Analysis of a Loss of Normal Feedwater ATWS with TRACE 5.0

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ABSTRACT

Among beyond design basis events, Anticipated Transient Without Scram sequences are one of the most important. Within these sequences the most limiting in PWRs are Loss of a Normal Feedwater and Turbine Trip. This type of sequence has to meet the acceptance criterion ASME level C (RCS pressure < 22.16MPa). The objective of this paper is to perform a power uprate analysis by means of the Integrated Safety Assessment methodology. The impact of several parameters in ATWS sequences has been analyzed, such as power uprate, moderator temperature coefficient and actuation times of ATWS mitigating system actuation circuitry, i.e. turbine trip and auxiliary feedwater injection.

Analysis results indicate that the power uprate is limited by ATWS sequences and also that it is possible to optimize the AMSAC actuation times.

1 INTRODUCTION

Anticipated Transient Without Scram (ATWS) events result from an anticipated transient, e.g., Loss of a Normal Feedwater (LONF), which requires the automatic shutdown of the plant via reactor trip and control rod insertion (CRI). However, during a postulated ATWS event, the reactor trip system is assumed to fail such that no CRI occurs. If there is insufficient negative reactivity feedback, the ATWS results in an unmitigated increase in reactor coolant pressure that leads to failure of the reactor coolant system (RCS) pressure boundary and subsequent core damage. Therefore, Pressurized Water Reactors (PWRs) ATWS mitigation capability is highly dependent on the moderator temperature coefficient (MTC). Part of ATWS mitigation is achieved with the ATWS mitigating system actuation circuitry (AMSAC) system, which automatically initiates the Auxiliary Feedwater (AFW) system and Turbine Trip (TT) under conditions indicative of ATWS as compensatory measures for higher unfavorable MTCs to prevent potentially excessive RCS over-pressure.

Through the years, there have been nuclear power plants performing power uprates. Power plant owners have worked power uprates to increase output from a little as 0.4% to as much as 20%. This requires higher enrichment fuel and often results in less negative MTC.
Two kinds of analysis are described in this paper: firstly, a sensitivity analysis with respect to MTC and power uprate is performed. Besides, a sensitivity analysis of AMSAC actuation times is also shown. This analysis is performed in order to optimize the actuation time for ATWS event. The aim is to obtain an improvement of TT and AFW injection actuation times through times Cartesian sampling. These ATWS analysis has been performed by means Almaraz NPP model with TRACEV5.0 patch 4 code, see [1].

2 ALMARAZ NPP TRACE MODEL

Almaraz NPP is a PWR Westinghouse located in Cáceres (Spain). The nominal power is 2947 MWt and 977 MWe. Almaraz Unit 1 TRACE model has 255 thermal hydraulic components including 2 VESSELs, 73 PIPEs, 43 TEEs, 54 VALVEs, 3 PUMPs, 12 FILLs, 33 BREAKs, 32 HEAT STRUCTUREs and 3 POWERs components, 760 SIGNAL VARIABLES, 1657 CONTROL BLOCKS and 66 TRIPS, Figure 2. Furthermore, this model has been validated with steady state and transient conditions and verified against an extensive set of transients; see [2], [3], [4].
- Last Almaraz NPP power uprate has increased thermal power of both units to 2947 MWt, an increase of nearly 10% from the initial plant capacity. Thus, Almaraz NPP model has been adequate to power uprate. Several systems and setpoints have been modified: reactor protection system, control rod system, PZR control system, steam dump control system and feedwater control system.

- The turbine control has been modified.

The values of main parameters after changes on the model show in Table 1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Almaraz NPP (100%)</th>
<th>Almaraz NPP Model T5P2 (100%)</th>
<th>Almaraz NPP (109%)</th>
<th>Almaraz NPP Model T5P4 (109%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core power (MWth)</td>
<td>2686</td>
<td>2686</td>
<td>2947</td>
<td>2947</td>
</tr>
<tr>
<td>Pressurizer pressure (bar)</td>
<td>155.04</td>
<td>155.04</td>
<td>155.4</td>
<td>155.1</td>
</tr>
<tr>
<td>Pressurizer level (%)</td>
<td>56.3</td>
<td>55.6</td>
<td>57.2</td>
<td>57.2</td>
</tr>
<tr>
<td>Primary coolant flow rate (%)</td>
<td>100%</td>
<td>4763.2 kg/s</td>
<td>4531.4 kg/s*</td>
<td>4596 kg/s</td>
</tr>
<tr>
<td>Average primary coolant temperature (K)</td>
<td>581.6</td>
<td>579.6</td>
<td>581.6</td>
<td>581.1</td>
</tr>
<tr>
<td>Steam Generator pressure (bar)</td>
<td>67.9</td>
<td>67.96</td>
<td>67.7</td>
<td>67.7</td>
</tr>
<tr>
<td>Main feedwater flow rate (kg/s)</td>
<td>491.7</td>
<td>492.8</td>
<td>550.2</td>
<td>545.9</td>
</tr>
</tbody>
</table>

*Value of Almaraz plant analyzer.

