PSA-2017

Crediting the Use of a Rapidly Deployable Mobile Pump to Recover from and Core Damage Events Caused by a Failure of the Turbine Driven Auxiliary Feedwater Pump

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Westinghouse will be the global nuclear energy industry's **first choice** for safe and efficient solutions as the world seeks clean, safe, environmentally sustainable energy programs now, and into the future.

We enhance our delivery of that vision by living our strong value system every day:

- Safety & Quality First
- Valuing Ethics, Integrity & Diversity
- Passion for Serving Our Customers Globally
- Dedication to Each Other Through Servant Leadership
- Fiscal Responsibility and Stability
- Consistently Delivering On Our Commitments

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- **BACKGROUND**
  - The turbine-driven auxiliary feedwater (TDAFW) pump provides a critical safety function for most pressurized water reactors (PWRs) at the onset of an extended loss of all AC power (ELAP) event
  - If all other auxiliary feedwater (AFW) pumps are unavailable due to the loss of electrical power, the steam-driven TDAFW pump injects water into the steam generators (SGs) and maintains a heat sink to remove decay heat from the reactor core
    - TDAFW pump cannot run indefinitely
  - Most PWRs have implemented post-Fukushima safety enhancements that include the use of portable pumps
  - Portable pumps deployed to feed the SGs in an ELAP event when normal plant pumps are not available
    - Typically be deployed within six to eight hours of the initiation of the event

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- **BACKGROUND**
  - Key assumption used in an ELAP or Station Blackout (SBO) analysis is that the TDAFW pump will start and operate during the event
  - If the TDAFW pump fails to start at the beginning of an ELAP event and there is a loss of feedwater (LOFW), thermal-hydraulic analyses show the SGs will boil dry and the core could uncover in two hours or less
    - Timing is highly dependent on reactor design
  - Contingency plans using a highly mobile makeup pump have been analyzed to determine if a success path for preventing core damage exists
  - A few PWRs rely on a standalone, diesel-driven AFW pump to provide the same safety function
    - Insights from this paper are applicable whether a plant has a TDAFW pump or a diesel-driven AFW pump

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- **INTRODUCTION**
  - Based on the potential for limited staffing availability, uncertainty in site conditions and overall uncertainty of the event, it could be challenging for utilities to cope with a loss of TDAFW early in the ELAP or SBO event
  - Second phase of the ELAP (coping through portable equipment), plant staff will align a portable pump capable of injecting into the SGs (redundancy for the safety function of the TDAFW pump)
    - Time to begin installing portable equipment is about six to eight hours following event initiation
    - Coping time range is supported by both an analytical basis and a detailed staffing study, and has been audited and accepted by the U.S. Nuclear Regulatory Commission (NRC)
  - The key assumption in this six- to eight-hour coping time is that the TDAFW pump starts and operates during the event

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- **INTRODUCTION**
  - Outside the United States, there are approaches developed for the potential loss of the TDAFW pump as additional defense-in-depth
    - Most approaches implement hardware solutions where an alternate means of injecting into the SGs is placed in a hardened, protected building, or additional redundancy is added via a new diesel- or steam-driven pump
    - At least one country has evaluated and demonstrated a success path for using mobile equipment following a LOFW to the SGs one hour into the event
      - Approach relies on a focused effort to rapidly depressurize the SGs and then supply water directly from a fire truck

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- **INTRODUCTION**
  - Pressurized Water Reactor Owners Group (PWROG) analyzed rapidly depressurizing the SGs
    - Sensitivity case as part of thermal-hydraulic analyses conducted to support implementation of NEI 12-06, “Diverse and Flexible Coping Strategies (FLEX) Implementation Guide
    - Analysis showed that if the SGs were empty, depressurization would occur quickly and a low-pressure feedwater source would be able to inject
    - Building on this case, Westinghouse performed additional analyses to answer the following questions:
      - Is there an impact from depressurizing a single SG and then feeding it versus performing the same with all SGs?
      - How much time does the plant operations’ staff really have to hook up a low-pressure pump to prevent uncovering the core?
      - Are there any limitations to the low-pressure injection flowrate or head?

