

XENON-POISONING UNDER NON-STATIONARY OPERATING CONDITIONS IN WWER-440 REACTOR

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Summary

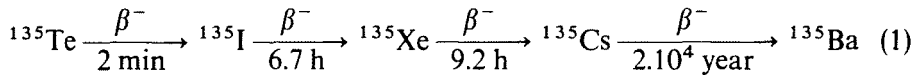
Nuclear power plants operating usually at base load at present shall accommodate themselves to variable loads within the energy system in the future. Thus e.g. nuclear power plants shall reduce their power at nights and during week ends. Under non-stationary operating conditions, we have to face special problems in operating due to xenon poisoning. This work analyzes the ways of remedy to such problems.

Nuclear power plants and among them those equipped with pressurized water reactor (PWR) are operated mainly at base load. However, this situation is expected to change later as the ratio of nuclear power plants within the energy system increases. Quite likely, nuclear power plants shall have a share in compliance with the schedule, e.g. they shall operate at reduced load at nights and during week ends. Even now some nuclear power plants are operated at variable load. Under such non-stationary operating conditions, we have to face special problems in operation due to poisoning.

Among reactor poisons, ^{135}Xe is predominating because it occurs rather frequently and also its neutron capture cross section is very large. In respect of operation, a contribution to the importance of this isotope is the fact that about 95% of ^{135}Xe are produced indirectly, as a so called secondary fission product, as a result of radioactive decay of ^{135}I . Therefore, the behaviour of xenon poisoning is very special under non-stationary operating conditions and also in case of steady load under certain conditions. In this work, a reactor is assumed to which a point model is a good approach, and the so called xenon instability resulting from space dependence need not be taken into account. Thus the results reported apply only below a certain power density and reactor size even at a rough estimate. Energetic reactors of type WWER-440 fall more or less still within this category.

Upon ^{235}U fission, ^{135}Xe is produced as primary fission product having a yield of about 0.3% and within the radioactive decay series

shown below (where ^{135}Te — the primary fission product) having a yield of about 6.1%:



Assuming that the fuel contains only one type of fission isotope ^{235}U , on the basis of the point model, the change in time of the concentration of ^{135}Xe nuclei can be described by means of the following differential equation system:

$$\frac{dI}{dt} = y_{1,25} \cdot N_{25} \cdot \sigma_{f,25} \cdot \Phi - \lambda_1 \cdot I \quad (2)$$

$$\frac{dX}{dt} = y_{\text{Xe},25} \cdot N_{25} \cdot \sigma_{f,25} \cdot \Phi + \lambda_1 \cdot I - X \cdot \sigma_{a,\text{Xe}} \cdot \Phi - \lambda_{\text{Xe}} \cdot X \quad (3)$$

where

- I — number of ^{135}I nuclides
- X — number of ^{135}Xe nuclides
- N_{25} — number of ^{235}U nuclides
- $y_{1,25}$ — yield of ^{135}I in case of fission of ^{235}U nuclei
- $y_{\text{Xe},25}$ — ^{135}Xe produced directly in case of fission of ^{235}U nuclei
- $\sigma_{f,25}$ — microscopic fission cross section of ^{235}U isotope for thermal neutrons
- Φ — thermal neutron flux
- λ_1 — decay constant of ^{135}I
- λ_{Xe} — decay constant of ^{135}Xe
- $\sigma_{a,\text{Xe}}$ — microscopic absorption cross section of ^{135}Xe isotope for thermal neutrons.

