Availability and Reliability Analysis of Independent Core Cooling at Oskarshamn 3

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Abstract: In unit 3 at Oskarshamn NPP an independent core cooling function has been installed (OBH). Besides incorporating the OBH function in the PSA, an analysis has also been performed of its availability and reliability. As the OBH function is designed to operate during long time periods and under severe conditions, the mission time was extended to 72 hours. Even though a "standard PSA" is supposed to be a realistic assessment, compromise is necessary in terms of the assumptions and simplifications, which may or may not contribute to the results of the PSA. Such assumptions and simplifications are of course an important aspect of the uncertainties. When a single system or function is analyzed, the importance of these may be more significant. A crucial part of the analysis was therefore to identify and reduce embedded conservatisms in the PSA. As a prolonged mission time was studied, another important aspect covered in the analysis was the repair of failed components. As the analysis covered both power operation mode and shutdown, different conditions for conducting repair were considered. The presentation will focus on challenges encountered and how they were handled including how the results were evaluated, i.e., was it possible to demonstrate that the OBH function is as reliable as expected.
Key words: PSA, PRA, Reliability, Availability

1 INTRODUCTION

In response to the Fukushima Dai-ich event in March 2011 the Swedish Radiation Safety Authority SSM in 2014 set out requirement that all operating Nuclear Power Plants in Sweden must be equipped with an independent core cooling function (OBH) by December 31st 2020 at the latest. In short, the requirements that needs to be fulfilled by the independent core cooling function are that the function shall be able to keep the core cooled for a duration of at least 72 hours without relying on external electrical grid or already available auxiliary power supply, i.e., an ELAP scenario (ELAP – **E**xtended **L**oss of **AC** **P**ower).

At Oskarshamn unit 3, an independent core cooling system has been installed which has its own dedicated diesel generator, independent from the other emergency diesel generators and gas turbines on site, a cooling water supply and residual heat removal that is independent from those dedicated to other safety systems.

An important part related to the design and installation of the independent core cooling function at Oskarshamn 3 has of course been to update the Safety Analysis Report (SAR) including the Probabilistic Safety Assessment (PSA) and necessary procedures such as Emergency Operating Procedures (EOP) and Severe Accident Guidelines (SAMG) (see paper FR84 for PSAM 16 – *PSA implementation of the Independent Core Cooling and New EOPs/SAMGsat Oskarshamn 3*).

The focus of this paper is to present the availability and reliability analysis that has been conducted for the OBH function at Oskarshamn 3 and what challenges that was encountered and how they were handled.

1.1 Definitions

The first part of the analysis was to define what definitions the analysis was to provide response to:

Availability – A system's ability to be in a condition at the onset of a scenario (time zero) so that it is able to fulfill its functional requirements. For the OBH function, which is a standby function, this means to determine the likelihood that the OBH function will not fail to start given the conditions of different scenarios.

Functional Safety – The ability of a system to fulfill its functional requirements during the period of time it has been designed for (mission time) and the conditions that will prevail during this time. For the OBH function this means to determine the likelihood that it will not fail during a mission time of 72 hours for different scenarios.

Reliability – The reliability of a systems is determined by combining the availability and the functional safety of a system. In addition, aspects such as the systems maintainability and organizational aspects of the maintenance organization also is included. Even though such aspects have also been looked into for the OBH function at Oskarshamn 3, those are not the focus of this paper.

2 METHODOLOGY

The baseline PSA model (Level 1, internal events) developed for Oskarshamn 3 was used as basis for the analyses. As the mission time used in this is 20 hours (with additional 28 hours for Level 2) the mission time needed to be extended to 72 hours for the analysis of functional safety. The functional safety ($\boldsymbol{R}$) was then calculated as the complement to the failure probability during the 72 hours mission ($\boldsymbol{Q_{72h}}$) according to formula (1).

$$R = 1 - Q_{72h} \tag{1}$$

As the focus of the availability analysis was to study the likelihood that the OBH function is not at a failed state at the onset of a scenario (time zero) it had to be considered what could make the function to be in a failed state that is not already included in the PSA. Factors that could make the system unavailable at time zero were defined as:

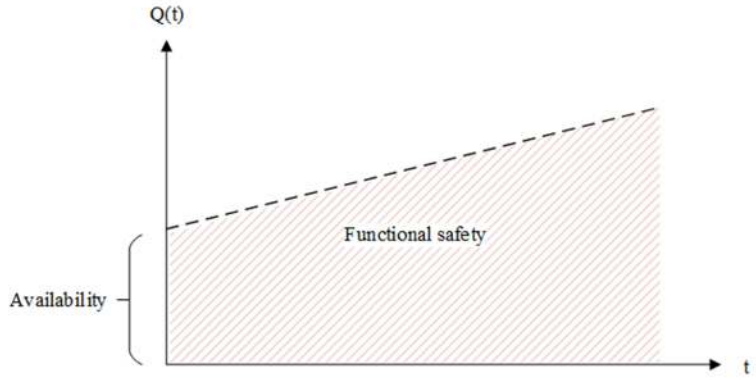
- Ongoing functional tests ($\boldsymbol{Q_{Test}}$)
- Ongoing maintenance or repair ($\boldsymbol{Q_M}$)
- System failures that could cause the failure mode "fail to start per demand" where the demand is defined by the conditions given by the initiating events considered ($\boldsymbol{Q_{Syst}}$). Such failures can be random, commons cause related or related to human errors.

