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Potential Need for Re-Definition of the Highest Priority Recovery Action in the Krško SAG-1

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ABSTRACT

Replacement of old SG (Steam Generators) [7] and the characteristic of new ones throws the question of proper accident management strategy, which leans on philosophy that repair and recovery actions have first priority. In the current NPP Krško SAMGs (Severe Accident Management Guidelines), water supply to the SG has priority over re-injection water into the core.

NPP Krško reconsidered the highest priority of SAG-1 (inject water to the SG), against the WOG (Westinghouse Owners Group) generic approach (inject water into the core) and potential revision of Severe Accident Phenomenology Evaluations using MAAP (Modular accident Analysis Program) 4.0.5 code.

1 INTRODUCTION

In consistence with the revised set of the Safety Standard Series, the IAEA developed a Safety Report on “Implementation of Accident Management Programmes in Nuclear Power Plants”. The Safety Report describes an AMP (Accident Management program) and makes suggestions on its preparation, development and implementation in an individual NPP. With the aim of facilitating the use of the above mentioned Safety Report and to assist Member States in the preparation, development and implementation of an effective plant specific AMP, the IAEA offered a Safety Service known as Review of Accident Management Programmes (RAMP) in NPPs.

According to the suggestions and recommendations of the RAMP mission [1], which was conducted on-site the NPP Krško (NEK) within the framework of the Regional Technical Co-operation Project RER/9/061 on Enhancement of Nuclear Safety Regulatory Authority Effectiveness NPP Krško revisited the highest priority of SAG-1, Inject water to the SG.

In the WOG SAMGs, SAG-1 is the severe accident guideline with the highest priority in the DFC (Diagnostic Flow Chart). It requires filling of the SG secondary side. Many other SAMG approaches (notably those of all other US plants) consider injecting into the primary side as the highest priority. The reason for the position of Krško NPP was twofold: to ensure heat removal as well as to prevent the creep rupture failure of the SG tubes or the hot leg. From the IPE, it appears that these failures are relatively early events in high pressure scenarios; hence this measure would correctly assume highest priority. The IPE considers uninterrupted severe accident scenarios, whereas in reality various operator actions could already have taken place, which could cause the picture to change. In addition, a prime objective of the SAGs is to protect fission product boundaries, where SAG-1 is the proper action to take. It may happen that the plant is already in a low pressure condition (and no SGTR (steam generator tube rupture) has been observed), in which case SAG-1-Inject water to the SG would not be appropriate and negative technical consequences can appear of feeding the SG. An important non-technical negative consideration in feeding the SG may be that it is ineffectual in a view of the evolution of the accident. Repair and recovery actions have first priority, i.e. repairs to ensure a water supply to the SG have priority over repairs that would make it possible to re-inject water into the core. This comes from the past with old SG, which tubes were in the bad condition and the probability for occurrence a tube rupture was high. Due to SG replacement it is recommended that the highest priority of SAG-1 is revisited by Krško NPP. This also concerns the WOG generic approach.

2 METHODOLOGY

The Modular Accident Analysis Program (MAAP) [4] is an integral systems analysis code for assessing off-normal transients that can progress to and include severe accidents. The code evolved into a major analytical tool for supporting the plant-specific Individual Plant Examinations (IPEs). Furthermore, the scope of MAAP (its design basis) was expanded to include Accident Management with the new models included in MAAP4.0.5. MAAP4's phenomenology models are state-of-the-art. Therefore, MAAP4 possesses a dynamic benchmarking capability to insure the code is consistent with all major experiments (both separate effects and integral effects) and plant transient experiences that are within its benchmarking library.

MAAP4 treats the spectrum of physical processes that could occur during an accident including steam formation, core heatup, cladding oxidation and hydrogen evolution, vessel and tube failure, core debris-concrete interactions, ignition of combustible gases, fluid (water and core debris) entrainment by high velocity gases, and fission product release, transport, and deposition. MAAP has a modular structure in which separate subprograms are dedicated to specific region models and physical phenomena. This facilitates code enhancements because improvements to phenomenological or region models can be made to relatively small subprograms.

Primary system components under stress at high temperatures will undergo irreversible strain known as creep. When the strain is large enough, the component can breach. Failure of primary system components by creep rupture may be predicted by application of the Larson-Miller parameter method [4].

