Xenon pit duration in a pressurized water reactor

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1 Definitions

- **Burnup**: The process where a nucleus captures a neutron and transmutates into another isotope.
- **Decay constant**: Probability of a nucleus to decay in an interval of 1 second.
- **Effective multiplication factor**: Ratio of neutrons produced by fission in one generation over the number of neutrons lost from the preceding neutron generation.
- **Macroscopic fission cross-section**: Probability of a neutron-nucleus interaction per centimeter of neutron travel.
- **Neutron capture cross-section**: Fictive area around an atom that represents the likelihood of an incident neutron to react with the nucleus.
- **Reactivity**: ρ: Deviation of an effective multiplication factor from unity.
- **Reactor trip**: Rapid emergency shutdown of the nuclear reactor. It corresponds to a rapid insertion of the control rods into the reactor to stop the fission chain reaction.
- **Xenon pit**: Time duration over which the negative reactivity due to Xenon is greater than the excess reactivity that reactor operators have.

2 Units

- barns: $1[\text{b}] = 10^{-28}[\text{m}^2]$
- milli-k: $1[\text{mk}] = 10^{-3}$
- per cent mille: $1[\text{pcm}] = \rho \cdot 10^{-5}$

3 Deviations from project proposal

In terms of questions to be answered, we couldn't give clear answers to "How long does the reactor has to wait before Xenon effects are no longer a threat to operation?" as we'll see that it heavily depends on parameters we couldn't find. Also we couldn't quantify gains of overriding the peak concentrations for the same reason.

The scenario where power was reduced was also modified. Due to a missinterpretation initially, it was decided to compute the reduction from different neutron flux values to 0 instead of starting from the nominal neutron flux and lowering to those different values. For example, computing a reduction from 50% to 0% instead of going from 100% to 50%. This was necessary as this is what the references for comparing our results did.

The recovery from a reactor trip was also very vague in the project proposal and a more precise scenario was developped for it.

The schedule in the project proposal started too early and correction of the project proposal wasn't submitted yet. The project hadn't officially started so we started 1 week later than anticipated. Computing the scenarios was done at the end instead of before upgrading the solver to Runge-Kutta, instead smaller tests were made. Delay from schedule was caught up in week 13 where it was designed for. In the last two weeks, "if time permits" scenarios were computed in parallel of reviewing the code and writing the report.

Overall the project went as described in the project proposal.

4 Introduction to the problem

26 April 1986, 1:23 AM, Chernobyl's unit 4 core exploded, creating the worst nuclear disaster that ever happenend. One of the key factors that led to this accident is the lack of knowledge on the effects of Xenon, a radio-isotope with a large capture cross-section, which captures neutrons more frequently than uranium and effectively slows down the chain reaction.

Xenon comes principally from the decay of Iodine-135, Tellurium-135 and as a byproduct of the fission of Uranium. It then either decays into Cesium-135 or gets burned-upby capturing a neutron and transmutating into Xenon-136. Both Cesium-135 and Xenon-136 have a much lower capture cross-section compared to Xenon-135 and thus have a negligible effect on reactor operations.

When the neutron flux (positively related to the reactor power) is drastically lowered, the Xenon concentration rises because it is less burned-up by the neutron flux. This can cause the reactor to stall as Xenon builds up and if the concentration of Xenon is too high, the reactor operators cannot override its effect.

And so, as Chernobyl's unit 4 raised their control rods trying to compensate for a high xenon concentration and preventing a stall, they quickly experienced it's burn-up and a rapid augmentation of the neutron flux. Coupled to other effects, the reactor got out of hands and exploded.

Nowadays, Xenon effects are taken seriously and must be accounted in the design of every reactor. It is important to ensure a high enough reactivity margin (available control over the chain reaction) after each power reduction, and eventually shutdown the reactor for a long enough period of time if Xenon effects are too important.

For example, this is very important for reactor and grid operators to know when the plant will be back up after an outage. Or for planning a slow enough power reduction. Or even try to shorten the Xenon pit duration (timespan over which we observe a too high concentration) to restart sooner after a short maintenance.

Definition of project scope

Processes to include

Our objective will be to assess how the xenon concentration affects the reactor kinetics and operability. For this, we will try to stick to a pressurized water reactor (PWR) as it's a common type of reactor in Europe.

