Analysis of APR1400 Restarting After Unplanned Shutdown: An Investigation on Xenon Oscillation and Boron Dilution Rate

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1. Introduction

Accidental scrams happen with a considerable frequency in Nuclear Power Plants. This kind of event represents a significant economic impact, and for this reason, all companies make a big effort in order to avoid them. However, besides minimizing the number of unscheduled reactor trips, it is worthwhile to prepare to manage these undesirable events. In nuclear industry, the safety must be in first place, regardless of circumstances, and reduction of the time of shutdown after an accidental scram is essential to decrease financial losses [1]. Despite having considerable amount of excess reactivity, Nuclear Power Plants (NPP) shows inherent post trip xenon behavior as a concern, and needs alternatives for minimizing its impacts. When the details of xenon oscillations are known, the reduction of shutdown-time become easier and a plan for start the reactor again tends to be prepared in more efficient way, raising the safety, and reducing costs.

2. Methods and Results

In this work, the APR1400 is used as a model, for this reason, simulations using its characteristics were performed by Master 3.0 code [2]. First, the normal operation of this NPP type was simulated, and then, scenarios with unplanned shutdowns followed by reactor restarting were tested. Regarding to these latter, the simulations were performed at different burnup stages, verifying many restarting times and rates of boron dilution. The results of normal operation cycle were compared with the cycles impacted with unplanned shutdowns in beginning and in end of cycle. After this comparison, the conclusions were formulated and then presented for future research.

2.1 Cycle Characteristics

The chosen cycle was a typical second cycle of the APR1400, where the biggest oscillations regarding to cycle length and pin peak factors are observed. The cycle length found after simulating this core was 17.61 GWD/MTU and the changes in Critical Boron Concentration (CBC) over the cycle are depicted in the Fig. 1. Based on this picture, it is possible to conclude that boron dilution is occurring under a rate of approximately 0.1 ppm/h. This value will be used as reference for the simulations in the next steps of this work. Another important information for this study is the maximum charging mass flow rate and the reactor coolant inventory mass, 11.47 kg/s and 204,505 kg, respectively [3].

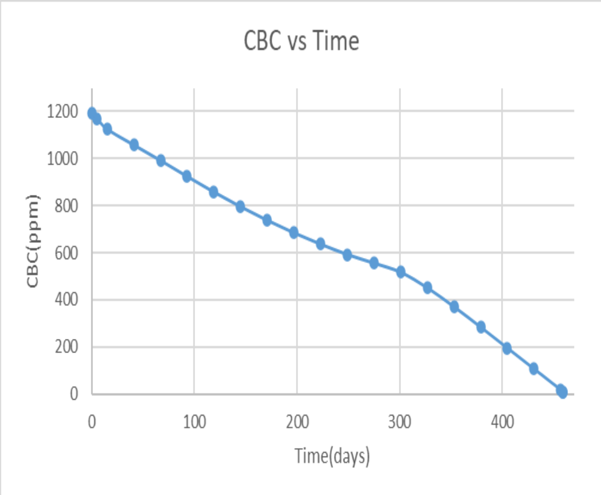

Fig. 1 Boron dilution during a typical second cycle

2.2 Restarting After Unplanned Shutdown at End of Cycle

The effect of xenon oscillations after an unplanned shutdown and subsequent restarting is more significant at the End of Cycle (EOC) than at Beginning of Cycle (BOC). This is because EOC has smaller excess reactivity than BOC [4]. Despite the xenon oscillations after a reactor trip, the APR1400 has enough negative reactivity worth of control rods to restart any time, even at EOC. Aiming to confirm this statement, many simulations of unplanned shutdowns were performed, when the CBC was only 50 ppm. Various shutdown-periods were tested, and, in all attempts, it was possible to make reactor critical and reach 100% power again, although some additional issues could be observed.

Despite reactor could restart at any time, in some simulations the reactor could not keep critical up to the end of cycle, as depicted in the Fig. 2. This picture shows the behavior of reactivity and the variation in xenon concentration, when an unplanned shutdown is simulated at time 0 and an attempt to restart the reactor happens 10.08 hours after, withdrawing all control rods and keeping a boron dilution rate constant at 0.1ppm/h. According to the graph, the reactor could be promptly restarted, however, observing the reactivity behavior during 5 days after scram, it turns out that reactor become subcritical for three times, where the biggest oscillation starts after 87.48 hours and finish after 111.02 hours, with the lowest reactivity observed of -0.00743 Δk/k or -743 pcm.

Regarding these oscillations, other simulations were performed using the same restarting time, but now with higher charging flow rates. In these simulations, it was possible to avoid the subcritical regions depicted in Fig. 2, without violating the maximum charging flow rate (11.47 kg/s). Although, the rates of boron dilution had a great variation and sometimes it was necessary to increase boron concentration in the primary coolant. These frequent changes in boron dilution rates and in the "boration" rates can cause an operational error and a new unplanned shutdown can occur. For this reason, instead of applying big variations in boration/dilution rates, this study searched the restarting times with its respective fixed boron dilution rates, which were able to avoid any subcritical region.

