Fission products poisons

The case of Xenon

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A report submitted for the Nuclear Reactor Laboratory class
at the Colorado School of Mines.

OCTOBER 12, 2016

ABSTRACT

While operating a nuclear reactor, one of the big concerns is the Xenon concentration in the core. Stable during nominal operations, the Xenon concentration builds up, from Iodine decay mostly, in the core in the hours following a shutdown. ^{135}Xe being a potent neutron poison, this buildup can cause the reactor to be inoperable for a couple of days afterward.

Moreover, ^{135}Xe buildup has an effect on the flux distribution within the core, flattening it in the most reactive fuel elements (where its presence is more noticeable). This is of particular importance in power reactors, in which Xenon oscillations happen.

It is consequently primordial to understand the Xenon effect and know its concentration in the core.

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A neutron poison is an element that absorbs neutrons of interest in a nuclear reactor core. In most reactors today, the neutrons of interest are the thermal neutrons, with low energies. Those are the neutrons driving the chain reaction, by fissioning the ^{235}U. Different types of neutron poisons can be identified, the design absorbers and the fission products absorbers. One of the most potent neutron absorber known is the Xenon, the fission product subject of this project. The impact of Xenon on a nuclear reactor was discovered in 1944 in the USA, when a reactor experienced strange behavior in its power buildup. Xenon is not the only poison of interest in a nuclear reactor. Indeed, Samarium is also to be taken into account, though in a much lesser way. The presence of Samarium (^{149}Sm) in a classical pressurized water reactor will not prohibit it from operating normally like Xenon can. However, it will impact the rod calibration if not accounted for while predicting the measurements.

One can note that in order to ease the reading, the terms Xenon and Iodine will be used interchangably with the terms ^{135}Xe and ^{135}I. The theory is based on the course handouts [1], as well as various Nuclear Reactor Physics books.

1.1 Fission products

The fission of an atom caused by a neutron create a number of neutrons and new atoms, fission products. Only a few of the fission products are responsible for most of their effects, the decay heat and additional neutron absorption. The most potent product fission absorber is the Xenon 135 (^{135}Xe). Another noteworthy fission product is the Samarium 149 (^{149}Sm).

