The Influence of Xenon-135 on Reactor Operation

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Abstract

Xenon-135 is a product of U-235 fission and has a very large neutron-capture cross section. It also decays radioactively with a half-life of 9.1 hours. Little of the Xe-135 results directly from fission; most comes from the decay chain, Te-135 (half-life, 0.5 min) to I-135 (half-life, 6.6 hr) to Xe-135. The combination of delayed generation and high neutron-capture cross section produces a diversity of impacts on nuclear reactor operation.

In the nuclear production reactors at the Savannah River Site (SRS), the flexibility in reactor charge design, the extensiveness of the reactor control system, and the multiplicity of monitoring systems for measuring the power distribution throughout the reactor enabled the effects of Xe-135 to be handled routinely. Occasionally, a Xe-135 disturbance arose that required special control measures, but for these also, the reactor systems were adequate.

This report describes measures that were necessary to handle the effects of Xe-135 in the day-to-day operations of power ascension, power level adjustment, reactor shutdown, and reactor restart. A few unusual but still significant cases of so-called "xenon oscillations" are discussed. The final section illustrates the effect of Xe-135 on the production process.

The time is Tuesday in late September 1944. The scene is the B Pile (graphite-moderated nuclear reactor) at the Hanford Reservation in Washington State. The dramatic discovery of the effect of Xe-135 is described this way (Rhodes 1986):

> The pile went critical at a few minutes past midnight; by 2 a.m. it was operating at a higher power level than any previous chain reaction. For the space of an hour all was well. Then Marshall remembers the operating engineers whispering to each other, adjusting control rods, whispering more urgently. 'Something was wrong. The pile reactivity was steadily decreasing with time; the control rods had to be withdrawn continuously from the pile to hold it at 100 megawatts. The time came when the rods were completely withdrawn. The reactor power began to drop down and down.'
>
> Early Wednesday evening B Pile died....
>
> Early Thursday morning the pile came back to life. It was running ... again. But twelve hours later it began another decline.

The culprit was Xe-135.

The solution for B Pile was to enlarge the core from the original 1500 tubes to 2004 tubes loaded with uranium. Provision had been made in the construction for such an eventuality.

Xenon-135, a fission product, has a neutron-capture cross section of 2,600,000 barns. In comparison, an atom of U-235 has a fission cross section of 550 barns. About 6.3% of fissions result in Xe-135, only 0.2% directly. The other 6.1% results from the radioactive decay of I-135, which has a half-life of 6.7 hours and a very small cross section for neutron capture. Xenon-135 decays radioactively with a half-life of 9.2 hours. This nuclide chain may be diagramed simply as in Table 1.

Under conditions of the operating Savannah River Site (SRS) nuclear reactors, Xe-135 is ten times more likely to be destroyed by neutron capture than by radioactive decay. These properties give Xe-135 its peculiar effects on reactor

Table 1. Nuclide chain

	Te-135	I-135	Xe-135	Cs-135	Ba-135
Half life	0.5 min	6.6 hr	9.1 hr	2.6 million yr	stable
Fission yield, %		6.1	0.2	0.1	

and reactor core design, operation (including oscillations in the spatial distribution of power), and productivity.

Reactor and Reactor Core Design

The SRS reactors have an extensive system of removable reactor poison that can be withdrawn as Xe-135 grows in from the decay of I-135. Each of the 61 control positions has a complement of 7 rods, 2 of which are designated for half-length rods for control of the axial power distribution. The other five are full-length rods and are withdrawn sequentially. The control rod complement is adequate to ensure that the reactor is sufficiently subcritical in its shutdown state. The full-length rods are withdrawn to bring the reactor critical, further withdrawn to compensate for the negative effect of temperature as the reactor power is increased, and further withdrawn for the negative effect of the Xe-135 poison that grows in.