The basic process of Xenon production can be modelled as follows.

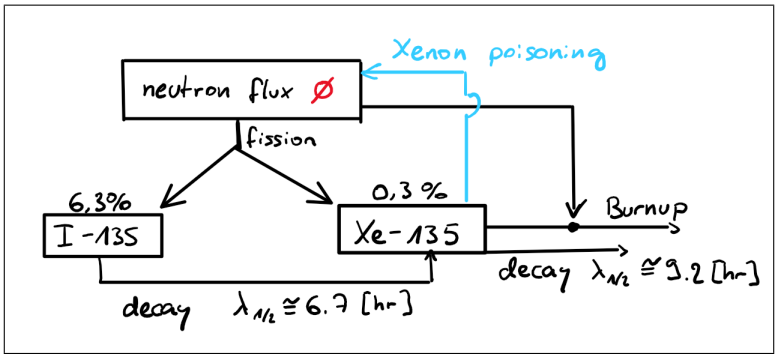


Figure 1: Schematic representation of the Xenon system

Where Iodine-135 and Xenon-135 are considered coming directly from the fission reactions inside the reactor core. Iodine-135 decays into Xenon-135 with an halflife of about 6.7 hours. The xenon concentration is affecting the reactor kinetics by lowering the multiplication factor between consecutive neutron populations. Xenon then either decays with an halflife of 9.2 hours or is burned up.

Processes to exclude

With this modelling, we exclude some processes by making the reasonable assumption that they only play a minor role.

- **Effect of the other reactor poisons**
  - Samarium 149
    It can be considered a stable isotope, that will not decay. Due to its much lower capture cross-section [2]. Its effect is therefor constant and can be ignored.
  - Other accumulating fission products
    We will also neglect them as their effect is more long-term related [2].
- **Spatial variations**
  We consider a point reactor (no dimension) to make the computations easier and avoid the complexity of finite elements methods.
- **Decay of Tellurium-135**
  Iodine-135 comes from this fission product who's halftime is of 19 seconds. As our time resolution will be much larger (hours), we will assume that the production of Tellurium immediately results in Iodine [2]. This is counted in the rate of production of Iodine-135.
- **Burnup of Iodine-135 by the reactor**
  It can be neglected due to its small microscopic absorption section [2].
- **Changes in neutron flux**
  We assume ϕ is perfectly controled and remains constant at the desired values by, for example, adjusting the control rods' position or the boric acid concentration.

Scenarios considered

The first scenario to consider will be a reactor trip from different values of the neutron flux. The reactor will start from different power levels: $\{100\%; 80\%; 60\%; 40\%; 20\%\}$ with Iodine and Xenon concentrations at equilibrium. Then, after one hour, the neutron flux will immediately fall to 0. The timestep for integration will be $600[s]$ in the first segment and then $1[h]$. The total duration of the scenario is 70 hours.

Secondly, we will simulate the increase of power to different values. Again, we start from equilibrium concentrations at $\phi = 0$ and the neutron flux is instantaneously increased to different power levels after 1 hour: $\{25\%; 50\%; 75\%; 100\%\}$. Timesteps are again $600[s]$ and $1[h]$ respectively and the duration is 70 hours.

Finally, we will look at a poison override scenario. We try to shorten the duration of the Xenon pit of a power drop from 100% to 0%. To do that we start by a 1 hour segment at equilibrium concentrations for a power level of 100% and a timestep of $600[s]$. Then the power is set to 0% for 4 hours with the same timestep. A spike of neutron flux of a duration of 45 minutes and intensity of 100% is then introduced. The timestep during this spike if of 1 minute. Finally, the neutron flux is set to 0% at 5 hours and 45 minutes into the scenario up until 70 hours.