Figure 1.1 presents the most common ^{135}Xe creation process in a nuclear reactor. Due to the short half-life of the Tellurium 135, it can be neglected, and the process will be simplified to the one presented in figure 1.2.
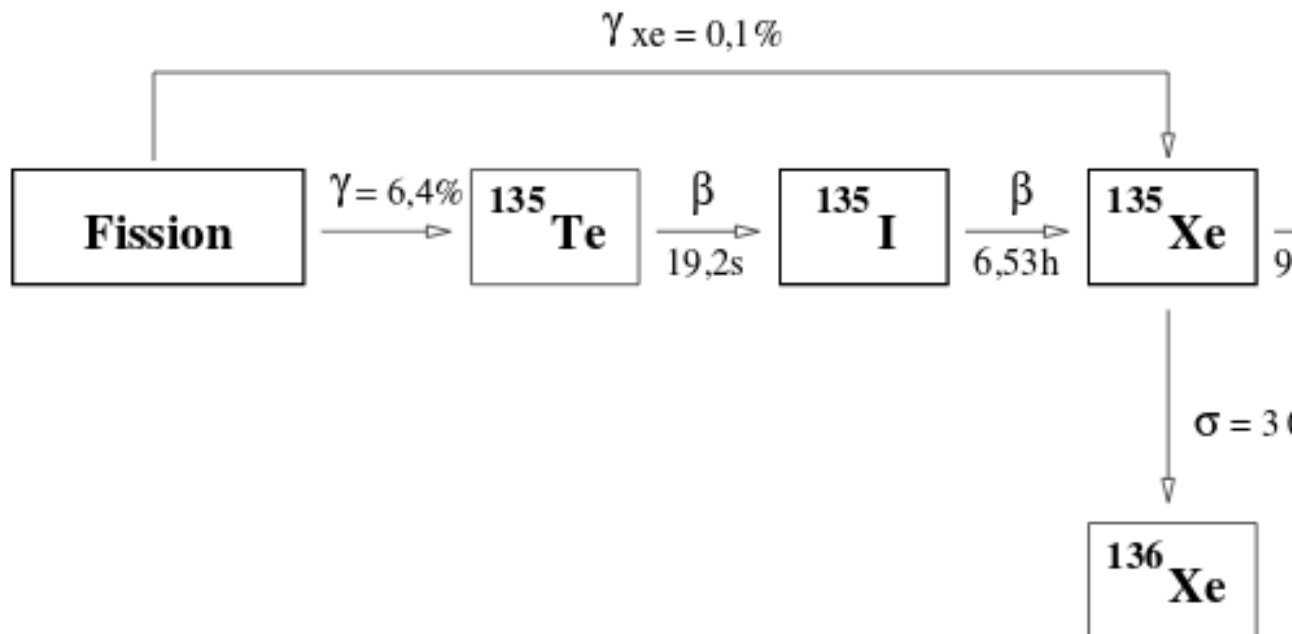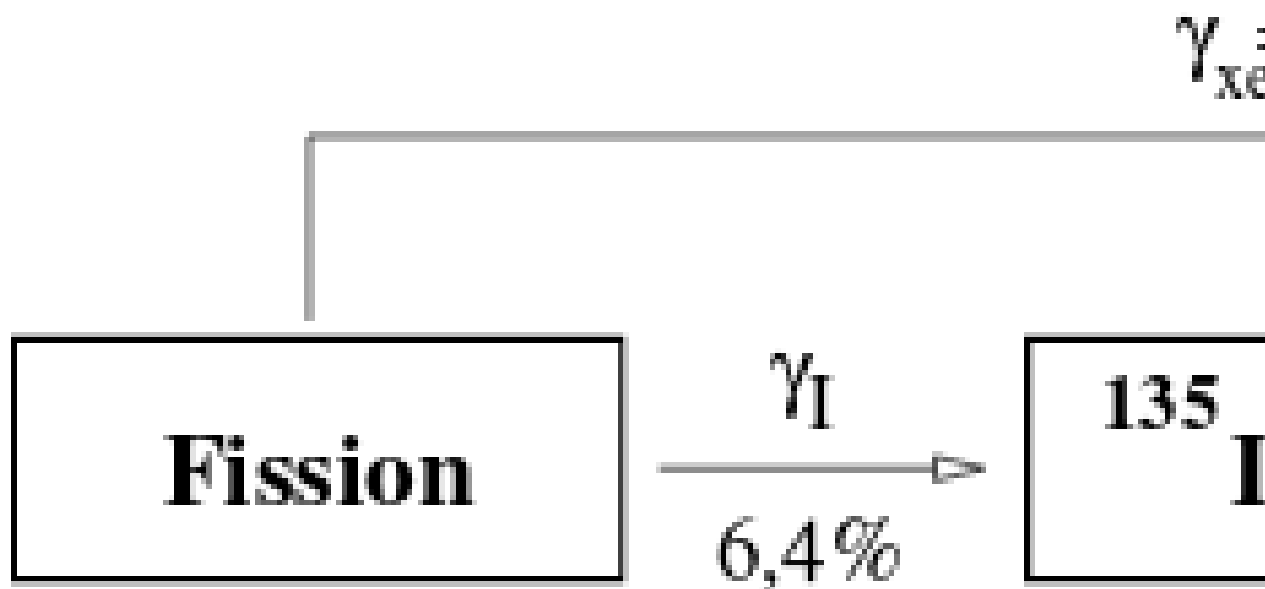
FIGURE 1.1. Creation process of ^{135}Xe.

FIGURE 1.2. Simplified creation process of ^{135}Xe.

We can describe this simplified process mathematically:

$$(1.1) \qquad \frac{dC_I}{dt} = \gamma_I \Sigma_f \phi - \lambda_I C_I$$

C_I = Population of ^{135}I per cm^3

γ_I = Fission product yield of ^{135}I

Σ_f = Macroscopic fission section

ϕ = Neutronic flux in $cm^{-2}.s^{-1}$

λ_I = Radioactive decay constant of ^{135}I in s^{-1}

$$(1.2) \qquad \frac{dC_{Xe}}{dt} = \gamma_{Xe} \Sigma_f \phi + \lambda_I C_I - (\lambda_{Xe} + \sigma_{Xe}\phi)C_{Xe}$$