The function of the SRS reactors is to produce materials, primarily tritium and plutonium, by transmutation of fertile material by neutron capture. So the reactor core is a mixture of fissionable material: namely U-235 to produce the neutrons; and of fertile material, namely Li-6 if the core is to produce tritium; and U-238 if the core is to produce plutonium. The mixture of fissionable and fertile materials must be nearly balanced if the reactor is to be able to operate, but an excess of fissionable material is necessary to allow for the effects of temperature and Xe-135. The control system compensates for the fissionable material excess.

Reactor Operation

After the reactor has operated for a few days, the I-135 and Xe-135 concentrations achieve an equilibrium level, and the poisoning effect of xenon is constant. However, if the power level is changed, the equilibrium is disturbed, and a transient in the Xe-135 concentration is generated. If the reactor is shut down, power is reduced to zero, the xenon transient is very large and in some cases cannot be compensated by the control system.

Power Level Changes

Initial Startup of a Reactor Core

Usually a reactor after startup is taken to full power in a series of steps, for example, 40%, 60%, 80%, 90%, and 100%. At each step, checks are made to determine that operations are normal. Power distribution shaping is also done with the control system.

Control rods are withdrawn to bring the reactor critical. Thereafter, the reactor remains very near critical, and control rods are moved only to compensate for other effects, such as power level changes, Xe-135 build-in, or fuel burnup. To take the reactor to 40% power, control rods are withdrawn to make the reactor slightly supercritical. The reactor responds by increasing power. The reactivity change from the associated change in temperature occurs within seconds. The 40% power corresponds to about 800 megawatts. The rate of rise is procedurally limited, so the total change takes maybe ten minutes. When the 40% level is reached, the control rod position is in equilibrium with the reactor temperature.

At the 40% level, Xe-135 starts to build in, and control rods must be withdrawn to compensate for the decrease in reactivity. The change is slow, so control rod motion can easily follow. Figure 1A is a graph of the reactivity change from Xe-135 in units of %k as a function of time. If no further change in power were made, the Xe-135 poison would reach its equilibrium level of 2 %k after about 36 hours.