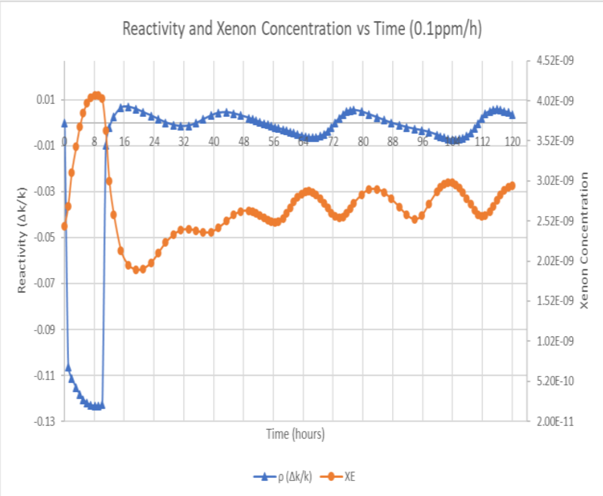

Fig. 2 Reactivity and Xenon behavior after reactor shutdown followed by restarting, using boron dilution rate of 0.1 ppm/h.

A search for the restarting time which could avoid subcritical condition was performed and the found time for a boron dilution rate of 0.1ppm/h was 69.6 hours. However, seeking to reduce this time, other simulations using higher boron dilution rates were carried out and results are depicted in Table I.

Table I: Boron dilution rate and its associated restarting time

Boron Dilution Rate (ppm/h)	Restarting Time (hours)
0.1	69.6
0.2	55.44
0.3	50.4
0.4	38.4

As expected, as long as the boron dilution rate increases, the restarting time decreases. Aiming to illustrate the reactivity behavior when reactor is restarted after proper time, the graph of reactivity versus time for a boron dilution rate of 0.2 ppm/h, it was plotted together with the curve of xenon variation, as depicted in the Fig. 3.

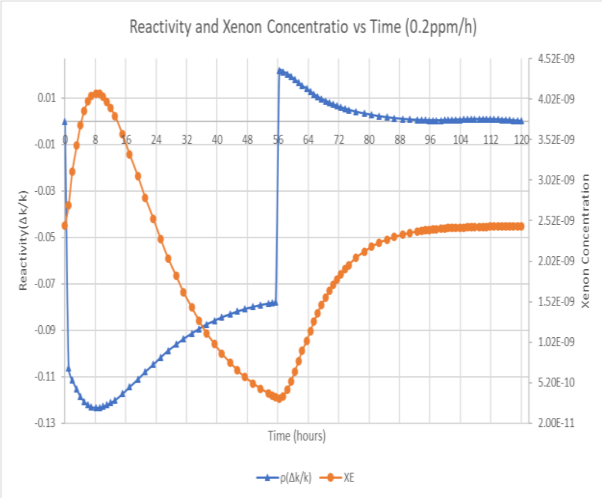

Fig. 3 Reactivity and Xenon behavior after reactor shutdown followed by restarting, using boron dilution rate of 0.2 ppm/h.

2.3 Restarting After Unplanned Shutdown at Beginning of Cycle

A similar procedure was applied to reactor at BOC when boron concentration was 950 ppm. A reactor trip was again simulated using MASTER 3.0. In the following, the first attempt of restarting was performed, again, 10.08 hours after reactor trip and utilizing a boron dilution rate of 0.1ppm/h. The obtained results showed that it is possible to restart APR1400 after this time, although, observing the reactivity behavior during 5 days after trip, it was noted that, as occurred at EOC, the reactor become subcritical during some moments of this analysis period. At BOC, however, the reactor stayed less time subcritical and the lowest reactivity observed was -22.8 pcm. Other Master simulations using a rate of 0.1 ppm/h were performed. The objective was searching for the reactor restarting time, where subcritical condition could be avoided, and the time found was 22.08 h. This interval is already short for a restarting time. Other simulations using the boron dilution rate of 0.2 ppm/h were also performed, and under this condition, it was verified that the reactor could be restarted and remained critical in the 5 days in following of an unplanned shutdown, not mattering the restarting time. The comparison between proper restarting times at BOC and EOC, according boron dilution rate, it is shown in Table II.

Table II: Restarting time according boron dilution rate and core age.

Boron Dilution Rate (ppm/h)	Restarting Time at BOC (hours)	Restarting Time at EOC (hours)
0.1	22.08	69.6
0.2	any time	55.44

3. Conclusions

The methodology presented in this work provided coherent results, such as, bigger restarting times at EOC and the decrease of restarting times as boron dilution rates raise. For this reason, this model is useful to improve the reactor restarting procedure and to find optimum boration/dilution rate for given restarting time after an unplanned shutdown, contributing for reducing costs and operational errors. In addition, this study can help the project of Chemical and Volume Control Systems of the Nuclear Power Plants, once that boron dilution rate is crucial in this kind of approach.

REFERENCES

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