about 60% power, all of the adjuster rods must be withdrawn in order to prevent consequent "poison-out" of the reactor.

Samarium149 is also produced indirectly through decay of Pm149; the prime differences being that its capture cross section (and hence its negative reactivity effect) is much smaller and that it is stable after formation while Xe135 is radioactive.

All isotopes experience collisions with neutrons, with various outcomes. For any given isotope in the reactor, the neutron reaction rate is given by:

$$R = \sigma_x^{\,i} \phi N_i$$

where $\sigma_x^{\,i}$ is the microscopic cross section of type "x", ϕ is the local neutron flux, and N_i is the number of atoms of isotope "i", at the local position.

The balance equation for the number of atoms of isotope "i" present can be written as:

$$\begin{bmatrix}\text{Rate of Change} \\ \text{for "i" atoms}\end{bmatrix} = \begin{bmatrix}\text{Rate of Formation}\end{bmatrix} - \begin{bmatrix}\text{Rate of absorption} \\ \text{plus rate of decay}\end{bmatrix}$$

For reactions taking place in fuel there will be a set of "**chains**" of isotope formation, neutron scattering, capture, fission, and isotopic decay. Each fission event produces two or more fission products, with a known probability-versus-mass distribution at a given incident neutron energy. Generally, this equation can be applied to model the time-dependent behaviour of each isotope, once the neutron flux is known. Of course, the concentration of a given isotope determines to some extent, the neutron flux. So we expect to find that the flux equations will include space-and-time dependence of their coefficients, in a quasi-linear fashion.

The whole set of reaction and decay rates of isotopes can be arranged in matrix form, thus:

$$\frac{dN}{dt} = -[A]N \qquad \text{where:}$$

$N = \left\{N^1, N^2, N^3, ..., N^n\right\}$ is a vector of isotope concentrations and $[A]$ is the matrix of isotopic reaction and decay terms.

Taking the minus sign inside the matrix bracket, we can write the solution of this equation as:

$$N(t) = \exp\left\{[-A]t\right\} N(0) = [Bt]N(0)$$

The most straightforward way to solve this equation is to expand the matrix [Bt] in series, and truncate the expansion when the n'th term is smaller than a given convergence criterion. [Q -What is the necessary and condition for convergence of this series?] The Euclidean norm of the n'th term is a convenient measure of its importance to the series. Therefore:

$$[Bt] = I + [-At] + \frac{[-At]^2}{2!} + \frac{[-At]^3}{3!} + \frac{[-At]^4}{4!} + ...$$

$$= I + \sum_{n=2}^{\infty} \frac{[-At]^{(n-1)}}{(n-1)!}$$

$$\varepsilon > \|\text{Term } n+1\|$$

This solution can easily be programmed as a general matrix exponentiation routine. For any particular case, the terms of matrix [A] can be generated and the vector of isotope densities at the end of the time interval can be found. It may be necessary in some cases to couple these equations in some manner to the flux equations, which also are time-dependent.

Direct radiation damage of fuel and fuel sheath materials sometimes leads to life-limiting effects. Activation of metals and corrosion products can result in high radiation fields in accessible areas. In CANDU, tritium production followed by leakage into the containment structure poses an additional design problem.

Fission products accumulate in the fuel elements at a rate approximately proportional to the time integral of the neutron flux. They absorb a significant number of neutrons, thereby reducing the excess neutrons per cycle (measured by the value of reactivity. Along with the depletion of fissionable isotopes (mainly U235 initially, partly balanced by the conversion of U238 to Pu239) and the buildup of the higher isotopes of plutonium, this additional absorption leads to a reduction of reactivity and forces discharge of the fuel bundle. Without steady refuelling, the rate of reactivity decrease in the CANDU 600 MWe design is about 0.4 mk per day.

The fission products consist of a large collection of neutron-rich isotopes, many of which are beta-active. They produce a significant fraction of the total fission heat; at steady-state full power about 7% of the total heat production in the reactor is due to fission products.