Following core uncovery in the progression of a severe accident sequence, natural circulation of superheated steam (and hydrogen) can occur in the reactor vessel and the reactor coolant system. Natural circulation flows have been shown to be a strong function of system pressure and are also quickly disrupted by forced circulation flows. The potential for creep rupture failure is dependent of the amount of in-vessel hydrogen generation and the time interval after core slump that reactor vessel failure occurs. Since zirconium-water reactions release a significant amount of heat we suppose the largest hydrogen production (no hydrogen burn).

Operator actions can have a significant impact on the severe accident progression and the potential for creep rupture failure of the reactor coolant system piping prior to reactor vessel failure. If an accident management strategy, or severe accident procedure is in place then the potential for failure of the reactor coolant piping prior to reactor vessel failure is precluded.

MAAP 4 subroutine CREEP is applied to the lower head, hot leg, surge line, and steam generator tubes. Its structure is rather simple, since it consists of initializing parameters for material properties and then finding the rupture time by Newton's method.

Key outputs of CREEP are:
SIGW (I) wall stress distribution, and
TRUP rupture time.

Key inputs are:

IN	number of nodes in wall,
XTW	wall thickness,
XRW	vessel radius,
DELTAP	pressure difference across structure,
MCM	corium mass,
TWALL (I)	wall temperature array,
SIGG (I)	guess stress distribution,
TRG	guess rupture time,
ISYTAB	dimension of yield table,
JSYTAB	number of yield table entries,
TSYTAB	temperature in yield table, and
PSYTAB	stress (pressure units) in yield table.

Analysis (example on isothermal creep data) from **Error! Reference source not found.** shows that stress in thousands of psi (ksi) could be plotted as a function of the Larson-Miller parameter:

$$\mathrm{LMP} = \mathrm{T_R}\left[\mathrm{A} + \log_{10} * \mathrm{t_{rh}}\right] \tag{1}$$

where LMP = Larson-Miller parameter
T_R = temperature, R
t_{rh} = rupture time, hours, and
A = best fit parameter, different for each material

The creep rupture time from equation (1) represents the fact that the specimen will undergo irreversible strain during the time interval until the strain is large enough to fail the specimen (typically 20% strain would occur). If the specimen were held at the stress and temperature for a fraction of the time, its strain would be some fraction of the strain at failure. We may approximate this fraction by the dwell time at the given condition divided by the rupture time:

$$f_{creep} = \frac{\Delta t}{t_r} \tag{2}$$

where fcreep = fractional contribution to creep rupture
Δt = dwell time, seconds, and
tr = rupture time, seconds

We can imagine holding the specimen at a series of stress levels and temperatures until it fails. Each interval provides a contribution to the failure represented by the irreversible strain that occurred during the interval. The sum of the creep fractions is thus 1.0 at the time of failure. We can regard the creep fraction as a dynamic variable and its rate-of-change with time is simply the derivate of equation (2):

$$\frac{df_{creep}}{dt} = \frac{1}{t_r} \tag{3}$$

The creep fraction for any section is thus a MAAP state variable update by the integrator.

For thick sections with non-negligible temperature gradients, equation (1) can no longer be directly applied because both the stress and temperature vary across the specimen. Amount of irreversible strain must be constant across the specimen. Thus, the creep rupture time is the same for any point in the specimen. Since this time is the same at all points but the temperature is different at all points, the stress must be different too at all points. The total force, or the average stress, borne by the specimen must be equal to that of the applied load.

The code MAAP quantifies the above statements by considering a specimen nodalized into N discrete laminae with individual temperatures prescribed as an initial condition. There is thus N separate stresses, whose weighted sum must equal the applied load, and one creep rupture time for the entire specimen. Each stress, temperature, and rupture time combination must fall on the correlation in **Error! Reference source not found.** and the total load must be borne by all the specimens. Therefore, we have a system of N+ 1 equation and unknowns.

$$\log_{10} \sigma_{ksi} = m_l * LMP + b_l \tag{4}$$

$$\ln \sigma = m * LMP + b \tag{5}$$

where
σ_{ksi} = stress in ksi,
σ = stress in Pa
m_l = fit parameter (line slope) defined by **Error! Reference source not found.**,
b_l = fit parameter (line intercept) defined by **Error! Reference source not found.**.