5 Approach used

The evolution of the Xenon and Iodine concentration can be modelled with the Bateman equation, which is a mathematical model describing the evolution of radioactive quantities in decay chains [4].

$$\frac{d}{dt}I = \gamma_I \cdot \Sigma_f \cdot \phi - \lambda_I \cdot I \tag{1}$$

$$\frac{d}{dt}X = \gamma_{Xe} \cdot \Sigma_f \cdot \phi + \lambda_I \cdot I - \lambda_{Xe} \cdot X - \sigma_{aX} \cdot X \cdot \phi \tag{2}$$

With:

- X: Concentration of Xenon-135 $[\frac{\text{n}}{\text{cm}^3}]$
- I: Concentration of Iodine-135 $[\frac{\text{n}}{\text{cm}^3}]$
- γ_I: Fission product yield of I-135 $[-]$
- γ_{Xe}: Fission product yield of Xe-135 $[-]$
- λ_I: Decay constant for I-135 $[\text{s}^{-1}]$
- λ_{Xe}: Decay constant for Xe-135 $[\text{s}^{-1}]$
- Σ_f: Macroscopic fission cross-section $[\text{cm}^2]$
- σ_{aX}: Microscopic absorption cross-section of Xe-135 $[\text{cm}^2]$
- ϕ: Neutron flux: $[\text{n}/cm^3 \cdot s]$

This is a deterministic, implicit modelling whose scope is to predict the concentration of both Xenon and Iodine. It is based on the conservation of mass. The difference of concentration is the difference between source terms and sink terms.

The approch chosen to solve this set of equation is the fourth-order Runge-Kutta iterative integration method. Given an initial value problem of the form $y'(t) = f(y(t), t)$ with $y(t_0) = y_0$, the algorithm for each iteration of time step h is as follows [3].

Algorithm 1 Fourth-order Runge-Kutta

1: $k_1 = f(y(t_0), t_0)$
2: $y_1 = y(t_0) + \frac{h}{2}k_1$
3: $k_2 = f(y_1, t_0 + \frac{h}{2})$
4: $y_2 = y(t_0) + \frac{h}{2}k_2$
5: $k_3 = f(y_2, t_0 + \frac{h}{2})$
6: $k_4 = f(y_3, t_0 + h)$
7: $y(t_0 + h) = y(t_0) + \frac{h}{6}(k_1 + 2k_2 + 2k_3 + k_4)$

This approach is quite similar to previous papers on the subject [4], so that we will be able to compare our results with those papers. More reliable studies take into account spatial variations inside the reactor core [9], consider other effects on the reactivity like the boron concentration, and use stochastic Monte-Carlo simulations on neutrons interactions to predict the reactor's behavior [5].

The effect of the Xenon-135 in terms of reactivity is then computed as follows [4]:

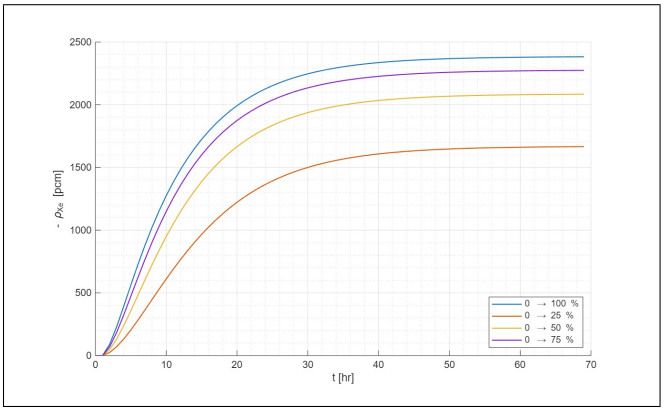
$$-\rho_{Xe} = \frac{\sigma_{\text{aX}} X}{\nu \Sigma_f} \tag{3}$$

Where ν is the average number of neutrons released per fission.

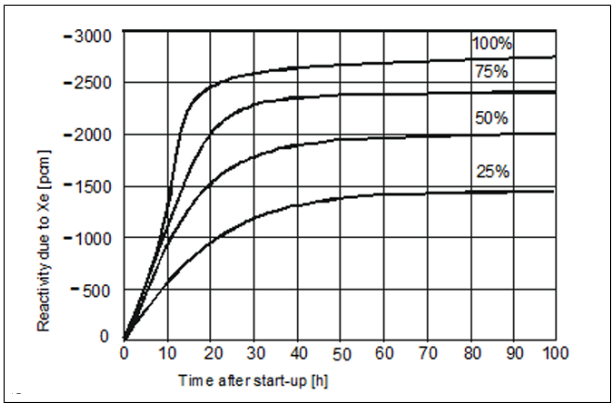
Lastly, we used the data provided in [4] to simulate the different scenarios but had to modify the neutron flux. In the later paper, a neutron flux of $4.42 \cdot 10^{20}$ was used but caused unphysical results in our computations, where the concentration quickly died or exploded. The code was reviewed thouroughly but the issue came from the neutron flux value to be too high as other books and papers suggest [2] (p. 7), [6] (p.31). Thus a value $\phi = 4.42 \cdot 10^{13}$ was used.

