REACTIVITY CHANGES

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Contents

Summary

During operation of a nuclear reactor fissile fuel is consumed and fission products build up. The reduction in the concentration of fissile fuel reduces the reactivity of the reactor. Adjustments must then be made via the neutron absorbing control system to reduce neutron absorption accordingly to compensate for the loss in reactivity and so restore the critical condition. Similarly the build-up of neutron absorbing fission products requires similar compensation.

One important fission product is iodine which decays within hours to xenon which in turn is a very strong neutron absorber. However, as xenon absorbs neutrons, it transforms into an isotope which no longer absorbs neutrons. Under steady state conditions, a certain equilibrium concentration of xenon is reached. The effect of this can be accommodated by the control system. If, however, the reactor is shut down after operating at a high load, the iodine present decays into xenon which now is not converted to the non absorbing form due to lack of neutrons, and builds up temporarily to such high levels that the reactor cannot be

restarted for some 40 hours. This has important implications on the operation of a nuclear reactor.

Another consideration is the transformation, by neutron absorption, of non fissile uranium (U-238) into fissile plutonium (Pu-239). Thus initially additional fissile fuel is created in the reactor and its reactivity actually increases slightly after fresh fuel has been loaded into the reactor.

The reactivity of a reactor is also affected by temperature due to various effects. Fissile fuel fissions more readily at lower temperatures due to the increased probability of absorbing neutrons but there are several other effects as well. Generally a reactor with a negative temperature coefficient of reactivity (decreased reactivity with increasing temperature) is thermally stable and safer with respect to power excursions so this is a desirable design requirement.
In water cooled reactors where steam is generated within the reactor, the void formation can affect the reactivity of the reactor. If the voidage reduces the moderation of neutrons, the effect on reactivity will be negative but if the voidage reduces the absorption of neutrons, the effect on reactivity will be positive. With a suitable negative coefficient, an increase in power will increase steam generation, increase voidage, reduce reactivity and reduce power. Under such conditions a reactor can be made self controlling over a certain range of operation.

1. Introduction

1.1. Effect on Reactor Operation

The previous section considered short term reactivity changes due to operational maneuvering including start-up and shut-down. This requires relatively small changes in reactivity to affect the desired result. In fact it is important that, except in the case of a reactor trip, such changes be small to ensure proper control of the reactor.

What is of concern however, is that there are other effects which, during normal operation, result in reactivity changes much greater in magnitude than are required for operational control purposes. These however occur over a much longer time frame and as such do not upset the normal control. They do however require a significant reactivity adjustment to maintain criticality in the reactor. These effects change one or other factors in the six factor formula given as follows:

$$k = p\varepsilon\eta f \Lambda_f \Lambda_t \qquad (1)$$

Here k is the neutron multiplication factor, p the resonance escape probability, ε the fast fission factor, η the reproduction factor, f the thermal utilization factor, Λ_f the fast neutron non leakage probability and Λ_t the thermal neutron non leakage probability. The result is a drifting of k from unity in a critical reactor. To restore criticality that factor must be returned to its original value or another adjusted to compensate for the change so as to bring k back to unity.

The effects causing these changes fall into two main categories:

- Fuel Effects
- Temperature Effects

The fuel effects are due to the depletion of the fuel, the buildup of transuranic nuclides and the production of fission products. Generally the depletion of Uranium-235 results in a reduction of the fission cross section $\Sigma_{\text{f fuel}}$ and hence a reduction in the reproduction factor η. However the build-up of Plutonium-239 by neutron absorption in Uranium-238 initially over compensates for this change due to its higher values for neutrons per fission ν and fission cross section σ_{f}. The production of fission products in the fuel results in an increase in the absorption cross section $\Sigma_{\text{a fuel}}$ and hence a reduction in the reproduction factor η. Xenon-135 and Samarium-149, both strong neutron absorbers, soon reach equilibrium levels but other less strong neutron absorbers gradually build up with increasing levels. Eventually the combination of depletion of fuel and build-up of neutron absorbers prevents criticality from being maintained and refueling with new fuel is required.

Xenon-135 in particular is troublesome as its equilibrium level in the reactor is maintained by it being destroyed by neutron absorption as fast as it is created. A reduction in reactor power decreases the neutron flux and hence its rate of destruction. This results in a surge of xenon production and an increase in neutron absorption. The consequent reactivity changes may be difficult to control especially after a significant power reduction such as a reactor trip.