We have N equations in the form of equation (1) relating the local temperature, local stress, and the rupture time:

$$\ln \sigma_i = m * T_i \left[c_1 + c_2 \ln t_r\right] + b \tag{6}$$

where i is the local index. The local balance equation is:

$$N\sigma_{avg} = \sum_i \sigma_i \tag{7}$$

where σ_{avg} = average stress, Pa

The average stress is defined as the total load divided by the total specimen cross-sectional area.

The stresses calculated from equations (6) and (7) must not exceed the ultimate stress of the material. When the stress calculated by the method above exceeds the ultimate stress, the stress is limited to the ultimate stress by replacing equation (6) with:

$$\sigma_i = \sigma_y(T_i) \qquad (8)$$

where σ_y = ultimate stress, Pa.

In the purpose of this study, three cases were analysed by MAAP4.0.5 and their results evaluated thereafter. The comparison between some specific variables and the events of the important scenarios was performed.

The base accident scenario starts with loss of all feedwater (MFW FORCED OFF, AFW FORCED OFF) including the disabled following engineering safety systems:

- HPI (High Pressure Injection) FORCED OFF
- LPI (Low Pressure Injection) FORCED OFF
- NO RCFC (Reactor Containment Fan Coolers)
- NO CONTAINMENT SPRAYS
- PS (Primary System) MAKEUP OFF
- LETDOWN SWITCH OFF

There were no parameter changes from original assumptions from NEK parameter file except prevention of hydrogen burn either in primary circuit or containment.

3 ANALYSIS

Three BDBA (Beyond Design Bases Accident) cases of LOAF (Loss of all feedwater), with manually controlled forced injection (LPI is manually actuated in the case CREEP1 just before predicted time for HL (hot leg) creep failure) in reactor vessel, were analysed by MAAP4.0.5. Important parameters for creep failure prediction according to the presented methodology were changed in the sensitivity cases.

JNUTUB and JNBTUB are the steam generator tube node numbers for tube rupture calculations in the unbroken and broken steam generators, respectively. These parameters allow the model to use the appropriate temperatures in the creep rupture calculations. The nodes are discussed in the PSHS-P subroutine description in the User's Manual. For U-tube steam generators the values can be 1 through 20, with the recommended value being 1, i.e., the lowest and hence hottest node on the hot-side "out" flow tubes. We did not change these parameters to favorize creep failures in the both SGs.

Case CREEP1

In the case CREEP1 analysis, core is uncovered and maximum core temperature has exceeded 2499 K at 4445 seconds but the LPI is recovered just before HL creep failures and recirculation is allowed when RWST is depleted. LPI did not prevent both hot legs creep failures and core was not quenched in the observed time window (13000s) but there was no reactor vessel failure and core condition is stable. SG U-tubes creep failures criteria have not been exceeded.

Events summary for CREEP1 scenario is the following:

42.282	REACTOR SCRAM
42.282	MSIV CLOSED
1080.487	BROKEN S/G DRY
1080.841	UNBKN S/G DRY
1570.744	Q/T RUPTURE DISK FAILED
2526.782	MCP SWITCH OFF OR HI-VIBR TRIP
2897.722	CORE HAS UNCOV
4445.235	MAXIMUM CORE TEMPERATURE HAS EXCEEDED 2499 K
5200.001	LPI SWITCH NO FORCED OFF
5432.730	BROKEN HOT LEG RUPTURE
5436.586	LPI ON
5437.481	UNBROKEN HOT LEG RUPTURE
5442.004	PZR EMPTY
5507.338	ACCUMULATOR WATER DEPLETED
11421.371	RWST WATER DEPLETED
12970.794	RECIRC SYSTEM IN OPERATION

Case CREEP2

For CREEP2 sensitivity case, the variables AG0BHL and AG0UHL (opening areas of HL creep failures) were set to 0.0 m^2 to prevent brake of hot legs due to exceeding creep failure criteria. Without LPI, HPI and AFW injection, core overheated (maximum core temperature has exceeded 2499 K at 4445 second) and reactor vessel fails at 9383 seconds. Under original precaution for model of creep failures (where SG U-tubes is calculated with «standard» methodology: known tube thickness FERSGT), SG U-tubes creep failures were happen at 5814.seconds for SG#1 and at 5864 seconds for SG#2.