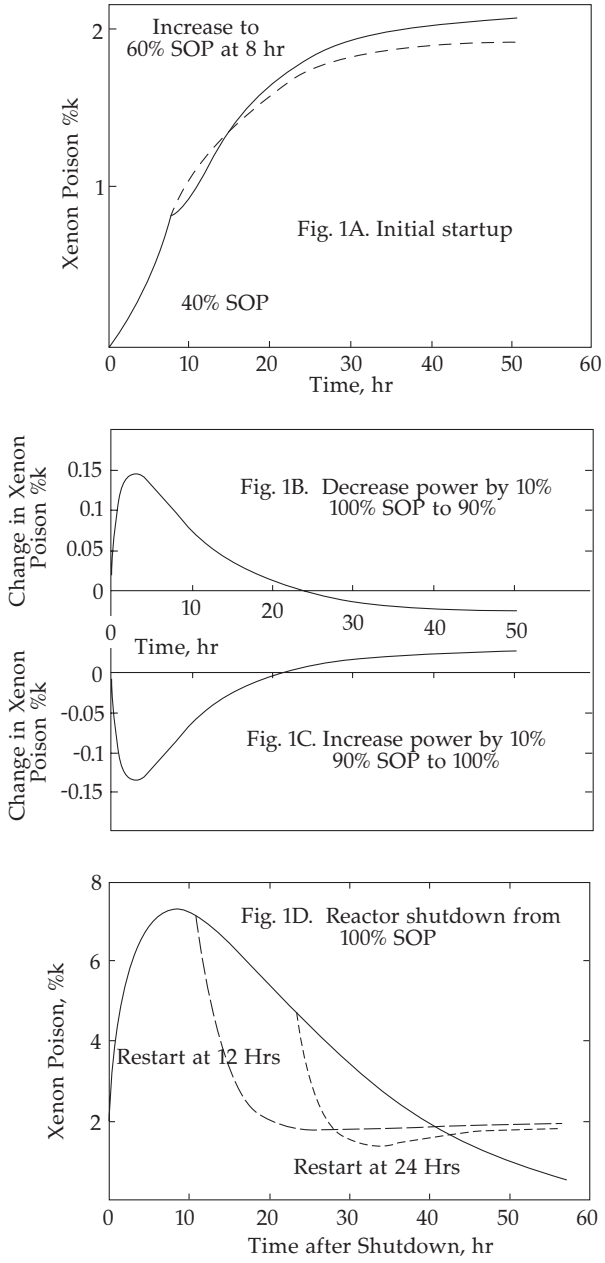

Figure 1. Xenon transients

Suppose that after eight hours the power level is raised further to 60% of full power. This is also illustrated in Figure 1A. After the rod position has equilibrated with the temperature changes, the control rod withdrawal rate is a little slower than it would have been without the power increase. The Xe-135 that had built in is burned up faster at the higher power than additional Xe-135 can grow in from the higher rate of I-135 production. But after another eight hours, the rate catches up, and the Xe-135 poison goes on to equilibrate at a slightly higher level than it would have at 40% power.

Power Level Adjustment

Suppose the reactor is at equilibrium at 100% power and for some reason it is desired to decrease the power say to 90%. This change produces a Xe-135 transient because at 90% standard operating power (SOP), Xe-135 is not burned up as fast as it grows in from the I-135 present. This transient is illustrated in Figure 1B. The increase in Xe-135 poison reaches a maximum in about three hours after the change and then gradually subsides to the new, slightly lower equilibrium level. To achieve the power level decrease, control rods are inserted over a few minutes, then withdrawn for three hours as the Xe-135 poison builds in, and then inserted as the Xe-135 transient dissipates.

If the reactor is at equilibrium at 90% power and then the power is increased to 100%, the Xe-135 transient is the reverse—nearly a mirror image across the time axis as illustrated in Figure 1C. Control rods are withdrawn over a few minutes for the power increase, inserted for a few hours for the decrease in Xe-135 poison, and then withdrawn over a couple of days to the new equilibrium level.

Reactor Shutdown and Restart

If a reactor is shut down after operating for a while at a high power level, the Xe-135 transient is large. The I-135 level is high because of the high power, and then after shutdown the I-135 decays to Xe-135 that is not burned up. The Xe-135 transient after shutdown is illustrated in

Figure 1D. The peak xenon poison occurs after about 10 hours. During the period of peak xenon, the reactor is very subcritical. Some of the reactor charges utilized at Savannah River, because of insufficient available reactivity, were limited as to the time at which they could be restarted. Others, however, could be restarted at any time.

Recovery situations are also plotted in Figure 1D. Power level at recovery is 40%. The high Xe-135 level burns up rapidly, then proceeds to the equilibrium level. For some SRS reactor charges, the recovery level was limited to 20% so that the reactivity from Xe-135 burnup is more easily managed.

Xenon Oscillations

Xenon oscillation is the name given to the redistribution of the power in local regions of the reactor caused by redistribution of the Xe-135 poison. For example, suppose the reactor is in an equilibrium state at a power level where Xe-135 poison is significant. At some time, the half-length control rods are moved down a short distance; the power in the top part of the reactor goes up and that in the bottom part of the reactor goes down. At the top, Xe-135 burns up faster than it is replaced by I-135 decay, increasing the reactivity and therefore the power in the top. After a while, the generation of I-135 at the top catches up, and Xe-135 concentration levels off and starts to increase and thereby to decrease the power at the top. The decrease in power continues until the generation of I-135 no longer replaces the I-135 that decays to Xe-135, and the Xe-135 concentration levels off and starts to decrease, and the power starts to increase. The oscillation has gone full cycle. Conditions in the reactor bottom are just the reverse.

Just described is an axial oscillation, but oscillations can occur on opposite sides of a reactor (an azimuthal oscillation) or, more complicated, a top-side vs. a bottom-opposite-side (a quadrupole oscillation). All types have occurred in the SRS reactors; examples of the experience will be discussed later. In the example of the previous paragraph, half-rod motion caused the perturbation in power distribution to initiate the oscillation. In effect, any perturbation in the power distribution will cause a xenon oscillation; its size and longevity depends on characteristics of the reactor charge and control operations.

