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General Comment

See attached file(s)

Attachments

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Review comments for NUREG-2195 "Consequential SGTR Analysis for Westinghouse and Combustion Engineering Plants with Thermally Treated Alloy 600 and 690 Steam Generator Tubes" Draft Report for Comment

Prepared by Douglas A. Fynan, Ph.D.
August 8, 2016

The following technical review comments for NUREG-2195 reflect my own personal and professional opinions and not of any past or present employers.

Comment 1 (page xxv, 4th paragraph):
"A key consideration for C-SGTR sequences is the relative timing between failure of SG tubes and failure of other locations of the reactor coolant system (RCS)."
I would like to suggest an alternative key consideration for C-SGTR sequences: the relative heating rate between the SG tubes and other RCS components. The prediction of failure time of RCS components is an opaque process involving several embedded calculations, the thermal-hydraulic (TH) and heat transfer to component heat structures primarily using system codes and a correlation (usually the Larson-Miller creep rupture model) to predict failure time. The creep rupture process is a threshold and exponential process so small deviations in the problem assumptions can lead to very different calculated results. This makes direct comparisons between even very similar simulations difficult. Heating rates are physical quantities representing conservation of energy. Quantitative comparisons of heating rates between different reactor types and calculations using different code systems can provide useful insights into C-SGTR. How heating rates change as a function of reactor type, sequence timing (e.g. early/late AFW failure) and secondary side conditions (SG pressure at MSSV setpoint pressure vs. atmospheric pressure from open ADV), and other factors such as SG tube bundle and hot leg geometry can provide a more normalized figure of merit to assess C-SGTR sequences.

Comment 2 (Page 2-6, lines 26-33):
Is the success of post core damage RCS injection via accumulator water to arrest core melt within the vessel conjecture or has this particular phenomenon been studied in detail by the NRC and industry? Later in this report, some MELCOR simulations were terminated when the accumulators started to inject. In the SAMG space for different PWR types with a faulted/isolated SG, can primary depressurization below accumulator pressure setpoints be achieved through secondary cooldown using the remaining SGs? Are secondary cooldown SAMGs "aggressive cooldown" procedures or are maximum RCS cooldown limits of 55 deg C/hr followed? How much additional time is provided to operators to align makeup water to RWST? After accumulator injection into degraded cores, how fast does the RCS re-pressurize? In CE plants, high pressure safety injection (HPSI) are medium-head pumps and cannot inject at

high RCS pressures near PORV setpoints; separate charging system with low flow pumps (~44 gpm/pump) is used for charging and chemical control. In WH plants, HPSI and charging system use the same high-head medium flow pumps. The implementation and success of SAMGs to limit SGTR release may be plant type and sequence timing specific.

Comment 3 (Page 2-8)
Alternative 1: what are the effective leak areas when 1 PORV or an SRV sticks open?
Alternative 4: what is the effective leak area of the stuck open SG PORV?

Comment 4 (Page 2-10, lines 1-6):
The free volumes of SG secondary sides are $O(10^2)$ m^3. SG secondary side pressures can range from approximately 8 MPa, MSSV setpoint pressures, to near atmospheric pressure, especially if an operator has purposely (following an EOP or SAMG) opened an ADV to depressurize the SG during a cooldown operation or depressurization operation to allow water injection to the SG at low pressure using low-head pumps, and steam densities are $O(10)$ kg/m^3 to $O(10^{-1})$ kg/m^3. When the SG is "dry", there is still a residual mass of superheated steam in the steam generator ranging from $O(10^3)$ kg to $O(10)$ kg acting as a large heat sink along with the mass of the Inconel SG tubes. The thermal mass of the heat sink is a function of the SG pressure and the countercurrent natural circulation flows on the primary side of the SG tubes are coupled by the heat transfer to these heat sinks. By assuming 0.5 in^2 secondary side leakage area, the SGs slowly approach atmospheric pressure after SG dryout and the natural circulation flow rates and cooling of primary side steam as it flows through the SG tubes are governed by this slow SG depressurization. The heating rate of the SG tubes may also be coupled to the SG secondary side depressurization. A primary side flow rate of $O(10)$ kg/s being cooled 100 deg C can raise the temperature of secondary side steam mass of $O(10^3)$ kg by approximately 1 deg C/s. These are some of the subtleties that should be considered when comparing the base cases with other sequences with different secondary side depressurization assumptions.