There is a direct relationship between the thermal neutron flux and the reactor power:

$$\Phi \cong K \cdot P \quad (4)$$

where K is a constant with good approximation, under conditions otherwise unchanged (constant temperature, constant fuel composition etc.). Taking this into consideration, the reactor power can be written in place of the neutron flux in differential equations (2) and (3):

$$\frac{dI}{dt} = y_{1,25} \cdot N_{25} \cdot \sigma_{f,25} \cdot K \cdot P - \lambda_1 \cdot I \quad (2a)$$

$$\begin{aligned} \frac{dX}{dt} = & y_{\text{Xe},25} \cdot N_{25} \cdot \sigma_{f,25} \cdot K \cdot P + \lambda_1 \cdot I - \\ & - X \cdot \sigma_{a,\text{Xe}} \cdot K \cdot P - \lambda_{\text{Xe}} \cdot X \end{aligned} \quad (3a)$$

Calculations were made for different non-stationary operating conditions, using the rather simple differential equations given above.

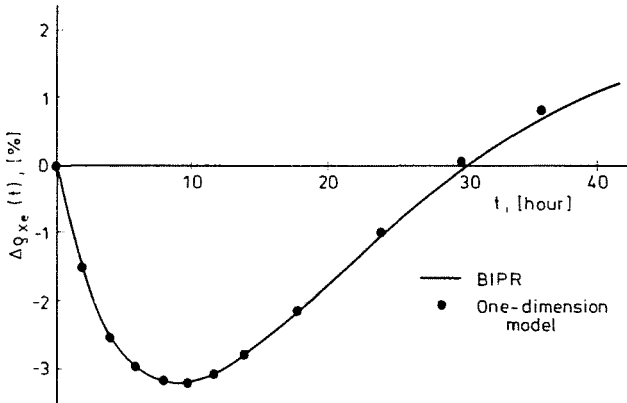


Fig. 1. Change of Xe-poisoning as a function of change in reactor power from 100% to zero % ($t_{\text{eff}} = 160$ days)

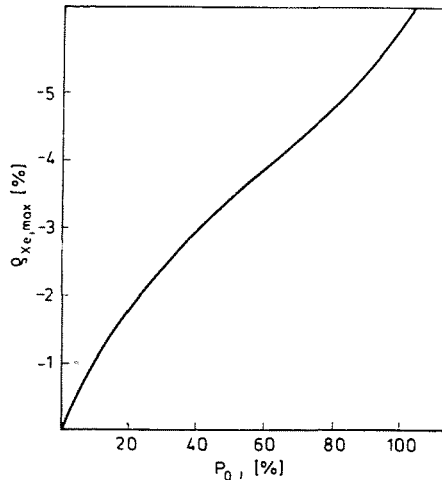


Fig. 2. Maximum poisoning after instantaneous shut-down of the reactor of different power levels (P_0) ($t_{\text{eff}} = 160$ days)

Testing the model calculations were made first in cases where results obtained by the computer program BIPR evaluated by the Soviet supplier were available.

The results obtained for identical conditions showed a fairly good agreement. This is illustrated in Fig. 1 showing the change of xenon poisoning in time after instantaneous shut-down of the WWER-440 reactor from nominal power.

As it is well known, maximum poisoning after shut-down highly depends on the reactor power before shut-down. This is shown in Fig. 2 for the WWER-

440 reactor. In the Figure, the overall xenon poisoning after shut-down is illustrated at the moment of maximum poisoning as a function of reactor power before shut-down.

It can be seen on the basis of Figs 1 and 2 that the change of reactor power and also shut-down result in special problems in reactor operation due to xenon poisoning. These problems may be especially severe at the end of the burn-up cycle — when the so called operative excess reactivity of the reactor is very small, sometimes almost zero. In such cases, the excess reactivity may become negative for certain time due to maximum poisoning after shut-down so that during this period the reactor cannot be started again. That means that the manoeuvrability of the reactor and/or of the nuclear power plant reduces considerably as a result of the behaviour of xenon poisoning described above. This fact cannot be left out of consideration when considering, or planning for, the operation of the nuclear power plant as a component of the energy system.

Let us now briefly analyze how can this unfavourable effect of xenon poisoning on the manoeuvrability be reduced. Since the problems arise most strikingly when the reactor is shut down, the investigations are concentrated on this event.