The oscillations can be damped, in which case each succeeding cycle diminishes, or undamped, in which case the amplitude of each succeeding cycle increases. The dividing line or threshold (in terms of power density) for undamped oscillations depends on several factors that are characteristics of a particular reactor charge. Characteristics that tend to lower the threshold are: lower fuel loading (e. g., end of fuel cycle vs. beginning); greater flatness of the power distribution (e. g., greater number of fuel assemblies operating at the same power); and smaller negative temperature coefficients of reactivity. Because of the large size, high power density, and great degree of power distribution flatness, most reactor charges that have been operated at SRS are susceptible to xenon oscillations despite their negative temperature coefficients of reactivity.

Reactor Instrumentation

To adequately control xenon oscillations, it is necessary to know the three-dimensional power distribution. The reactor cooling system is comprised of six loops, each with two heat exchangers. The six loops feed a common plenum at the reactor top that supplies D_2O coolant to all fuel assemblies. The flow goes down each fuel assembly and then out the bottom into the bulk moderator space. Each of the six loops then draws flow from the bulk moderator via six exit nozzles evenly spaced around the bottom of the reactor vessel.

The primary detector for measuring the radial power distribution is the temperature monitor. There are four thermocouples associated with each fuel position. These thermocouples monitor the effluent temperature from the fuel

assembly. The effluent temperature along with the plenum inlet temperature and the assembly coolant flow provides the assembly power. The on-line computer processes the data and provides a complete radial power map.

Operating off the same thermocouples is the radial power monitor. The on-line computer processes the data also to provide the average power of the six fuel assemblies surrounding each control position.

The third radial system and the best for monitoring azimuthal xenon effects on the radial power distribution is that of measuring the so-called pump suction temperatures. Thermocouples are located in the lines from the reactor effluent nozzles to the coolant pumps. The pump suction temperature along with the plenum inlet temperature and the loop coolant flow provides a measure of the power in that one-sixth sector of the reactor.

The instrumentation for determining the axial distribution is a system of nine rods, each placed interstitially among three fuel assemblies. The nine rods are located strategically throughout the reactor so as to provide complete coverage. Each rod contains seven gamma thermometers and a thimble for irradiating a wire. The gamma thermometer is a small iron pin attached to a heat sink at one end. Thermocouples are attached to each end of the pin to measure the temperature difference between the ends. This temperature difference is proportional to the gamma ray energy flux at the location of the pin and therefore to the fission rate and power generation in the vicinity of the pin. The seven gamma thermometers in a rod provide a good measure of the axial power distribution. The wire irradiation with subsequent measurement of the gamma ray activity along its length measures the axial neutron distribution and is used to periodically calibrate the gamma thermometers.

Operating Experience

Under normal conditions, xenon effects are not specifically monitored. Close control of the power distribution is maintained as part of standard operations and is usually sufficient to eliminate problems from xenon. Circumstances under which xenon problems are encountered occur infrequently and do so in charges that are unusually susceptible to oscillations with damping factors less than unity. Examples of xenon oscillations are given below.

The clearest example of an inadvertent undamped oscillation is illustrated in Figure 2A. This occurred during power ascension when control of the power distribution is relaxed somewhat from the requirements at full power. The ordinate is the change in one pump suction temperature from an equilibrium value in arbitrary units; this was an azimuthal oscillation so that the oscillation on the opposite side of the reactor was 180 degrees out of phase with the illustrated oscillation. The arrows indicate points at which control rods were moved; the motion was not sufficient to control the oscillation. Control at the end of about 50 hours required a relatively large amount of control rod trim.

This illustrates that, even though there is sufficient time for control, sufficient and correct control procedures must be supplied. The method of control in this case was to force the perturbation to zero and hold it there. This works, but requires a larger amount of reactivity change than the method illustrated in the next example.