Events summary for CREEP2 scenario is the following:

42.282	REACTOR SCRAM
42.282	MSIV CLOSED
1080.487	BROKEN S/G DRY
1080.841	UNBKN S/G DRY
1570.744	Q/T RUPTURE DISK FAILED
2526.782	MCP SWITCH OFF OR HI-VIBR TRIP
2898.292	CORE HAS UNCOVERED
4445.235	MAXIMUM CORE TEMPERATURE HAS EXCEEDED 2499 K
5814.318	UNBROKEN SG TUBE RUPTURE
5864.372	BROKEN SG TUBE RUPTURE
7343.622	RELOCATION OF CORE MATERIALS TO LOWER HEAD STARTED
7345.788	RELOCATION OF CORE MATERIALS TO LOWER HEAD
9383.903	RV FAILED

Case CREEP3

Sensitivity case CREEP3 was run with modified variable FBVSGT (100.0 towards 0.0 in original NEK parameter file) to favorize SG tube creep failure. FBVSGT is the bobbin voltage for the faulted tube. If this value is greater than 0, it is used to calculate the faulted tube thickness instead of parameter FERSGT. The tube thickness is correlated to the burst pressure and bobbin voltage as follows:

- Burst pressure: PBUKSI = -1.37E0*LOG(FBVSGT)+7.85E0
- Tube thickness: XTHT = XTSG * PBUKSI/11.E0

where XTSG is the input parameter for the tube wall thickness.

The variables AG0BHL and AG0UHL (opening areas of HL creep failures) were not set to 0.0 m^2 and operator action to recovery AFW system injection in the both SGs were modelled after 5200s. It was presumed to check if AFW injection is able to prevent hot leg creep failures and SG U-tubes creep failures (expected around 5800 seconds) happened in CREEP2 sequence analyses. CREEP3 calculation shows that there were no SG U-tubes creep failures but both HLs failed (creep failure criteria have been exceeded). We could not conclude that delayed AFW injection is success criterion for assumed scenario CREEP3.

Events summary for CREEP3 scenario is the following:

42.282	REACTOR SCRAM
42.282	MSIV CLOSED
1080.487	BROKEN S/G DRY
1080.841	UNBKN S/G DRY
2526.782	MCP SWITCH OFF OR HI-VIBR TRIP
2897.722	CORE HAS UNCOV
4445.235	MAXIMUM CORE TEMPERATURE HAS EXCEEDED 2499 K
5200.001	MOTOR-DRIVEN AUX FEEDWATER ON
5262.445	BROKEN S/G NOT DRY
5262.445	UNBKN S/G NOT DRY
5454.920	BROKEN HOT LEG RUPTURE
5459.920	UNBROKEN HOT LEG RUPTURE
5530.664	ACCUMULATOR WATER DEPLETED
11377.723	RELOCATION OF CORE MATERIALS TO LOWER HEAD STARTED
16567.289	RV FAILE

On the following pictures are shown the average corium temperature and RCS pressure for three different cases, as discussed up.