6 Results

First of all, in scenarios where the neutron flux was raised from shutdown conditions, we observe that the reactivity effects and thus the concentration of Xenon-135 comes to an equilibrium after 40 to 50 hours following the neutron flux rise. This is coherent with what is found in some course material of the International Atomic Energy Agency [1], which was based on different parameters we didn't have access to, where we also observe an equilibrium after 40 to 50 hours since startup. The order of magnitude of reactivity is also similar between both simulations. As a whole, this indicates that our results are sound.



(a) Simulated Xe-135 reactivity after a power rise.

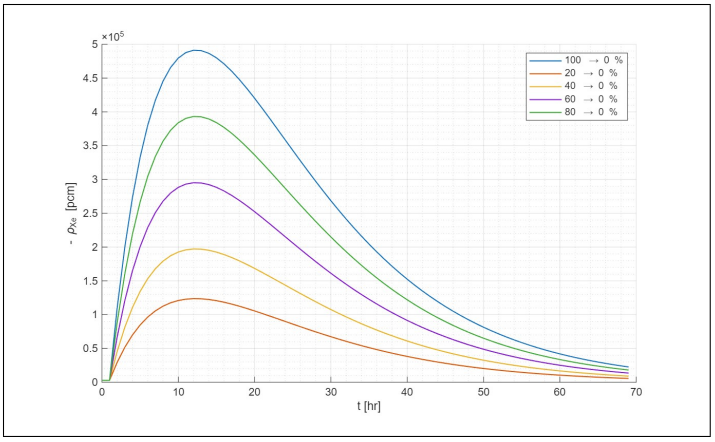


(b) Xenon reactivity effect versus time after startup for different reactor power levels [1].

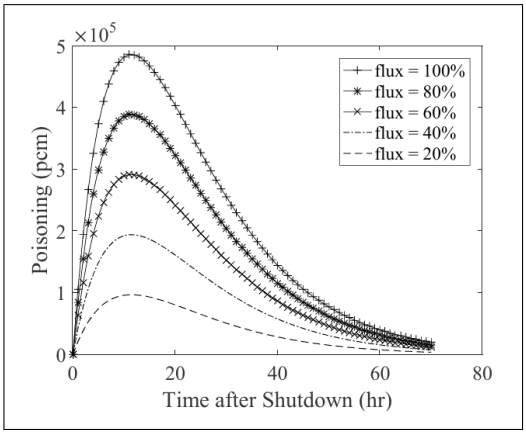
Figure 2: Xenon reactivity comparison

Secondly, in scenarios where the neutron flux was suddenly dropped, we observe that peak reactivity is greater when the power drop is bigger. The equilibrium reactivity due to Xenon when the neutron flux is completely stopped approaches zero, which matches our expectations as there is no more xenon to affect the reactor in such a case.

When comparing results with [4], with a neutron flux $\phi = 4.42 \cdot 10^{15}$ instead of $4.42 \cdot 10^{20}$, we observe practically identical curves. However we should be very sceptical of these results as those high flux values are unrealistic as previously stated, such data causes numerical instabilities in other scenarios and the modelling doesn't give feasible results as we chose unfeasible inputs. We considered it to be an unreliable source of comparison.