The most complex and difficult-to-control oscillation to occur had a quadrupole nature. This oscillation was in the axial direction, but the oscillation on one side of the reactor was 180 degrees out of phase with the oscillation on the other side of the reactor. Figure 2B shows the oscillation in terms of the change in relative

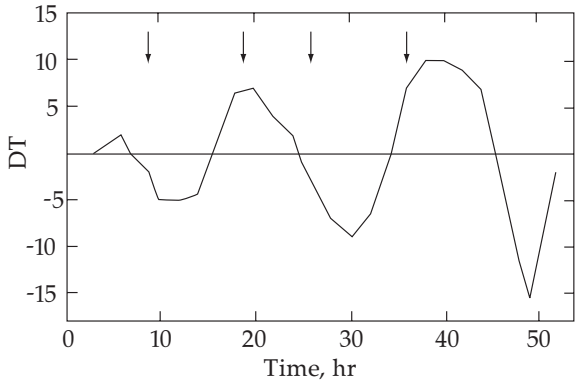

Figure 2A. Observed undamped azimuthal oscillation

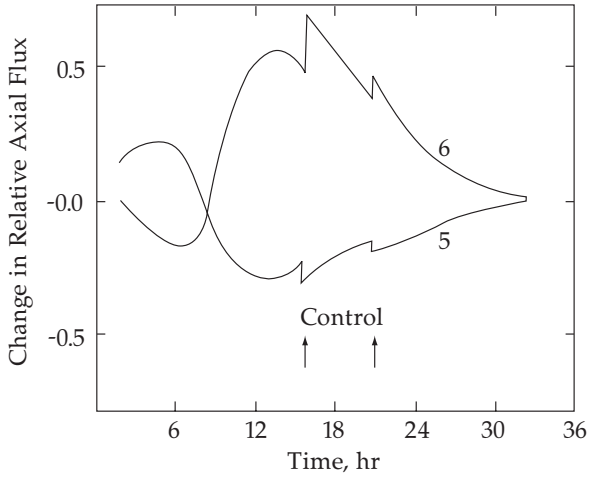

Figure 2B. Quadrupole oscillation

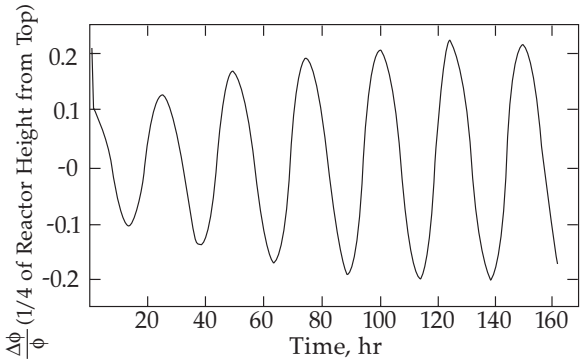

Figure 2C. Axial xenon test in SRS reactor

Figure 2. Xenon oscillations

axial power in the top of the reactor on the two sides as measured by the axial power monitor (gamma thermometer rods); the numbers at the two curves are the numbers of the indicating gamma thermometer rods. To damp the oscillation, partial rods in five septifoils in the vicinity of #6 were moved down. At the same time, partial rods in five septifoils in the vicinity of #5 were moved up. This illustrates a more efficient method of bringing under control an oscillation that has become large. The coming action is anticipated and counterbalanced. In regions where the power is high but is starting to decrease, indicating that xenon is growing faster than it is burning up, rods are moved to keep the power high in order to burn up xenon. A relatively small amount of reactivity is required.

A series of controlled experiments with deliberately induced xenon oscillations was carried out in one of the SRS reactors. The majority of the tests dealt with axial oscillations and a few with azimuthal oscillations. The results of one of the more interesting axial tests is shown in Figure 2C. The ordinate is the change in power at a point one-quarter of the way from the top of the reactor under conditions of constant reactor power. The oscillation diverged for a few days and then appeared to saturate for an unknown reason.