Comment 5 (Page 2-12, line 3):
What is the technical basis for assuming 21 gpm per pump RCP seal leakage? Are these plant specific/installed pump seal package values or just assumptions? What is the effective leak path area modeled to obtain 21 gpm at operating RCS pressures? For all analyzed sequences in Chapters 3 and 7, it would be helpful to see a plot of the integrated mass flow through the pump seal leaks as a function of time compared to integrated mass flows through the pressurizer PORVs and SRVs. For the past 25 years, much time and effort has been spent in the severe accident simulation community agonizing over pump seal leakage modeling and many NUREG and topical reports have sections or chapters dedicated to the topic. However, it remains unclear whether the small mass and enthalpy flow rates through modeled nominal RCP seal leaks actually matter to any of the severe accident phenomena of interest in these studies.

Comment 6 (Page 2-15, line 29-41):
Is the discussion in this paragraph conjecture or has technical work or simulations been performed to support these statements? To clarify, this paragraph appears to be discussing the blowdown of the high presssure RCS through SG tube breaks to the low pressure SG secondary side. The collapse of the countercurrent flow regime in the RCS primary side would be analogous to the temporary breakdown of the countercurrent flow when the pressurizer PORV or SRVs cycle. Is the conclusion of this paragraph that guillotine break of three tubes causes the blowdown of the RCS that disrupts the countercurrent natural circulation flow? In lines 31-33, would such a blowdown event depressurize the RCS such that the accumulators inject possibly arresting core melt?

Comment 7 (Section 3.1.2, Page 3-7, Lines 11-50):
Additional CE Plant Considerations
All CE plants in the USA are/were operating with replacement SGs from a variety of manufactures including Westinghouse/ENSA (ANO-2 and Waterford-3), Framatome (St. Lucie-2), BWI (Calvert Cliffs, St. Lucie-1, Millstone-2), ABB/CE/Ansaldo (Palo Verde), MHI (SONGS and Fort Calhoun), and CE (Palisades). Only Palo Verde and Palisades replacement SGs retained the original "square" bend U-tube design of CE SGs. The OPR1000 and APR1400 series reactors in Korea and UAE based off of CE System 80 design also feature square bend U-tube SGs manufactured by Doosan Heavy Industries. All other replacement SGs have semi-hemispherical tube bundle bend regions. The second major difference is tube diameter. CE steam generators are 3/4 inch outer diameter tubes with the exception of the delta 109 RSG for ANO-2 which has 11/16 inch diameter tubes. The Westinghouse AP1000, a 2x4 plant, has delta 125 SGs with 11/16 inch diameter tubes manufactured by Doosan. The Zion NPP WH model 51B SGs are 7/8 inch outer diameter tubes and with the power rating of Zion of only 3250 MWt, one of the lowest power rated 4-loop WH PWRs, the tube bundle heights are short. In contrast, the delta 94 replacement SGs for South Texas Project, the highest power rated 4-loop PWRS are 3853 MWt, are significantly taller and 11/16 inch diameter tubes. Tube diameter and tube bundle height are important factors controlling the natural circulation flow rates. Inlet plenum geometry is of second order importance.

Comment 8 (Section 3.3 Computational Fluid Dynamics, pages 3-8 to 3-12):
a) The recirculation ratio and hot tube fraction values for CE SG reported in Section 3.3.3 differ from previous reported values in NUREG-1788 by almost a factor of 2. A standalone report should be published clearly detailing the CFD model evolution that produced such a discrepancy. The scientific method requires reproducibility. All boundary conditions applied to the CFD models should be documented because numerical results of CFD simulations are highly dependent on the boundary conditions.

b) Page 3-11, lines 34-36, what are the target pressure drops and heat transfer rates of the prototypical steam generator that the CFD models are calibrated to and how were they originally determined?
c) How does the current use of CFD differ from the earlier use of the COMMIX finite element code (Domanus and Sha, NUREG/CR-5070, 1988) in calibration of system code models related to the TI-SGTR analysis?

Comment 9 (Page 3-13, lines 29-35):
The SG tubesheet is a huge thermal mass and offers several feet of heat transfer length per tube. A CFD or finite element model study using controlled boundary conditions would be useful to investigate how the tubesheet affects the natural circulation flow. In particular, estimate the enhanced heat transfer due to *vena contracta* and possible larger temperature differential from primary steam to the large steel volume.