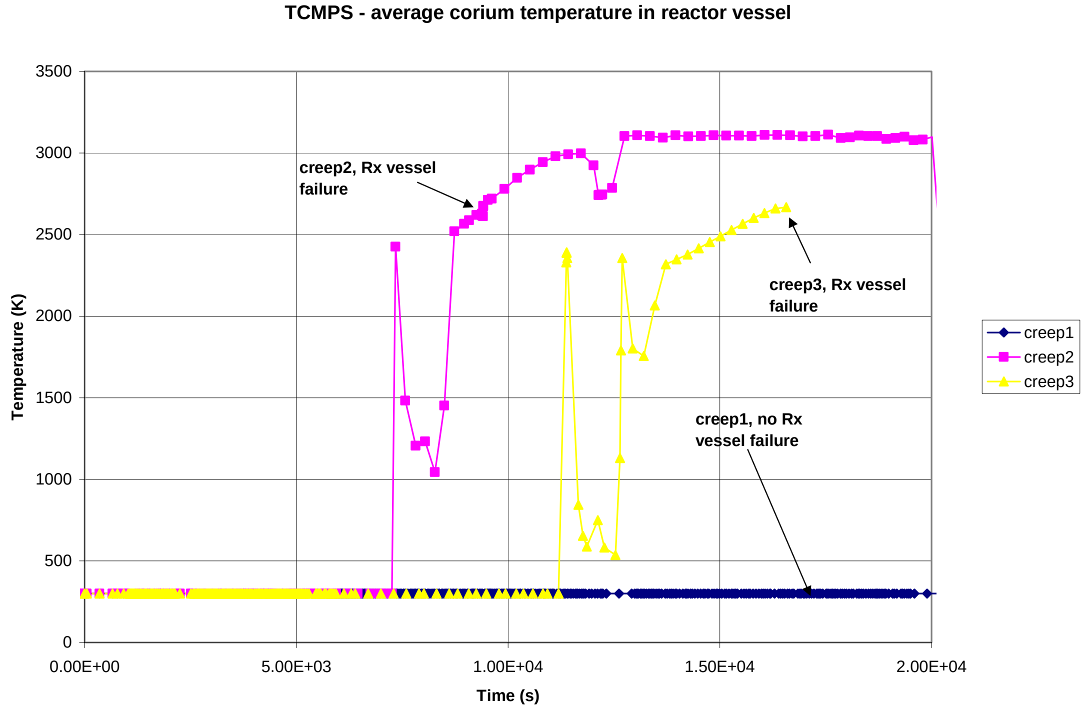

Figure 1: The average corium temperature in the function of time

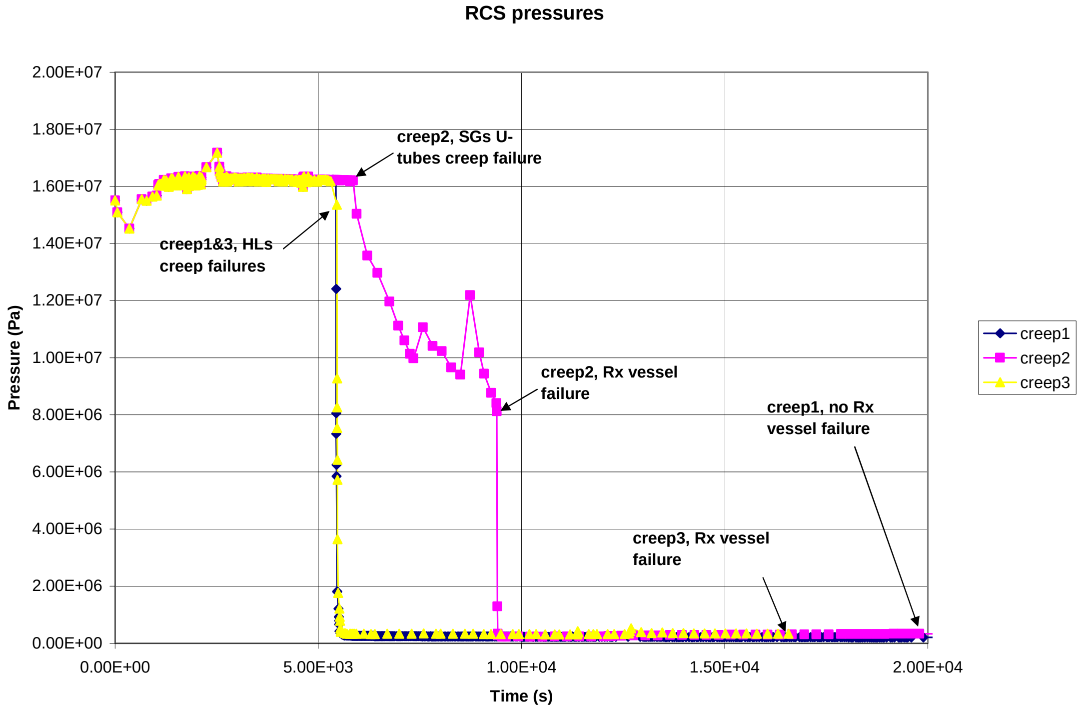

Figure 2: RCS pressure in the function of time

4 CONCLUSION

The preliminary study of possible creep failures of HLs and SGs U-tubes in the severe case of loss of all FW (LOAF) with beyond design bases unavailability of safety systems, shows that the importance of the generic SAMG recovery action (also the highest priority action in NPP Krsko plant specific SAMGs) to inject of AFW to SGs is prejudiced for the accident sequences when severe core degradation occurred and that more importance has to be focused on recovery of water injection (LPI, HPI or charging pump) to reactor vessel. Results of CREEP3 case show that even if delayed (severe core degradation occurred) injection of AFW into SGs is success and prevent SG U-tubes creep failures, hot leg creep failures and consequence reactor vessel failure are occurred.

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