The temperature effects are related to the neutron absorption characteristics of the fuel and moderator. The temperature of the whole reactor increases from the cold shutdown condition to the hot zero load condition. The temperature of the fuel then increases further as power is raised from the zero load condition to the full load condition. It is desirable that the overall effect on the reactivity due to temperature be negative so that the natural tendency of the reactor is to go sub-critical (k less than unity) during a temperature excursion. This enhances the stability of the reactor giving it a degree of self regulation and hence increased safety.

2. Fission Product Effects

2.1. Magnitude of Effects

The effect of Xenon-135 is the most significant. The reduction in the value of the reproduction factor η following a reactor trip from the full load condition causes a change in the value of the neutron multiplication factor k from unity to about 0.9 after about 10 hours. This would require an increase in reactivity of some 100 mk to restart the reactor. For safety reasons this is beyond the capability of the control systems of most reactors. Xenon-135 does decay and this condition is alleviated after some 40 hours.

The effect of Samarium is much smaller and the changes slower. The resultant reactivity

changes can be accommodated by the control systems.

The effects of fuel burnup and transuranic nuclide build-up are very slow and can be compensated for by the gradual withdrawal or burnup of neutron absorbing materials in the moderator or fuel. This allows the value of k to be maintained at unity without excessive insertion or withdrawal of the control rods. Boric acid is commonly added to the moderator and its concentration maintained at an appropriate level. Some reactors may have rods containing a burnable neutron absorber which is destroyed at just the right rate to compensate for fuel depletion and transuranic build-up.

The effects mentioned above are an important consideration in the restart of a reactor. On restart the value of k for the reactor will not be the same as that immediately before shutdown. Hence inserting the same amount of reactivity as was withdrawn on shutdown will not give a value of k equal to unity. In other words the control rods will not be withdrawn to their original positions. The approach to criticality will thus be towards an unknown point as was the case during any previous start-up.

2.2. Xenon Transients

During the fissioning of the fuel in a nuclear reactor a range of fission products is produced. The relative yield of each of these fission products varies with the type of fissile material and the energy of the neutrons. Generally Uranium-235 is fissioned by thermal neutrons and it is the relative yield of fission products from this reaction that dominates. Of the many fission products that are produced most are unstable and decay to other nuclides. Most of these daughter nuclides are not neutron absorbers since they have decayed from fission products with an excess of neutrons. A few however end up as strong neutron absorbers and this is detrimental to the continuation of the fission chain reaction. Xenon-135 is the most important neutron absorbing nuclide produced as a result of the fission process. Xenon-135 is produced directly as a fission product and also as a daughter of Iodine-135, another fission product. Xenon-135 being a strong neutron absorber soon transmutes to Xenon-136 a stable nuclide which is a very weak neutron absorber.

The result of the above in an operating reactor is the production of Iodine-135 and Xenon-135 due to the fission process, the decay of Iodine-135 to Xenon-135 by β-particle emission, the burnup or transmutation of Xenon-135 to Xenon-136 by neutron absorption and the decay of Xenon-135 to Cesium-135 by β -particle emission. These four processes associated with Xenon as well as the influence of Iodine are illustrated graphically in Figure 1 and lead to various transients determined by the decay and burnup rates of the different nuclides. The burnup rate in turn depends upon the neutron flux level or reactor power level. This complicated process can however be analyzed mathematically if the decay constants, relative yields and cross sections are known. These values are well known though the exact values quoted by different sources vary slightly. The values given below are from Glasstone and Sesonske.

For Iodine-135:	fission yield	γ_I	= 0.061
half-life	$t_{1/2}$	=	6.7 h

decay constant λ_I = 0.103 h^{-1}

decay constant λ_I = 2.87 x 10^{-5} s^{-1}

For Xenon-135: fission yield γ_{Xe} = 0.003

half-life $t_{1/2}$ = 9.2 h

decay constant λ_{Xe} = 0.075 h^{-1}

decay constant λ_{Xe} = 2.09 x 10^{-5} s^{-1}

cross-section $\sigma_{a\,Xe}$ = 2.65 x 10^6 b

The mathematical equations may be derived by considering the build-up and decay of both Iodine-135 and Xenon-135 and noting that the decay of the former contributes to the build-up of the latter.