Comment 10 (Page 3-13, lines 37-45):
See comment 1 about heating rates. Here relative heating rates would be an excellent figure of merit to measure the effects of various heat transfer coefficients on the severe accident progression.

Comment 11 (Page 3-14, lines 13-26):
Secondary-side relief-valve fail open modeling is a red herring. Lines 24-26 correctly identify that there are procedures, both in EOP space and SAMG space, that tell operators to intentionally open secondary side relief valves. For CE plants during SBO, this is likely the ADV that must be manually opened at the valve location using the handwheel, but this is sometimes difficult (see USNRC Information Notice No. 89-38, Atmospheric Dump Valve Failures at Palo Verde Units 1,2, and 3). An alternative strategy that might be implemented from the control room is opening the MSIV bypass valve, 4 inch air operated and solenoid controlled valve, and the air operated turbine bypass valves to allow secondary depressurization to the condenser.

Comment 12 (Page 3-15, lines 37-41):
Caution should be employed when performing cross code comparisons and excessive tuning of models to attain agreement with a different model that may be using different boundary conditions, assumptions or solution structures should be avoided. For example, what are the natural circulation lengths input on cards 801 and 901 for the U-tube heat structures of the SCDAP/RELAP5 model? Compare to the characteristic length on cards 500 and 700 for the U-tube heat structures of the MELCOR model. Are the MELCOR lengths equal to the hydraulic diameter of the U-tube (~ 2 cm) and are the RELAP5 heights equal to the heat structure height (~ 1 m, a function of the user selected nodalization). The natural convection heat transfer coefficients that are calculated by RELAP5 and MELCOR (using different correlations) are directly proportional to these lengths. A major difference between the RELAP5 and MELCOR

models might be that different heat transfer rates are calculated which determine natural circulation flow rates. Furthermore, what heat transfer coefficients were applied as user defined boundary conditions on the external U-tube wall in the new CFD calculations?

Comment 13 (Page 3-15, lines 43-49):
Is there a reference that can be cited detailing the new method? Is this paragraph referring to the opposed pump control function models that are applied to the split hot leg flow paths? What are the actual deltaP's of the pumps in Pascals calculated by two methods for a representative severe accident natural circulation? What are the calculated pressure drops through hot leg volumes using active control? If active control is not used and the split hot legs are just modeled as pipes with conventional wall friction loss, what are the calculated pressure drops through the hot leg volumes? The delta P's of the active control pumps are probably on the order of 5 - 10 Pa whereas the pressure drop due to friction in the U-tubes are $O(10^3)$ Pa and changes in gravitational head from density change of steam and U-tube height are $O(10^3)$ Pa.

Comment 14 (Page 3-19, lines 34-35):
Please quantify the statement "...were found to be higher than those of Fluent". Why do higher (and quantify how much higher) hot-leg velocities prefer tube over HL failure? Do heat transfer coefficients and residence time change as a function of velocity? See comment 1: the result of different heat transfer coefficients and residence time can be observed in the heatup rates.

Comment 15 (Page 3-20, line 32):
This behavior *is* scenario dependent. Most of the cases presented later in Ch. 3 assume the 0.5 in^2 secondary leakage which also controls secondary depressurization after TI-SGTR and RCS blowdown to the secondary side. See Figure 3-5 on page 3-26 from 23000 seconds to 26000 seconds. If the initial depressurization is modeled as an opened ADV, the release to the environment will be much greater.

Comment 16 (Page 3-21, line 26):
What are the RCS depressurization mechanisms in the sequences that experienced reflood via accumulator injection? Larger RCP seal leakage due to blowout of seal internals? Blowdown through the TI-SGTR break?

Comment 17 (Pages 3-26 to 3-40, comments on figures)

A figure showing together the decay power and power from metal-water reactions calculated by the COR package as a function of time would be helpful. During the onset of core damage, there can be time periods when the power from metal-water reaction exceeds, by over a factor of 2, the decay power.

Fig. 3-5: at ~16000 s, what is causing the bifurcation in the SG A and B pressures? Are there two different valves modeled on the pressurizer and what are the setpoints and open areas? It appears the SG pressure bifurcation is correlated to the jump in RCS pressure. See comment 5: here seeing the the mass and enthalpy flow out the pressurizer would be helpful.

Fig. 3-7: Reproduce a Fig. 3-7b showing the detail of the heatup rates leading to first component failure. Limit x-axis from 12000 s to 24000 s and y-axis from 600 K to 1100 K.