C_{Xe} = Population of ^{135}I per cm^3

γ_{Xe} = Fission product yield of ^{135}I

Σ_f = Macroscopic fission section

σ_{Xe} = Microscopic absorption section

ϕ = Neutronic flux in $cm^{-2}.s^{-1}$

λ_{Xe} = Radioactive decay constant of ^{135}I in s^{-1}

^{135}I can be produced by the fission of ^{235}U with a yield γ_I, hence a production of $\gamma_I \Sigma_f \phi$ atoms of ^{135}I, and it can disappear by decay, $\lambda_I C_I$. On the other hand, ^{135}Xe can be created by the fission of ^{235}U with a yield γ_{Xe}, and by decay of ^{135}I, hence a production of $\gamma_{Xe} \Sigma_f \phi + \lambda_I C_I$ atoms of ^{135}Xe. It can disappear by radioactive decay and by capturing neutrons, thus a disappearance of $\lambda_{Xe}C_{Xe} + \sigma_{Xe}\phi C_{Xe}$.

Similarly, we would be able to compute the population of ^{149}Sm, given by the decay of the fission product neodymium to prometheum. Prometheum 149 has a half-life of around 53 hours and Samarium 149 is stable. This means that the Samarium starts habing an impact after the core has been shut down for approximately two weeks. Thus, after a reloading operation at a nuclear reactor, the presence of the samarium must be taken into account when computing the reactivity of the core.

Other fission products can act as neutron poisons, though nowhere near as problematic as Xenon or Samarium. However, lumped together, their impact is to take into account. In nuclear power reactor, those are often considered within the scope of the ageing (out-of-flux) of the fuel elements, building up the fission products concentration. They will not prevent the reactor from diverging, but they can modify the peak factor in the reactor and needs to be taken into account when designing the core, especially during the power ramp at startup.

Those poisoning fission products, Xenon, Samarium and various others, are of concern in thermal flux reactor. The Xenon cross-section for fast neutrons, for example, is negligible. In hard spectrum reactors, other poisons can be used.

1.2 Other neutron poisons

Poisons are naturally used in a reactor core design, in the fuel elements directly or in the control rods. Their goal is to allow for the control of the reactor or to modify the neutron flux locally, for example to limit the fluence received by the reactor vessel. The most common design absorbers are the Hafnium, boron carbide (B4C), and AgInCd (AIC, Silver, Indium, Cadmium).

1.3 Impact of neutron poisons

As seen previously, the Xenon has the most impact on the reactor. In the following analysis, this element will be the one looked at. The impact of Xenon poisoning in the core is two-fold. It can prevent the reactor startup, by introducing enough negative reactivity that the critical state cannot be reached, and it can oscillate in the core due to some asymmetry, causing potential local power peaks.

1.3.1 Negative reactivity

^{135}Xe is one of the most efficient thermal neutron absorbers known, with a cross-section (whcih can be seen as of probability of interacting with neutrons) of approximately 3 millions barns for such low-energies neutrons, compared to 550 barns for the ^{235}U. This means that neutrons are way more likely to interact with the Xenon than with Uranium, hence potentially shutting down the reactor by preventing the chain reaction.

This effect is especially seen during the Xenon peak, within eight hours of the reactor shutdown. Then the Xenon concentration is at its maximum, building upon its equilibrium population from the iodine decay. Luckily, ^{135}Xe is not stable, and decays away at a higher rate than the iodine decay buildup.

In effect, this implies that a power reactor has a short window after a shutdown to be able to start up again, before the Xenon peak prevent that. After that time, the operator must wait approximately two days, for the Xenon to decay (half-life of around 9 hours), to start up again. One solution is to shut down progressively. This allows the equilibrium population of iodine and xenon, dependent on the flux, to get low enough that the Xenon peak will not add enough negative reactivity to prevent the following start up.

A minimum Xenon concentration must be considered when computing the reactivity insertion potential of a reactor, to be conservative. Indeed, if the limits are based on a maximum Xenon concentration, once the Xenon peak is passed, the reactivity increases back to nominal levels and can damage the core.

1.3.2 Xenon oscillation

The negative reactivity insertion is troublesome from an operation point of view. One issue that is more important to the reactor safety is the xenon oscillation in the core. This can indeed cause a local power peak, translating to higher temperature and potential fuel damage.