5. Long Time Scales

The longest time range is that of structural damage to reactor materials. This damage occurs continuously over the life of the reactor. Macroscopic evidence of damage does not appear earlier than a few months. The most important factor in CANDU reactors is damage to the zirconium alloy structures. Knock-on collisions between fast neutrons and atoms in the metal lattice result in dislocations, similar to cold working but on a sub-microscopic scale. The material hardens considerably, with an increase in ultimate tensile strength of about 30 percent and a decrease in ductility. A very important effect is enhancement of stress- induced creep as well as stress-independent growth due to changes in the shape of the crystal lattice. The stress effect arises because of the introduction of glide planes near dislocations. The pressure tubes and calandria tubes tend to sag, lengthen, and dilate due to the creep effect.

The same dislocations tend to shorten the major axis of zirconium crystals and widen the minor axes. Since the manufactured tube has many of the major axes oriented perpendicular to the wall of the tube, the tube lengthens with time. Over a period of 30 years, the pressure tubes will stretch as much as 15 cm over their 6 m length. Obviously, such large changes require careful design considerations to adapt to them.

Radiation damage in light water reactors results in embrittlement of in-core and pressure vessel steels. Fast breeder reactors use stainless steel internal structures. In this case the most important damage effect is swelling of steel due to production of helium atoms. Helium is formed in (n,

alpha) reactions with the high fast-neutron fluxes existing during operation. Fast neutron fluxes cause hardening and embrittlement of pressure vessels and vessel internal structures of light-water reactors

Another type of radiation damage that occurs in CANDU reactors is radiolysis of water in the core. The water molecules are split up by collision with high-energy particles; free oxygen can then react with the structural zircaloy. To reduce this effect the heat transport water is doped with excess hydrogen to speed up the recombination of hydrogen and hydroxyl ions and thereby reduce the metal oxidation rate. Radiolysis also is important in the moderator water, because hydrogen can be produced in the cover gas and result in explosive mixtures. This effect is countered by circulation of the cover gas through catalytic recombiners.

Free hydrogen migrates into the zircaloy (primarily into pressure tubes) and forms a solid solution. Over a long period of time, the concentration can exceed the solid solubility limit. When this point is reached hydrogen precipitates as zirconium hydride. Zr hydrides are quite brittle, but have little effect on the structural properties unless the material is under high stress, because the hydride platelets are randomly oriented. However, in a high tensile stress field the platelets reorient with their planes perpendicular to the stress, and tend to migrate to the areas of maximum stress. In this orientation the platelets can crack and produce a slow progression of cracking, local stress enhancement, migration, and further cracking which leads eventually to tube failure. This process is referred to as 'delayed hydride cracking'.

Figure 4 is a summary of the various characteristic time scales governing dynamic behaviour of a power reactor. At this point we can go on to specific cases required for different parts of design analysis. The analyst will carefully choose to neglect those time-dependent behaviours that are not relevant to the question under study. But the overall picture must be kept in mind at all times so that the analysis captures all of the essential elements to permit the correct design decision to be made.

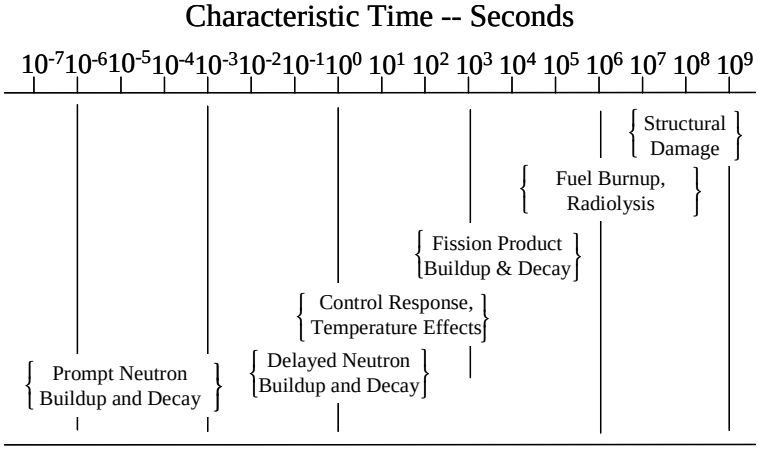

Figure 4 – The time scales relevant to reactor dynamic analysis

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