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- **Introduction**
  - PWROG Analysis
    - Questions answered by using the Combustion Engineering Nuclear Transient Simulation (CENTS) computer code with a plant model representative of a CE PWR with a large, dry containment
      - CENTS computer code has been endorsed by the U.S. NRC to perform ELAP analyses up to the transition from two-phase natural circulation flow to reflux cooling in the reactor coolant system

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- **Total Loss of Feedwater Flow**
  - Westinghouse analyzed a scenario assuming no actions during an ELAP with a LOFW to determine the time until the core uncovers
  - Results used for evaluating the success of taking certain follow-on actions, including their timing and whether or not the approach is reasonable
  - Base case confirmed that in an ELAP with a LOFW at the start of the event, the SGs dry out in approximately 50 minutes, core uncovers just before two hours
  - Analysis demonstrates that correct timing is essential for recovering feedwater to prevent fuel damage, shows that recovering feedwater should be the main focus of the operator

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- **Total Loss of Feedwater Flow**
  - Current Emergency Response Guidelines (ERGs) and FLEX Support Guidelines (FSGs) do not make recovering feedwater the first priority
    - ERGs and FSGs initially assume that the problem is with the water source rather than the pump, and direct operators to align to alternate suction
    - Later in the procedure the operator is directed to again check the SG water level and flow
      - If flow is not adequate then establish a low-pressure feedwater source
    - Following the current procedures, there are many other actions that operators may take before executing the alternate SG feed strategy
      - Restore power
      - Begin DC load shedding
      - Perform initial plant assessments and begin to stage all of the portable equipment
    - While the current procedures would eventually steer operators to depressurize the SGs and feed them with a low-pressure water source, by the time the operators mobilize and deploy the pump, it could be too late to prevent fuel damage

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- Recovery Actions
  - Same scenario analyzed but modeled two key recovery actions:
    - 10 minutes into the event, rapidly depressurize both SGs at the maximum rate
    - One hour into the event, restore feedwater injection into one SG using a fire truck
  - Analysis showed that the feedwater flow was adequate to remove decay heat
    - Feedwater flow eventually had to be throttled and was initiated in time to avoid activating the pressurizer safety valves (PSVs)

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- Recovery Actions
  - Case confirms with a rapid SG depressurization and injection from a low-pressure water source, the plant will be able to cope with a LOFW event even if all feedwater is lost at the beginning of the event (Figure 1)
  - Need focus by the plant staff to ensure two critical actions can be accomplished in a short period of time:
    - SG depressurization
    - Mobilization of a low-pressure feed source