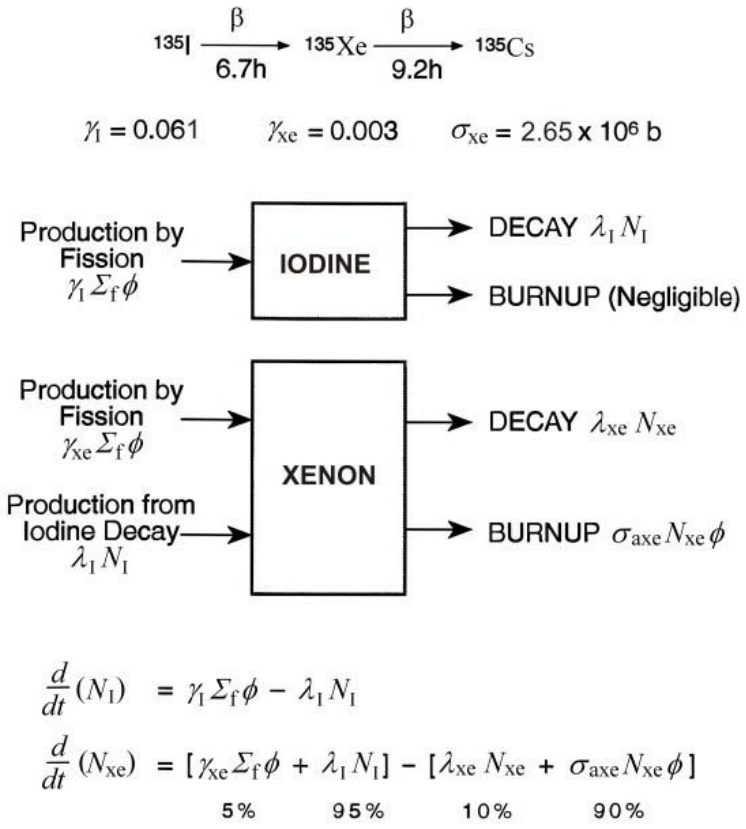


Figure 1. Iodine and xenon production and loss equations

The Iodine-135 builds up from its own fission yield and decays according to its half-life. The rate of change of Iodine-135 is thus given by:

$$dN_I / dt = \gamma_I \Sigma_f \varphi - \lambda_I N_I$$

Here the macroscopic fission cross section Σ_f multiplied by the neutron flux φ gives the

total number of fuel nuclei fissioned. Multiplying this by the fission yield γ_I gives the number of Iodine-135 nuclei produced. The decay rate is equal to the number of Iodine-135 nuclei N_I multiplied by its decay constant λ_I.

The Xenon-135 builds up from its own fission yield in the same way as the Iodine-135 and also from the decay of Iodine-135 to form Xenon-135. It decays according to its half-life and is also burned up by the absorption of neutrons. The rate of change of Xenon-135 is thus given by:

$$dN_{Xe} / dt = \gamma_{Xe} \Sigma_f \varphi + \lambda_I N_I - \lambda_{Xe} N_{Xe} - \sigma_{a\,Xe} N_{Xe} \varphi$$

Here the microscopic absorption cross section σ_a multiplied by the neutron flux φ and the number of nuclei N_{Xe} gives the number of nuclei destroyed. The other terms in this equation are similar to those of the equation for Iodine-135. Note that the decay of Iodine-135 gives Xenon-135 so the term $\lambda_I N_I$ appears in both equations. For a typical operating reactor the dominant terms are $\lambda_I N_I$ and $\sigma_{a\,Xe} N_{Xe} \varphi$ showing that most Xenon is derived from decay of Iodine-135 and most lost by burnup due to the neutron flux.

At equilibrium when the rate of change of each has stabilized the two equations may each be set to zero. The first equation gives the following:

$$0 = \gamma_I \Sigma_f \varphi - \lambda_I N_{I\,eq}$$

$$N_{I\,eq} = \gamma_I \Sigma_f \varphi / \lambda_I$$

The second equation gives, with substitution from the first equation, the following:

$$0 = \gamma_{Xe} \Sigma_f \varphi + \lambda_I N_{I\,eq} - \lambda_{Xe} N_{Xe\,eq} - \sigma_{a\,Xe} N_{Xe\,eq} \varphi$$

$$N_{Xe\,eq} = (\gamma_{Xe} + \gamma_I) \Sigma_f \varphi / (\lambda_{Xe} + \sigma_{a\,Xe} \varphi) \qquad (2)$$

This equation shows that the equilibrium value of Xenon-135 $N_{Xe\,eq}$ is strongly dependent upon the neutron flux φ. It is roughly proportional to the flux at low flux levels but at high flux levels it approaches a maximum value. This is illustrated in Figure 2 which shows that the equilibrium value increases substantially (with increasing neutron flux) up to about 20% but above about 60% there is very little increase up to 100%.

The whole process may be modeled by using a water level analogy where water accumulates in two tanks representing Iodine-135 and Xenon-135. The two inflows are controlled by valves representing the neutron flux as is the major outflow from the second tank. Outflows representing decay are not controlled but vary according to the volume in the tank. Figure 3 shows such an arrangement where the tank volumes represent the accumulation of Iodine-135 and Xenon-135 and the valve openings represent the magnitude of the neutron flux. If drawn to scale this model allows the process to be easily

visualized and any transients can be qualitatively analyzed.