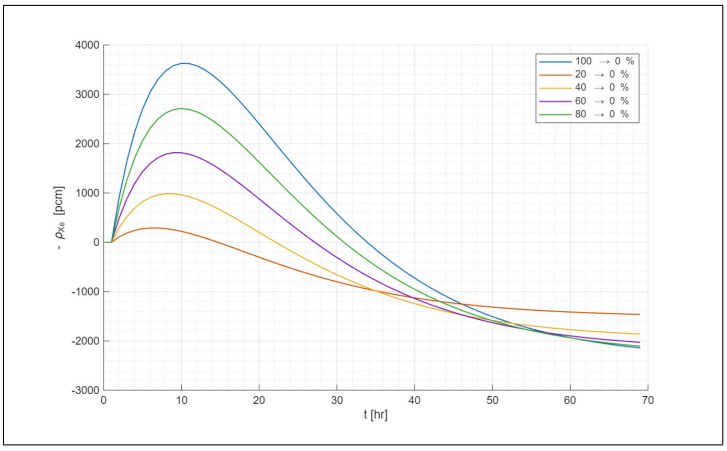
(a) Simulated Xe-135 reactivity after a power drop.



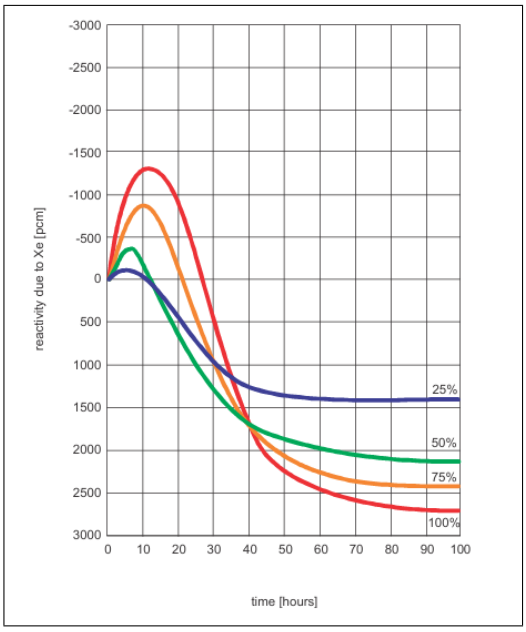
(b) Reference reactivity values after a power drop [4].

Figure 3: Xenon reactivity comparison

When comparing with [6] with the more realistic value $\phi = 4.42 \cdot 10^{13}$, we observe similar trends where the reactivity effect of a drop from 100% of the neutron flux to 0% has a higher peak initially but falls below other scenarios later. Peak values from our computations are higher but this heavily depends on the reactor parameters. Overall this indicates that our method gives sound results. The dynamics correspond well with the litterature, however the lack of precise data for benchmarking prevents us from doing error analysis and we cannot know for sure if our results are accurate enough, and so we can't benefit from larger timesteps in the RK4 integration if we're not sure it will converge.



(a) Simulated Xe-135 reactivity after a power drop.



(b) Reference reactivity values after a power drop [6].

Figure 4: Xenon reactivity comparison, initial reactivity taken as origin

As we don't know what reactivity margin our fictive reactor has, we cannot say precisely for how long the Xenon peak concentration is a threat to operation. But we have orders of magnitude to have an idea. For example, if the reactivity margin was of 1'000 [pcm], the xenon concentration woulnd't be a threat when reducing the power from 40% of less. With higher values of neutron flux, the Xenon pit duration could go up to 29 hours, during which the reactor couldn't be restarted as not enough positive reactivity could be introduced.

Lastly, we tried lowering the peak Xenon concentration in a similar way as [8] and see that our model can predict mitigation scenarios. However we lack information about the reactivity margin of our reactor to quantify the benefits of such manoeuvres.

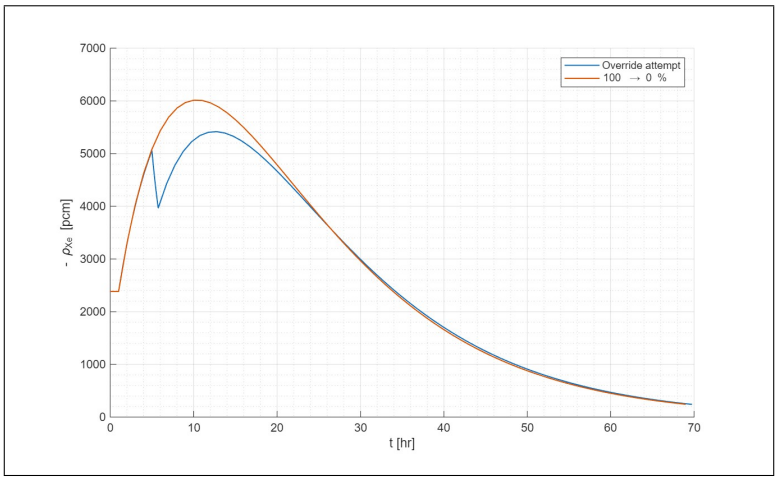


Figure 5: Override of the Xenon peak concentration.