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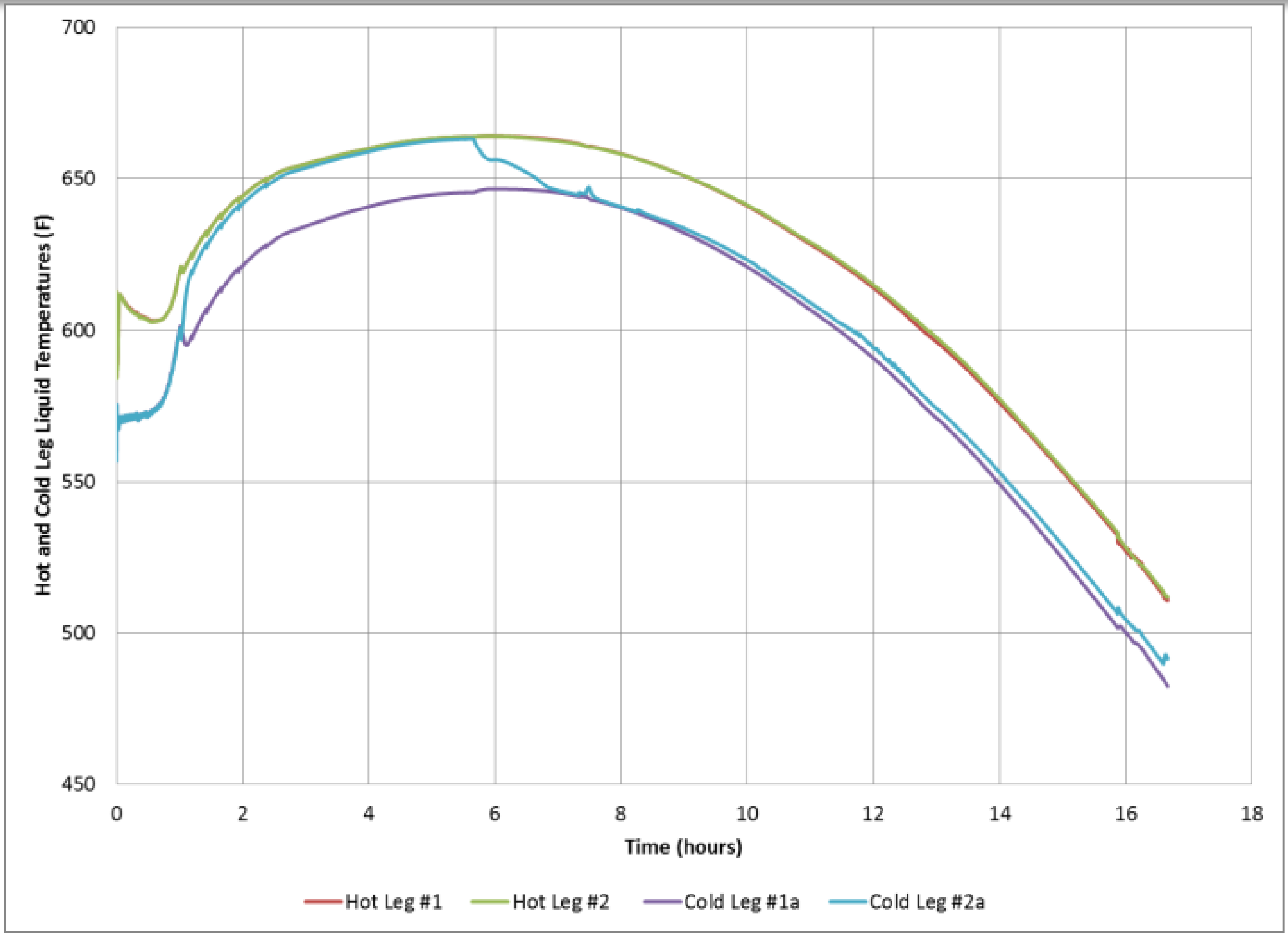