The oscillation is initially caused by a dissymetry in the system, often due to control rods positioning and relative worth, but also due to fuel loading patterns. This dissymetry causes a higher flux in a region of the core, and a lower flux in its symmetric region. A higher flux, as seen in the previous concentration equations, implies that the Xenon will absorb more neutrons, and thus disappear, causing the flux to actually increase. On the other hand, when the flux is lower, the Xenon actually continues to build up from Iodine decay, subsequently lowering the flux even more. Consequently, Iodine concentrations increases with high flux and decreases with low flux. Eventually, this Iodine buildup will reverse the effect, creating the oscillation.

The danger come from the high flux part of the oscillation, where, locally, the power can increase a lot and potentially damage (high temperature) the fuel assemblies. This effect must thus be considered when obtaining the limits on the insertion of reactivity.

1.4 Xenon reactivity calculation

The Xenon-free excess reactivity (ρ_e) and the rod control calibration curves are given for the GSTR.

(1.3)
$$\rho_e = 3.44\$$$

(1.4)
$$\rho_{transient} = 9.332139E - 15 * p^5 - 2.001355E - 11 * p^4 + 8.071354E - 9 * p^3$$
$$+4.851361E - 6 * p^2 + 5.73739E - 5 * p$$
$$\rho_{shim1} = 1.9124E - 12 * p^4 - 7.5364E - 9 * p^3 + 7.2250E - 6 * p^2$$
$$+4.3259E - 4 * p$$
$$\rho_{shim2} = 2.112741E - 12 * p^4 - 7.624993E - 9 * p^3 + 7.107704E - 6 * p^2$$
$$+2.741928E - 4 * p$$
$$\rho_{regulation} = 1.83246E - 12 * p^4 - 1.017529E - 8 * p^3 + 1.174461E - 5 * p^2$$
$$-3.147143E - 4 * p$$

The total rods worth can thus be computed, based on the real up position in the GSTR:

$$\rho_{transient} = 2.296\$$$
$$\rho_{shim1} = 2.034\$$$
$$\rho_{shim2} = 1.80\$$$
$$\rho_{regulation} = 3.088\$$$

(1.5)

The Xenon-free reactivity needed to reach criticality is hence given by:

(1.6)
$$\sum_i \rho_i - \rho_e$$

$i = $ [transient, shim1, shim2, regulation]

This works for a criticality achieved at 5W, where the value ρ_e is given. In order to compute the Xenon-free reactivity needed to reach criticality, one can assume that over a small period of time, say 20 minutes, the Xenon concentration remains unchanged. That can be considered true given the ^{135}I half-life of approximately 6 hours. Thus, from a critical state at 5W, the power can be increased to nominal value and the reactivity difference can be considered Xenon-free.

1.5 Procedure

Given the timeframe of ^{135}I and ^{135}Xe concentration changes, with half-lives between 6 and 10 hours, this lab should take several days. The reactor is thus run at full power for 8 hours, shut down, and turned back on the following morning. The position of the rods are noted at various intervals, at constant power. Those position, using the control rods calibration curves, relates to a certain amount of reactivity.

Thus, one can obtain the Xenon reactivity in the core as a function of time, to obtain the Xenon transient.

I n this section, the Xenon transient at the GSTR is measured and presented, according to the theory presented in the previous section. Given the procedure limitation, notably the time limitation, the value of the Xenon peak, happening around 7 hours after shutdown, will be guessed.

2.1 Results

The detailed data is presented in appendix A. The xenon reactivity as a function of time is drawn on figure 2.1, along with an estimate of the Xenon peak, based on the fact that this peak would have occured roughly 7 hours after shutdown. The graph shows clearly the impact of higher flux on the Xenon distribution in the core, with a sharp decrease of the negative reactivity inserted by the Xenon when the core is at full power.

Is is also interesting to note the positive reactivity inserted by the Xenon at startup. This is due to the high flux at nominal power which eats up the Xenon. In the meantime, ^{135}I concentration builds up from nuclear fission of uranium. Eventually, ^{135}Xe production from Iodine overtakes its destruction in high flux, hence the increase in negative reactivity after one and a half hour. The Xenon concentration (and consequently the negative reactivity inserted) will eventually reach an equilibrium after 40 to 50 hours.