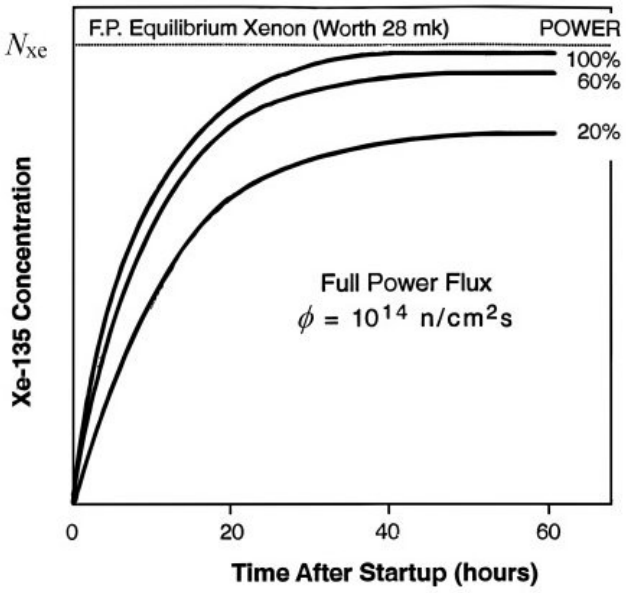
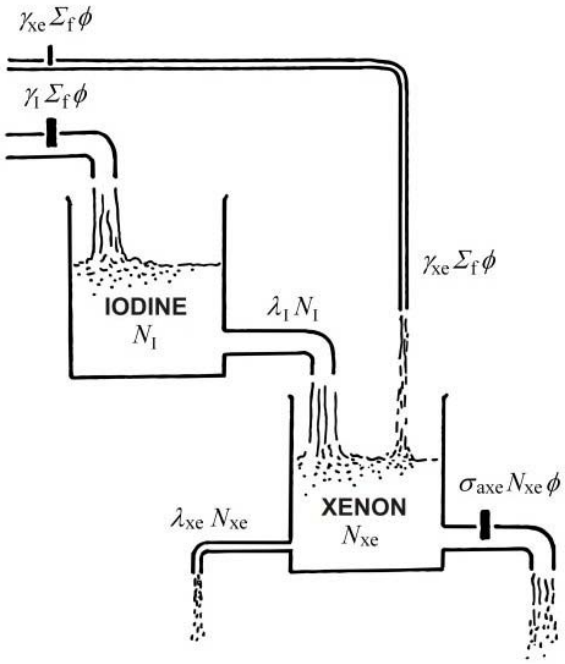


Figure 2. Build-up of Xenon-135 towards its equilibrium value



$$\frac{d}{dt}(N_I) = \gamma_I\Sigma_f\phi - \lambda_I N_I$$

$$\frac{d}{dt}(N_{xe}) = [\gamma_{xe}\Sigma_f\phi + \lambda_I N_I] - [\lambda_{xe}N_{xe} + \sigma_{axe}N_{xe}\phi]$$

5% 95% 10% 90%

Figure 3. Iodine and Xenon water level analogy

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Biographical Sketch

Robin Chaplin obtained a B.Sc. and M.Sc. in mechanical engineering from University of Cape Town in 1965 and 1968 respectively. Between these two periods of study he spent two years gaining experience in the operation and maintenance of coal fired power plants in South Africa. He subsequently spent a further year gaining experience on research and prototype nuclear reactors in South Africa and the United Kingdom and obtained M.Sc. in nuclear engineering from Imperial College of London University in 1971. On returning and taking up a position in the head office of Eskom he spent some twelve years initially in project management

and then as head of steam turbine specialists. During this period he was involved with the construction of Ruacana Hydro Power Station in Namibia and Koeberg Nuclear Power Station in South Africa being responsible for the underground mechanical equipment and civil structures and for the mechanical balance-of-plant equipment at the respective plants. Continuing his interests in power plant modeling and simulation he obtained a Ph.D. in mechanical engineering from Queen=s University in Canada in 1986 and was subsequently appointed as Chair in Power Plant Engineering at the University of New Brunswick. Here he teaches thermodynamics and fluid mechanics and specialized courses in nuclear and power plant engineering in the Department of Chemical Engineering. An important function is involvement in the plant operator and shift supervisor training programs at Point Lepreau Nuclear Generating Station. This includes the development of material and the teaching of courses in both nuclear and non-nuclear aspects of the program.. He has recently been appointed as Chair of the Department of Chemical Engineering.