If the operative excess reactivity of the reactor is sufficiently large, then the reactor can be started again at any time as far as xenon poisoning is concerned. In this case, xenon poisoning will change as a function of time in the way shown in Fig. 3. It can be seen in the Figure that xenon poisoning reduces rapidly after the reactor has been started again and/or the excess reactivity release is considerable within a rather short time. This fact shall be taken into consideration in planning the control system and programming its operation in order to ensure safe, reliable operation.

Since maximum poisoning is the most severe problem after shut-down, a remedy to the problem is to reduce the maximum poisoning. The following ways to reduce poisoning have been investigated:

- Shut-down by reduction of the reactor power at a slow rate instead of instantaneous shut-down.
- Starting of the reactor for a certain time shortly after shut-down, followed by final shut-down.
- Utilization of the temperature coefficient of reactivity.
- A combination of the above methods.

In case of shut-down at a slow rate, a linear reduction of power has been assumed. The results obtained for three different cases are illustrated in Fig. 4. It can be seen in the Figure that the magnitude of maximum poisoning reduces only slightly (by 0 to 5%) but there is a considerable shift in the time at which maximum poisoning occurs, the extent of this shift corresponding to about 60% of the shut-down period. Because of what has been said above, this method is of little importance in respect of an overall solution to the problem.

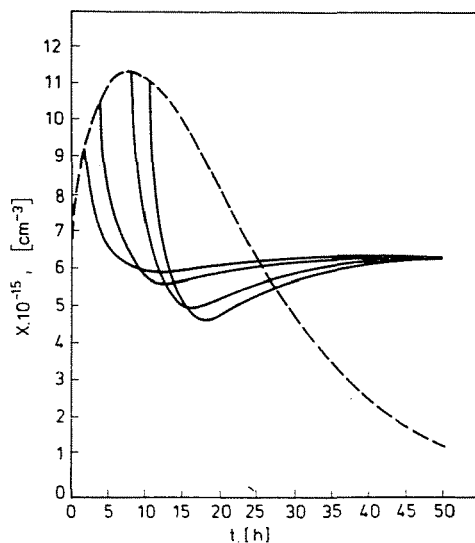


Fig. 3. Concentration of Xe-nuclei after start-up subsequent to shut-down. Rapid shut-down at 100% load, then rapid increase of the reactor power to 100% after a time of $t = 2, 4, 8, 10$ hours

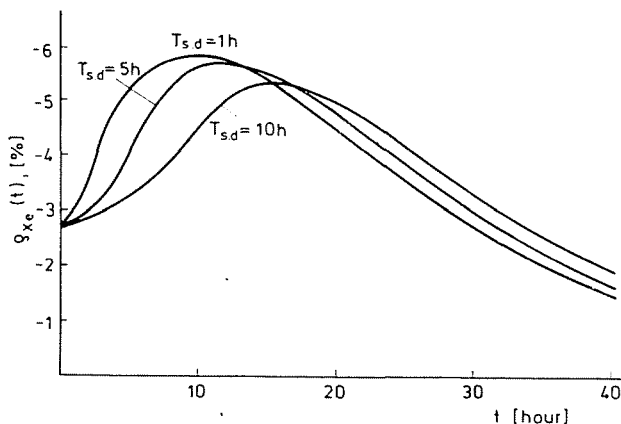


Fig. 4. Xe-poisoning after a shut-down by reducing the power linearly from 100% to zero (time of shut-down procedure: 1.5 or 10 hours)

The effect of temporary re-start-up after shut-down on xenon poisoning can be derived on the basis of Fig. 3. Here the following question had to be answered: how should the flux and/or power be changed so that the specified xenon poisoning curve might be achieved. An optimization programme has been elaborated for this purpose, offering solution to two different problems: (1) minimization of maximum xenon poisoning after shut-down, and (2) minimization of xenon poisoning at given time. Assuming a WWER-440