2.2 Uncertainties

Several uncertainties sources can be observed in the system. First, the control rod calibration curves and the Xenon-free excess reactivity are given within a certain uncertainty interval, as seen in the previous lab report relative to the transient rod calibration. Moreover, the positions of
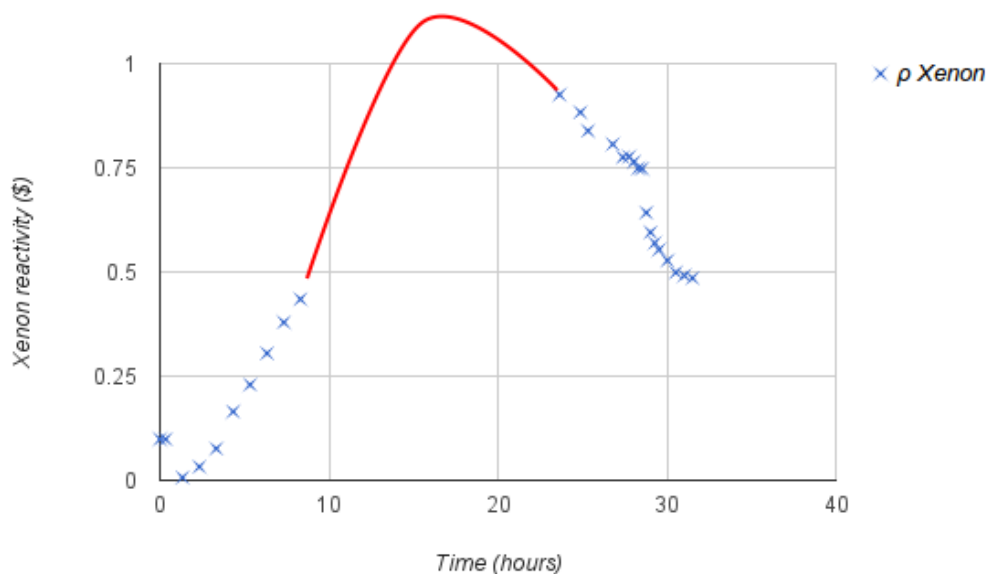
FIGURE 2.1. Reactivity of ^{135}Xe in the GSTR.

the rods given in the control room are error-prone, ± 2 steps. All this considered would give an uncertainty of approximately ± 0.01 \$, or $\pm 1\ cents$, that is roughly ± 1 %.

It can be noted that the water temperature impacts the water density and consequently changes the neutron moderation and allows for an improved use of the thermal neutron population. However, this does not impact in any meaningful way the reactivity in the GSTR core. Indeed, the evolution of the temperature that can be observed is not very important in a TRIGA reactor ($\Delta T = 20K$), and it does not translate to any change in the linearity of the antireactivity brought in by the Xenon. This impact is secondary compared to the flux-induced change in Xenon concentration.

Finally, the power is kept stable within a certain margin. An uncertainty on the power translates to an error on the rod positions, hence an error on the reactivity needed to be critical associated. This source of uncertainty can however be considered included in the $\pm 1\%$ aforementionned.

All in all, the uncertainties relative to this system are relatively limited, and the evolution of the Xenon concentration in the core can be taken with quite high confidence. This is notably due to the long time frame inherent to this experiment, allowing for a certain masking of the uncertainties over time.

CHAPTER

3

CONCLUSION

The project targeted by this report was to qualify the role of Xenon, a fission product neutron absorber, in the reactivity present in the core. In order to do so, the core was run at full power for a period of eight hours, allowing for Xenon buildup, though far from equilibrium concentration, and then shut down. During the shut down state, a Xenon buildup happens from the decay of Iodine. The goal is to detect the amount of antireactivity caused by the Xenon, and its evolution, when the reactor is started up again the next day.

This shows that the Xenon population indeed increases during the shutdown. Due to logistical reasons (time), the Xenon peak cannot be observed, and has to be inferred from theory. This gives an estimated maximum Xenon antireactivity of around 1.25$ 15 hours after the initial startup, 7 hours after the shutdown. The antireactivity then decreases with the flux, considering that the GSTR has more than enough excess reactivity to overcome the presence of Xenon at the time of start-up the next day.