The phenomenon of xenon oscillations is an interesting one in that the theoretical description is simple and remarkably accurate. The theoretical aspects are not treated here, but extensive theoretical studies were made and were a great assistance in dealing with the phenomenon.

Effect of Xe-135 on Productivity

The purpose of the Savannah River Site reactors is to produce materials not found in nature in recoverable quantities. They do this by utilizing neutrons produced from fission of U-235. At the high power density levels at which the SRS reactors operate, only a small fraction of the Xe-135 decays radioactively; most is destroyed by neutron capture. These neutrons otherwise could have been used in production processes.

Consider the production of tritium, an isotope of hydrogen with an atomic mass of three.

The production process is

Li-6 + neutron —> H-3 + He-4.

A neutron is absorbed by an atom of Li-6 and the resulting Li-7 splits into a tritium nucleus and a He-4 nucleus plus energy. The energy is carried off by the two resulting particles and dissipated in the substrate material.

Reactor charges for production of tritium are composed of uranium highly enriched in U-235, lithium enriched in L1-6 contained in suitable fuel, target elements, and assemblies. The elements and assemblies use aluminum as the diluent and encasing material.

For greatest efficiency, it is desirable to maximize the number of neutrons available to the production process. Impact of Xe-135 can be understood from the "neutron economy".

Fission of an atom of U-235 produces on the average 2.43 neutrons. Uranium-235 also absorbs neutrons to produce U-236 so that each neutron absorbed by U-235 produces 2.08 neutrons after accounting for the U-236. Since one neutron must be available for absorption in U-235 for the next generation, 1.08 neutrons are potentially available for the production process.

Other processes subtract from the neutrons available for production. For the SRS reactors, about 3% of neutrons leak from the reactor core and are absorbed by the reactor tank wall or the reactor shields. This takes 0.06 of the neutrons from the neutron economy. (Use of only lithium-bearing assemblies in the outer ring of the reactor and having the target elements extend above and below the fuel elements utilize some of the leakage neutrons for production.)

The neutron moderator, D_2O, the aluminum in the fuel, and target assemblies absorb another 5% of the available neutrons. This subtracts 0.10 of the neutrons from the neutron economy.

During the lifetime of the reactor core, fission products build up in the fuel assemblies. The fission products (including Sm-149) other than Xe-135 absorb about 3% of the available neutrons; this subtracts another 0.06 from the neutron economy.

Xenon-135 is essentially all destroyed by neutron capture. Since each fission produces 0.063 atom of Xe-135, the Xe-135 subtracts 0.06 from the neutron economy.

The remainder 2.08 - 1.00 - 0.06 - 0.10 - 0.06 - 0.06 = 0.80 neutron per fission is available for production of tritium. The neutron economy may be summarized as shown in Table 2.

Table 2. Neutron Economy

	Production	**Utilization**
Fission	2.08	
Next generation		1.00
Leakage		0.06
Absorption in D_2O and structure		0.10
Fission products other than Xe-135		0.06
Xe-135		0.06
Production		0.80
Total	2.08	2.08

References

Rhodes, Richard, 1986, *Making of the Atomic Bomb*, Simon and Schuster, ISBN 0-671-44133-7.

Biography

With a Ph. D. degree in Experimental Physics from Indiana University, Mr. Roggenkamp joined the Du Pont Co. on October 1, 1952, in the reactor training program at the Argonne National Laboratory. Coming to Savannah River the next year, he joined the Experimental Physics Division of the Savannah River Laboratory (SRL). During the period of 1957 to 1964 in the Reactor Technology Section of the Savannah River Plant (SRP), he supervised work on the physics aspects of the nuclear reactor operations. During this period of time, production of Pu-238 was begun. Returning to SRL in 1964 as Research Manager of the Theoretical Physic Division, he was instrumental in the development of the high flux demonstration program, and of the curium and californium production programs. During the ten years prior to retirement in December 1987, he was in charge of the Advanced Operational Planning Division of SRL, which provided long-range studies for operation of SRP and for the integration of SRP operations into the Department of Energy complex.