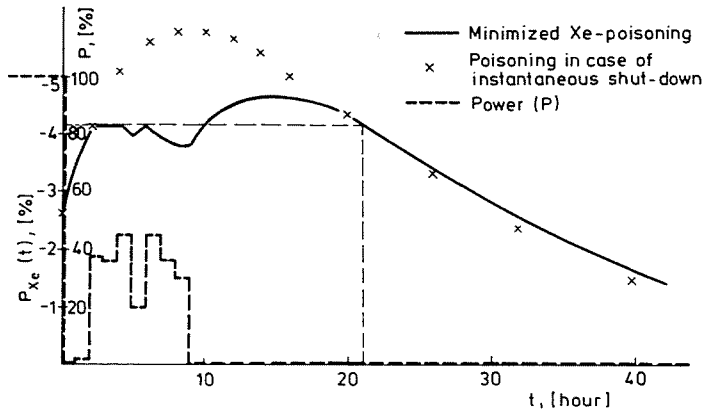


Fig. 5. Minimizing of Xe-poisoning by a 9-hour shut-down procedure ($t_{\text{eff}} = 160$ days)

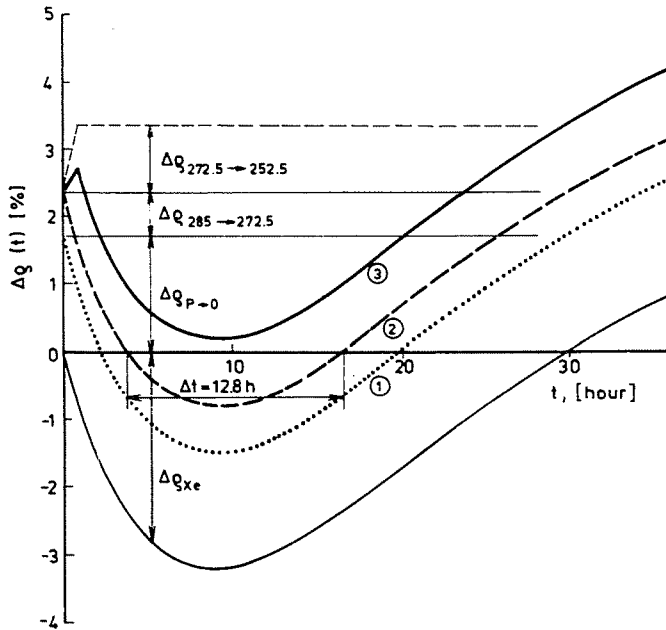


Fig. 6. Behaviour of excess reactivity after shut-down (in case of a boric acid concentration of $c = 0$): ① Xe-poisoning and power coefficient taken into consideration in association; ② Taking into consideration Xe-poisoning, power factor, and an average reduction in cooling water temperature of $\Delta t_{H_2O} = 285 - 272.5 = 12.5$ °C; ③ Taking into consideration Xe-poisoning, power coefficient and an average reduction in cooling water temperature of $\Delta t_{H_2O} = 285 - 252.5 = 32.5$ °C