Fig. 3-8: Loop B (without the pressurizer) is being predicted to fail first. Loop B tube heatup rate is greater than Loop A. Some previous TI-SGTR studies concluded that the pressurizer loop heats up faster. Very interesting result and should be investigated more.

Fig. 3-10: Appears to be significant movement of hydrogen to the U-tube bundle after the TI-SGTR and RCS begins to blowdown to faulted SG. Was this hydrogen produced earlier and was residing in a different location (what location) or does the RCS blowdown initiate additional water metal reactions?

Fig. 3-11: Make a cut-out of the I and Cs release and rescale to show detail and place in the blank space to the left of the Te curve.

Fig.3-14: Repeat the rescaling that was done for Fig. 3-7b.

Figs. 3-17 and 3.18: a Table summarizing the heatup rates from SG dryout to first RCS component failure for the two sequences would be a more informative way to present the very important data contained in the figures.

Fig. 3-21: rescale, See Fig. 3-14b

Figs 3-22 and 3-23: Make cut-outs from 60000 s to 70000 s and rescale to show detail and place in the large blank space to the left of the curves.

Figs. 3-27 and 3-29: rescale figure

Comment 18: (Page 3-41, line 46)
The rise is not linear. At approximately just before 15000 s, although it is hard to see on the current scale, there appears to be a discontinuity in the first derivative (heatup rate) of the temperature curves. Note that this is about the same time as the pressure bifurcation in Fig. 3-5.

Comment 19: (Page 3-41, line 48)

Quantify the statement "a little slower". This is a very significant result. Although the heatup of RCS components is occurring at very different absolute times (over 6 hours difference) the *heatup rates* are approximately the same.

Comment 20: (Page 3-42, line 40)
See comment 17: show power from water metal reactions as function of time.

Comment 21: (Section 3.7 Potential Future Analyses)
This section may be the most important section of the NUREG because it identifies limitations and subtleties of the current work and recommends specific technical items to address in the future.

To resolve the loop seal clearing problem, please consider developing a SBO MELCOR model for the WH AP1000 that will serve as a surrogate model for once through natural circulations resulting from loop seal clearing for other PWRs. The AP1000 RCPs draw suction directly from the SG outlet plenums so there are no cold leg suction legs where the loop seals form. Secondly, the startup feedwater system doubles as the non-safety grade AFW system using AC powered pumps. During SBO, there appears to be no available AFW for the AP1000. At the 10 SBO events at commercial NPPs, the SBO was not the initiating event and the NPPs were in various stages of cooldown procedures (Fukushima Diachii 4 of 6 units, Fukushima Diani 3 of 4 units), hot standby (Maanshan Unit 1), and refueling outages (Vogtle 1 and Kori 1). A key component of the AP1000 passive safety system is the 4th stage of the automatic depressurization system (ADS) employing the large squib valves that if spuriously activated will cost the plant millions of dollars. Are there operation procedures during low power or shutdown that isolate or lock out the ADS?

Comment 22 (Section 3.8 Conclusions)
Page 3-49, lines 33 - 37: The TH phenomena are coupled to the SG secondary side conditions and valve modeling. Excellent insight.
Page 3-50, lines 4-7: Excellent insight. See comments 4, 11, and 14.

Comment 23: (Page 4-1, line 25)
How typical is the Zion NPP? Of the 30 operating WH 4-loop PWRs in the USA, Indian Point are the only units with a lower power rating than Zion. The average rated power of WH 4-loop plants are 8.3% higher than what is assumed in the Zion analyses. South Texas Project reactors are almost 19% higher rated power.

Comment 24: (Page 7-23, Lines 27-44)
What happens when you put cold water into a very hot dry SG? How might radionuclide transport and release be affected when this is implemented in EOP space (before significant core

damage), in SAMG space after core damage but during RCS component heatup stage before TI-SGTR, in SAMG space after TI-SGTR has occurred but before other RCS component failure?

Comment 25: (Page 7-35, Line 5)
Pressure drop in SG tubes as a function of tube diameter and tube bundle height is very important.

Comment 26: (Page 7-36, Lines 16-18)
How might these measures affect radionuclide transport during SAMG space before and after TI-SGTR? In particular, portable low-flow high-head pumps are available at plants for RCS injection (FLEX pumps at Palo Verde and Kerr pump at Surry). What happens when low flow rates of cold water are applied to partially degraded cores at high pressure?