Although the model corresponds to Almaraz NPP, the ATWS sensitivity analysis is generic base on a 3-loop PWR Westinghouse-design.

3 LONF ATWS BASE CASE

A LONF ATWS base case has been analyzed at 100% of nominal power, according to common hypothesis of previous studies, see [5], [6], [7]. The following assumptions are performed in this simulation:

- No credit for automatic reactor trip
- No credit for automatic control rod insertion as reactor coolant temperature increases.
- The MTC is -15.2 pcm/K corresponding to BOL conditions.
- Main feedwater mass flow drops to 0 % of nominal flow in the first four seconds on the transient.
- The AMSAC signal is activated when the steam generator water level reaches 12 % of narrow range. TT occurs at 30 seconds and AFW injects 30 seconds later at full of pumps capacity (30 kg/s).
- Transient begins at 5100 seconds of simulation.

The LONF ATWS simulation results, see Table 2, show that after the loss of feedwater combined with scram failure, the steam generators (SGs) can no longer remove all the heat produced in the core. This results in higher primary coolant temperature and pressure, Figures 3(a) and 3(b).
At first, when the RCS pressure begins to increase, the pressurizer (PZR) sprays actuate. The secondary water inventory decreases to reach the point when the U-tubes are starting to uncover, later the heat transfer from primary to secondary side starts to decrease rapidly. This produces Low SG level AMSAC signal, namely, when two out of three SG Narrow Range Level signals reach 12%. The AMSAC signal is produced and 3 seconds later the turbine is tripped and the steam dump is opened, Figure 4(a).

Later, when the PZR pressure reaches the relief valves setpoint and they open, releasing first cycling. Subsequently, the nuclear power reaches 95% of nominal, Figure 4(b), although RCS pressure continues going up, Figure 3(a). After turbine trip, secondary pressure Figure 5(a) is increased as much as to open the main steam PORVs, and the first three main steam SVs.

According to hypothesis of analysis, AFW injects 30 seconds after turbine trip. Approximately 10 seconds later, the nuclear power gets 75% of nominal valve, Figure 4(b). PZR-SVs reach their setpoint when RCS pressure continues increasing and they open.

Meanwhile, PZR-PORVs cycling occurs until they open completely. Then, PZR becomes solid, Table 2. As steam is relieved via main steam SVs, the secondary pressure decreases until the collector pressure reaches of Low Steam line pressure signal (S3 Signal). Due to this signal, main steam isolation valves close and High Pressure System Injection (HPSI) is demanded, Figure 5(a). Otherwise, HPSI starts to inject 10 seconds after to S3 Signal. However, HPSI injection has a low impact on pressure evolution.

The maximum RCS pressure is obtained at 107 seconds with a lower value (190 bar) than pressure limit (221.4 bar), Figure 3(a). When volume increases by expansion less than decreases by discharge through valves, RCS pressure is decreased. On the other hand, the nuclear power reaches 41% of nominal power, Figure 4(b). Furthermore, the maximum average RCS temperature occurs 30 seconds later and primary coolant start boiling, Figures 3(b) and 5(b).

Finally, first signs of PZR bubble appear, which shows in PZR level, nuclear power is stabilized 300 seconds later, Figure 4(b); and the simulation is ended 900 seconds after LONF.

<table>
<thead>
<tr>
<th>Time from LONF (seconds)</th>
<th>Transient description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>LONF</td>
</tr>
<tr>
<td>4</td>
<td>MFW flow completely lost</td>
</tr>
<tr>
<td>20</td>
<td>Beginning of pressurizer sprays actuation</td>
</tr>
<tr>
<td>25</td>
<td>U-tubes uncover</td>
</tr>
<tr>
<td>27</td>
<td>Low SG level (12%) AMSAC signal</td>
</tr>
<tr>
<td>30</td>
<td>Turbine trip via AMSAC signal. Hypothesis of analysis</td>
</tr>
<tr>
<td>30.3</td>
<td>Steam dump opens</td>
</tr>
<tr>
<td>33.4</td>
<td>Beginning of PZR-PORV cycling (162.3bar)</td>
</tr>
<tr>
<td>35</td>
<td>95% Nuclear Power</td>
</tr>
<tr>
<td>36</td>
<td>Main steam line PORVs open (78.1bar)</td>
</tr>
<tr>
<td>43</td>
<td>Main steam line SVs open (84.1, 85.6, 86.6, 87.3 and 88.05bar)</td>
</tr>
<tr>
<td>60</td>
<td>Full AFW flow injects. Hypothesis of analysis (TT + 30s)</td>
</tr>
<tr>
<td>87</td>
<td>Beginning of PZR-SVs cycling (173.4 bar)</td>
</tr>
<tr>
<td>----</td>
<td>----------------------------------------</td>
</tr>
<tr>
<td>90</td>
<td>Solid PZR</td>
</tr>
<tr>
<td>104</td>
<td>Main steam line isolation (Low Steam line pressure signal, 48.1 bar) Minimum secondary inventory</td>
</tr>
<tr>
<td>107</td>
<td>Maximum RCS pressure (190 bar) 41% Nuclear power</td>
</tr>
<tr>
<td>116</td>
<td>HPSI starts injection (Low Steam line pressure signal + injection delay)</td>
</tr>
<tr>
<td>136</td>
<td>Maximum average RCS temperature (625 K) Beginning of RCS boiling</td>
</tr>
<tr>
<td>208</td>
<td>PZR bubble</td>
</tr>
<tr>
<td>550</td>
<td>Nuclear power stabilization at 10%</td>
</tr>
<tr>
<td>900</td>
<td>End of simulation</td>
</tr>
</tbody>
</table>