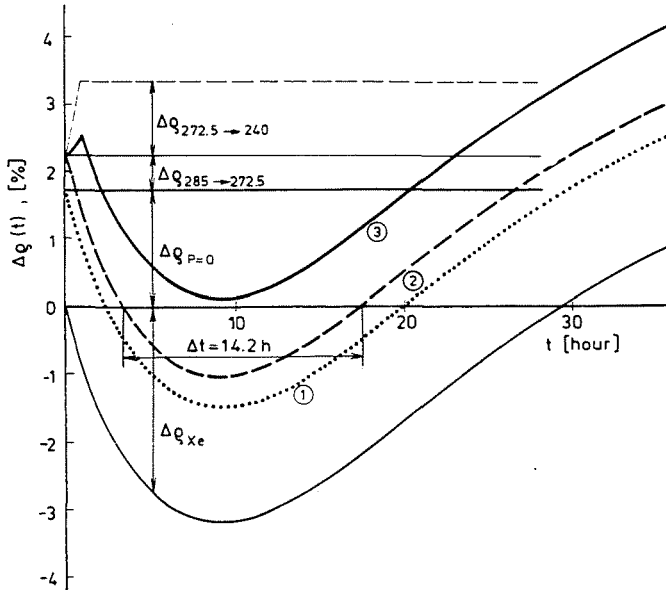


Fig. 7. Behaviour of excess reactivity after shut-down (in case of a boric acid concentration of $c = 2.86$ g/kg): ① Same as in Fig. 6 ①; ② Same as in Fig. 6 ②; ③ Taking into consideration Xe-poisoning, power coefficient and an average reduction in cooling water temperature of $\Delta t_{H_2O} = 285 - 240 = 45$ °C

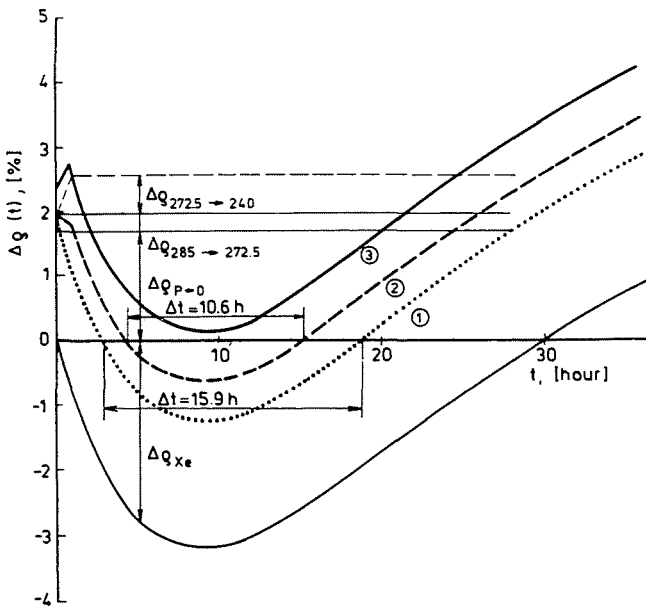


Fig. 8. Behaviour of excess reactivity after shut-down (in case of a boric acid concentration of $c = 5.72$ g/kg): ① Same as in Fig. 6 ①; ② Same as in Fig. 6 ②; ③ Same as in Fig. 7 ③

reactor, the result obtained for this latter problem is shown in Fig. 5. It can be clearly seen in the Figure that although xenon poisoning can be significantly reduced in this way, the manoeuvre takes a rather long time and thus also the shut-down procedure is prolonged. Therefore, the gain in time is little, if any. Of course, this method can be used only in case the factor necessitating reactor shut-down does not contraindicate at the same time a temporary re-start-up of the reactor. Apart from these restrictions, the fact that due to the reduced range of reactivity change, also the range in which boric acid concentration is changed, is smaller, is considered an advantage from an economical point of view.

Because of the negative temperature coefficient of reactivity, the problems resulting from the deficit in reactivity after shut-down may be mitigated by reducing the average cooling water temperature after shut-down. Since the temperature coefficient is a function of boric acid concentration, the resultant benefit depends on the boric acid concentration in the cooling water.

To illustrate what has been said, given in Figs 6, 7, and 8 are the results obtained for three different boric acid concentrations in case of the WWER-440 reactor. In the calculations, also the effect of the negative power coefficient has been taken into consideration. It can be seen on the basis of the Figures that the method improves the chances of re-start-up considerably. This is especially important at the end of the burn-up cycle where the temperature coefficient is highly negative due to the rather low boric acid concentration. Because of the small excess reactivity, manoeuvres like this are most needed in this period.

It seems also feasible to combine the different methods, e.g. to reduce the average temperature of cooling water while the reactor is shut down at a slow rate simultaneously. In many cases — especially towards the end of the burn-up cycle — such operating manoeuvres may be very efficient. Research into possible methods requires that investigations be continued. The authours' work is presented to show on the basis of rather simple models that we do have operating instruments to improve the manoeuvrability of nuclear power plants.

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