Figure 1: RCS Temperatures

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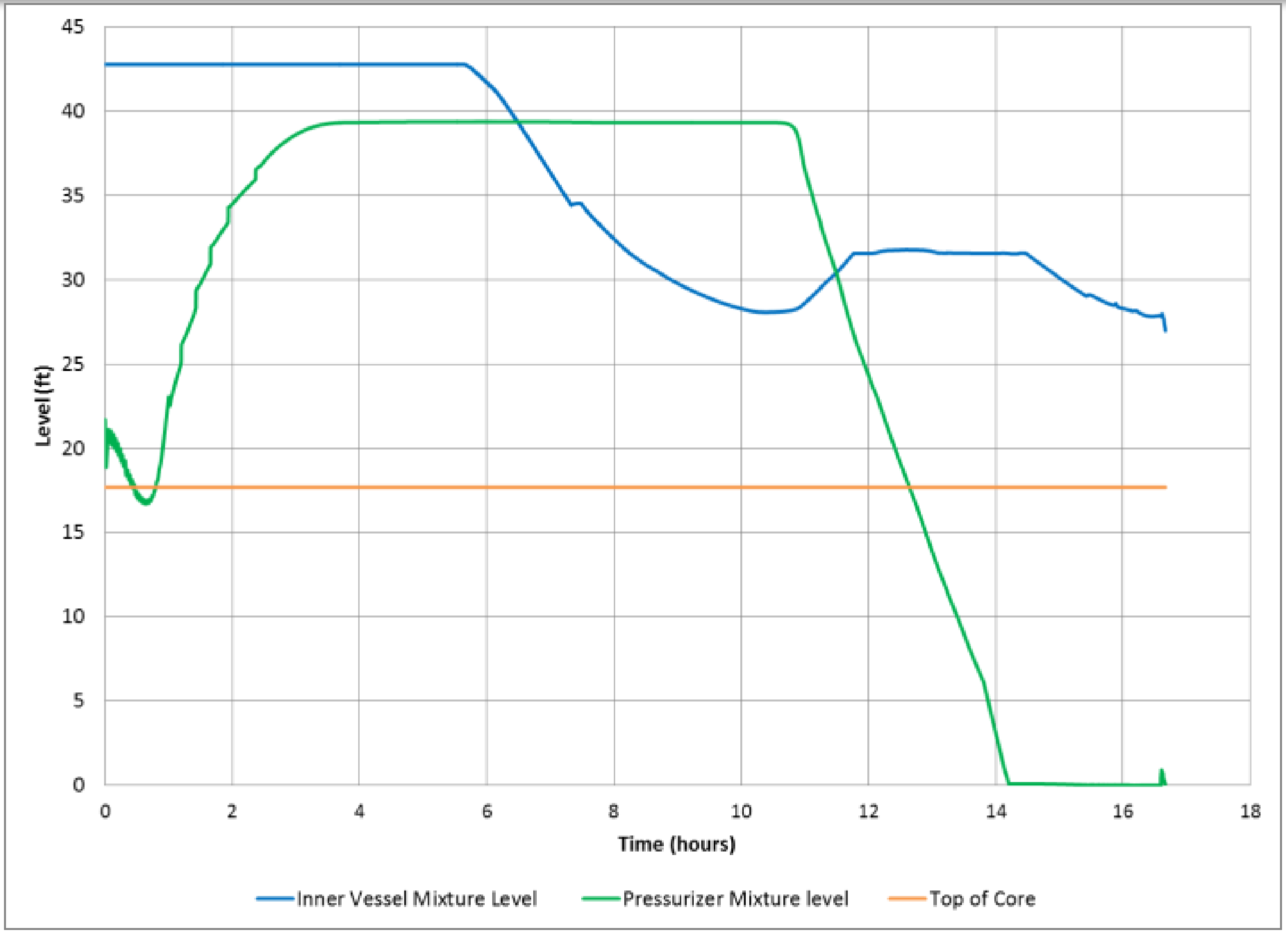

Figure 1: RCS Levels

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- Strategy Implementation
  - Analyses demonstrate using FLEX equipment and connections can prevent core uncovery for a LOFW event, even if it happens at the time of reactor trip
  - Analyses also demonstrate that time is of the essence for this event, and that the plant staff must be focused on connecting equipment rapidly and quickly depressurizing the SGs
  - To implement this strategy on a plant-specific basis, items that need to be addressed include:
    - Plant staff must be able to quickly deploy and connect a low-pressure, moderate-flow pump
      - Other alternatives could be credited such as a pre-staged, passively driven pump (e.g. an air-driven pump)
      - These pumps exist but do not generate high-discharge head, so SG depressurization would be critical

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- Strategy Implementation
  - The plant must have the capability to depressurize the secondary side with minimal operators, preferably using DC power from the control room
  - The plant must ensure that nitrogen from the accumulator or safety injection tank does not inject into the primary system and impact natural circulation
  - The reduction in the time to reach reflux cooling due to the lifting of the PORVs or PSVs and increased reactor coolant pump seal leakage caused by the elevated RCS temperature and pressure should be evaluated
  - If the SGs are fed with cold water after they heat up, an analysis of SG integrity may need to be conducted