Had we tried to start up the reactor 7 hours after running it at full power for two days straight, it is likely that the core could not have gone critical.

DETAILED DATA TABLES

This appendix presents the raw data from the experiment in table A.1. It then explicits the various calulcation steps in table A.2.

Time (h)	$p_{transient}$	p_{shim1}	p_{shim2}	p_{reg}	Power
0.00	548	543	546	552	5 W
0.33	767	764	763	771	905 kW
1.33	758	758	759	752	905 kW
2.33	759	759	759	759	905 kW
3.33	764	761	763	767	905 kW
4.33	774	774	772	779	905 kW
5.33	784	785	783	784	905 kW
6.33	796	792	792	796	905 kW
7.33	801	804	803	809	905 kW
8.32	811	813	812	816	905 kW
23.65	612	608	607	614	5 W
24.88	611	611	611	601	5 W
25.33	608	604	604	601	5 W
26.80	602	603	600	601	5 W
27.40	600	601	601	596	5 W
27.77	600	598	594	602	5 W
28.05	596	598	598	600	5 W
28.30	594	600	594	599	5 W
28.53	877	873	872	867	905 kW
28.78	849	849	850	849	905 kW
29.03	840	839	841	841	905 kW
29.28	834	839	838	834	905 kW
29.53	834	836	833	831	905 kW
30.03	832	831	830	825	905 kW
30.53	824	824	825	823	905 kW
31.03	824	824	825	820	905 kW
31.52	824	824	820	820	905 kW

Table A.1: Raw data - Critical state rods positions

Time (h)	$Cal_{transient}(\$)$	$Cal_{shim1}(\$)$	$Cal_{shim2}(\$)$	$Cal_{reg}(\$)$	$\sum_i Cal_i(\$)$	Xe-free ($)	$\rho_{Xe}(\$)$
0.00	1.47	1.32	1.22	1.86	5.88	5.78	0.10
0.33	2.09	1.84	1.68	2.72	8.33	8.23	0.10
1.33	2.07	1.83	1.67	2.66	8.24	8.23	0.01
2.33	2.08	1.83	1.67	2.69	8.26	8.23	0.03
3.33	2.09	1.83	1.68	2.71	8.31	8.23	0.08
4.33	2.10	1.85	1.69	2.75	8.39	8.23	0.16
5.33	2.12	1.87	1.71	2.76	8.46	8.23	0.23
6.33	2.14	1.88	1.72	2.79	8.53	8.23	0.30
7.33	2.15	1.90	1.73	2.83	8.61	8.23	0.38
8.32	2.16	1.91	1.75	2.85	8.66	8.23	0.43
23.65	1.70	1.50	1.37	2.14	6.70	5.78	0.93
24.88	1.69	1.51	1.38	2.08	6.66	5.78	0.88
25.33	1.68	1.49	1.36	2.08	6.62	5.78	0.84
26.80	1.66	1.49	1.35	2.08	6.58	5.78	0.81
27.40	1.66	1.48	1.35	2.06	6.55	5.78	0.78
27.77	1.66	1.48	1.34	2.09	6.55	5.78	0.78
28.05	1.64	1.48	1.35	2.08	6.54	5.78	0.76
28.30	1.64	1.48	1.34	2.07	6.53	5.78	0.75
28.53	2.23	1.98	1.81	2.96	8.98	8.23	0.75
28.78	2.20	1.96	1.79	2.92	8.87	8.23	0.64
29.03	2.19	1.95	1.78	2.91	8.82	8.23	0.60
29.28	2.19	1.95	1.78	2.89	8.80	8.23	0.57
29.53	2.19	1.94	1.77	2.88	8.78	8.23	0.55
30.03	2.18	1.94	1.77	2.87	8.76	8.23	0.53
30.53	2.18	1.93	1.76	2.86	8.73	8.23	0.50
31.03	2.18	1.93	1.76	2.86	8.72	8.23	0.49
31.52	2.18	1.93	1.76	2.86	8.72	8.23	0.49

Table A.2: Data - Period, differeital and integral reactivity worth

[1] T. DEBEY, *USGS reactor lab: Xenon poisoning*.
Handouts.
Accessed: 2016-10-05.