### Figure 3: LONF ATWS BASE case. (a) Primary pressure. (b) Primary average temperature.

### Figure 4: LONF ATWS BASE case. (a) Narrow range level. (b) Nuclear power.
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Figure 5: LONF ATWS BASE case. (a) Secondary pressure. (b) Reactivity balance.

4 DAMAGE DOMAIN POWER UPRATE

Damage Domain (DD) of a sequence is defined as the region of the space of uncertain elements (times or parameters) of interest where a plant transient would result in the exceedance of some limit.

In LONF ATWS transient the limit is acceptance criterion ASME level C (RCS pressure < 22.16MPa). Besides, the uncertain elements are power and MTC. The maximum power chosen is 121% because it is the maximum power uprate reached in a 3 loop PWR-reactor and the interval in the region is 100% - 121%.

On the other hand, taking into consideration previous ATWS studies, it has been decided to simulate the MTC interval from -8 pcm/K to -17 pcm/K for each power considered. Thus, a total of 80 cases have been simulated. The results allow obtaining several conclusions, Figures 6(a) and 6(b):

- DD border follows: \[ P_{\text{uprate}}^{\text{max}} = f(MTC) \], being linear; \[ P_{\text{uprate}}^{\text{max}}(\%) = -\frac{21}{8} MTC + \frac{611}{8} \]. This line indicates the maximum power uprate as a function of MTC value.
- It has observed that there is a huge margin of MTC to reach the DD in 100% of nominal power, with constant MTC being -9 pcm/K the limit.
- At the present time, Almaraz NPP (109% of nominal power) has also a large margin to reach the damage region, with constant MTC being -12 pcm/K.
- Moreover, the maximum power for MTC corresponding to base case (-15 pcm/K) is 117%. Therefore, there is also a large power margin from present power (109%).

Figure 6: Power-MTC DAMAGE DOMAIN. LONF ATWS
5 SENSITIVITY ANALYSIS OF AMSAC ACTUATION TIMES

It is well known from previous analysis, AMSAC actuation times can change the transient evolution, see [7]. Therefore, it has performed at Cartesian sampling of actuation times to obtain information about ATWS actuation times.

The first simulation of the Cartesian sampling is LONF ATWS base case (green point in Figure 7(a)). Then, it was decided to perform simulations each 15s to TT times and AFW-TT times, altogether, 48 simulations have been performed.

The sensitivity analysis results show that the most important parameter is TT time because maximum RCS pressure is more sensitive to this parameter. Figures 7(a) and 7(b) show that from 75s the TT the maximum pressure is unchanged.

LONF ATWS base case has adequate AMSAC actuation times because it is observed that this case corresponds to the region with lower maximum pressure. Thus, it is a case optimum. The values of the red region have been marked because their pressure contour is non-linear and they will be analysed with more detail on future works.

![Figure 7: Sensitivity analysis of AMSAC. LONF ATWS](image)

6 CONCLUSIONS

Analysis results indicate that the power uprate is limited by ATWS sequences and also that it is possible to optimize the AMSAC actuation times. Results of damage domain power uprate and sensitivity of AMSAC actuation times analysis show that:

- DD border follows: \( \text{P_{uprate}}^{\text{maximum}} = f(MTC) \), being linear. This line indicates the maximum power uprate as a function of MTC value.
- Maximum pressure increases for higher power and higher MTC values (less negative value).
- Currently, this generic analysis shows a large margin according to power uprate and MTC to reach the damage region.
- Maximum RCS pressure versus AMSAC actuation times reaches an upper limit that depends more strongly on TT delay than AFW start up delay.
- Sensitivity analysis of AMSAC allows optimizing TT and AFW delay times.
- In AMSAC actuation times sensitivity analysis, LONF ATWS base case has adequate AMSAC actuation times because it is observed that this case corresponds to the region with lower maximum pressure.
ACKNOWLEDGMENTS

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REFERENCES