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- **Probabilistic Risk Assessment (PRA) Modeling and Benefits**
  - A LOFW with loss of the plant TDAFW pump event has been addressed at a CE PWR by crediting a staged diesel-driven FLEX SG low head makeup pump
  - The scenario is different than the ELAP condition previously described but it demonstrates a reduction in risk that may be achieved by crediting a FLEX pump for SG makeup
  - A realistic analysis using the EPRI Modular Accident Analysis Program (MAAP) showed that a LOFW event at the plant requires restoration of high or low pressure feedwater within 75 minutes of trip to prevent core damage
    - Recognition of a loss of all feedwater may take 10-15 minutes as post-trip actions are taken
    - Actions to attempt auxiliary feedwater recovery or use of condensate for SG makeup would not normally begin until post-trip actions are completed

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- **PRA Modeling and Benefits**
  - The plant credits a staged low head diesel-driven FLEX SG makeup pump in its Equipment Out Of Service (EOOS) model in accordance with NEI 16-06 and NRC RIS 2005-18
    - A single human reliability analysis (HRA) event developed
      - Included SG depressurization via Atmospheric Dump Valves and hookup of the pump hoses to the FLEX connections, fill and venting the hoses and piping, and operation of the pump
      - These proceduralized actions are estimated to take 18 minutes total based on operator interviews
      - Modeled in in the EPRI HRA Calculator
      - The total HRA failure probability for these actions was calculated to be 0.1
    - The pump failure probabilities were determined to be 4.7E-3 for the failure to start and 9.0E-5/hr for the failure to run
      - Based on Bayesian updated data for non-safety diesel driven pumps

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- **PRA Modeling and Benefits**
  - 52% reduction in core damage frequency (CDF)
  - 41% reduction in large early release frequency (LERF)
  - The EOOS model used for this calculation is based on a PRA model that includes internal events and a pre-Regulatory Guide (RG) 1.200 fire PRA model
    - The reduction in the RG 1.200 fire PRA model CDF and LERF from this feature would be expected to be similar in percentage but higher in absolute risk reduction due to the higher risk from the RG 1.200 fire PRA model versus the pre-RG 1.200 fire PRA model

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- **PRA Modeling and Benefits**
  - This example is a specific case in which the plant identified the need for additional diverse backup for SG makeup and recognized the need could be met using FLEX equipment
  - Guidance for optimizing the use of FLEX and other portable equipment is provided in NEI 16-08
    - The purpose of NEI 16-08 is to maximize the benefit of site investments in procuring portable equipment and to identify opportunities to optimize plant operations
    - NEI 16-08 is intended to provide licensees with a process to identify, prioritize, evaluate and implement uses of portable equipment to improve operating margins
  - In addition, guidance for plants to credit portable equipment in regulatory applications and to reduce plant risk using qualitative, semi-quantitative, or direct PRA modeling approaches is provided in NEI 16-06
  - In most cases, the modeling of portable equipment in a PRA is very similar to modeling of permanently-installed equipment, however, NEI 16-06 Section 7 calls attention to aspects that might be different from what has been encountered previously in building a PRA model for a nuclear power plant

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- **Conclusions**
  - The TDAFW pump has been shown to be very important to the overall safety of the plant
    - Example plant's PRA core damage frequencies are significantly impacted based on whether the TDAFW pump is available
    - Implementation of FLEX assumed that a TDAFW pump would be operating at the beginning of the event
  - If the TDAFW pump does not start at the beginning of an ELAP event, there is a success path that has been demonstrated through an analytical basis
    - Completely depressurize at least one SG
    - Inject makeup flow utilizing the FLEX connections and equipment that already exist
  - Time is of the essence for this strategy to be successful, likely would need to be some modifications to existing EOPs and even FSGs to implement it
  - With these few modifications, a significant safety enhancement can be made at the plant, not just for ELAP response but for all loss of feedwater events
  - The safety enhancement may be a potentially significant reduction in the plant's core damage frequency, roughly 50% reduction in CDF

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