7 Conclusion and outlook

The main objective was to assess how Xenon poisoning affects reactor operability after power reductions and to estimate the time interval during which negative reactivity due to Xenon prevents a reactor restart.

The approach taken was to model the Xenon-Iodine system using a simplified point-reactor representation whose dynamics followed the Bateman equation. Then the results were computed using a fourth-order Runge-Kutta scheme. The impact of Xenon-135 on reactor kinetics was finally quantified in terms of reactivity.

We saw that our computations reproduced the trends seen in the litterature but that the duration of the xenon pit couldn't be quantified exactly as we lacked data on the excess reactivity. Finding such data of real PWR reactors and their operative guideline would allow us to compare if our results would be good enough for proposing real procedures.

However this project is subjected to several limitations. The model relies on a point-reactor approximation and neglects spatial variations within the core. Also, we assumed that the neutron flux was constant, which ignores feedback effects from the Xenon but also from temperature for example. The macroscopic fission cross-section of the core was taken as constant but in reality it depends on the concentration of every isotopes that are in the reactor, which changes constantly. Further modelling of the reactor dynamics with a point-kinetic equation could allow to make better neutron flux time series when power is raised for example. This would make more realistic scenarios. And larger datasets could be used such as [7] to update the reactor parameters at each iteration.

In conclusion, we saw that a relatively simple model can capture the essential physics of Xenon poisoning and provide a solid foundation for more advanced modelling. Although not advanced enough for real operations, it could serve as an educational tool or a first level of approximation that doesn't require the computational time of spatial models.

8 References

References

[1] *5.XENON POISONING*. https://nucleus.iaea.org/sites/connect/RRIHpublic/CompendiumDB/Shared%20Documents/Slovenia/Protocols%20in%20PDF/Slovenia_5%20Xe%20Poisoning.pdf. (Visited on 12/13/2025).

[2] *Chapter 3: Elementary Physics of Reactor Control, Module D: Fission Product Poisoning*. https://www.nuceng.ca/ep6p3/class/Module3D_XenonJun21.pdf. 2021. (Visited on 12/10/2025).

[3] Erik Cheever. *Fourth Order Runge-Kutta*. https://lpsa.swarthmore.edu/NumInt/NumIntFourth.html. (Visited on 12/11/2025).

[4] Zechuan Ding. "Solving Bateman Equation for Xenon Transient Analysis Using Numerical Methods". In: *MATEC Web of Conferences* 186 (2018). Ed. by H. Akca, R. Luca Tudorache, and L. Abdullah, p. 01004. ISSN: 2261-236X. DOI: 10.1051/matecconf/201818601004. (Visited on 12/01/2025).

[5] Khalefih Husam and Kim Yonghee. "A Study on Xenon Estimation During Load-Follow Operation Using Sliding Mode Observer in APR1400 for A Predictive Soluble Boron Control". In: *Arabian Journal for Science and Engineering* (2024). (Visited on 12/13/2025).

[6] *Module I, Nuclear Physics and Reactor Theory*. 2015. (Visited on 12/13/2025).

[7] A. Nichols, E. McCutchan, and P. Dimitriou. *INDC International Nuclear Data Committee*. Tech. rep. BNL–114827-2017-IR, 1413963. Dec. 2017, BNL–114827-2017-IR, 1413963. DOI: 10.2172/1413963. (Visited on 12/01/2025).

[8] Zoltan Rezso Rosztoczy. *OPTIMIZATION STUDIES IN NUCLEAR ENGINEERING*. 1964. (Visited on 12/10/2025).

[9] Sicheng Wang et al. "Verifications and Applications of NECP-Bamboo2.0 for PWR Whole-Core Multi-Cycle Pin-by-Pin Simulation". In: *Progress in Nuclear Energy* 177 (Dec. 2024), p. 105447. ISSN: 01491970. DOI: 10.1016/j.pnucene.2024.105447. (Visited on 12/01/2025).