The likelihood that the system fails at the onset of a scenario ($\boldsymbol{Q_{T=0}}$) can then be calculated according to formula (2).

$$Q_{T=0} = Q_{Test} + Q_M + [1 - (Q_{Test} + Q_M)] \times Q_{Syst} \tag{2}$$

Taking both the availability and the functional safety as defined above into account the reliability of a system could be visualized as in **Figure 1** below.

Figure 1   Relationship between availability and functional safety



2.1 Initiating events considered

As both analysis of the availability and the functional safety of the OBH function needed to be considered the conditions for different scenarios, an extract of all possible initiating events (scenarios) from the PSA model were selected consisting of:

- No specific initiating events
- Large top break LOCA
- SCRAM with no other specific conditions
- Loss of off-site power
- Clogging of cooling intake

In case any of the above listed scenarios were made up of multiple initiating events (only large break LOCA) the initiating event within that group which contributed most to the core damage frequency was selected.

For analysis of refueling outage the only initiating event considered were loss of residual heat removal (RHR).

2.2 Handling of conservatisms in the baseline PSA model

It is not unusual in a PSA to have some conservative assumptions and simplifications and as long as they do not have any significant impact on the core damage or release frequencies they are often left as they are. When the individual system fault trees in a PSA are analyzed such conservatisms and simplification may become more significant though. This was also very much true for the system fault trees in the baseline PSA model of Oskarshamn 3 for the systems that together form the OBH function. As these system fault trees did form the basis for the analyses conducted such conservatisms and simplification had to be dealt with before the analyses could be performed. Such conservatisms and simplifications were identified by analyzing the minimal cutsets generated by the system fault trees in the baseline PSA.

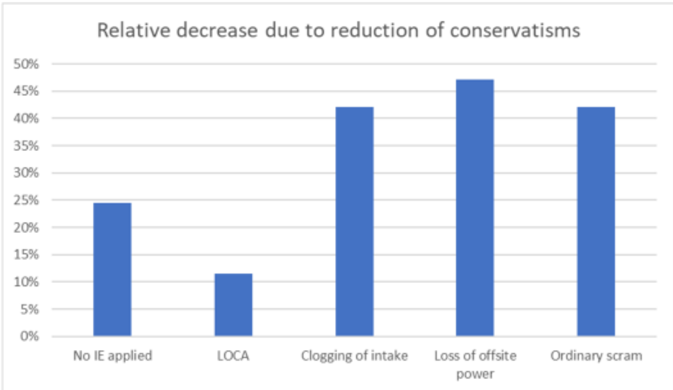
In general, two different types of conservatisms/simplifications were identified:

1. Specific event combinations identified through review of minimal cutsets generated from fault tree analysis for the systems that were included in the OBH function.
2. Assessment of the likelihood that components are unavailable due to corrective maintenance upon demand.

Regarding the first type, four different event combinations were identified during the review of cutsets considering the contribution from each cutset to the failure probability of the OBH function. The conservatisms could either be related to the assessment of operator actions (or lack of credit of operator action) or conservative assessment of failure data for equipment where no operating experience have been recorded. In each case, a reduction factor of 1/10 was implemented in the fault trees which removed the identified cutsets from the top cutsets.

The second type of conservatism was of a more generic nature. The probability for a component to be taken out of service for corrective maintenance, and therefore being unavailable upon demand, is assessed using the failure data for the component and the conservative assumption that the repair time always equal the allowed outage time according to the Technical Specifications. As the majority of the components included in the Oskarshamn 3 PSA have failure data that is derived from the T-Book the measure which this was dealt with was simply to use the repair times listed in the T-Book instead. This adjustment was only made for the components included in the cutset generated from the fault tree representing the OBH function. As can be seen from **Figure 2**, the measures taken reduced the unavailability of the OBH function with a factor of 2 for the initiating events clogging of intake, loss of offsite power and ordinary scram; and a factor of 9 for the LOCA case. When no initiating event conditions were applied, the reduction was a factor of 4.

Figure 2 Relative decrease in system unavailability due to reduction of conservatisms (20 hours mission time).

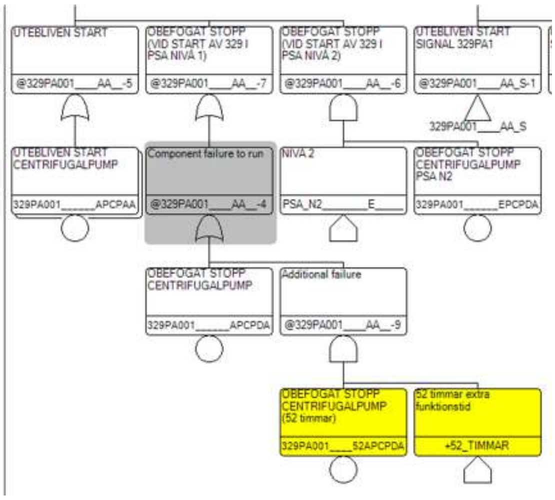


Reduction of the conservatisms embedded in the baseline PSA was an important part of the analysis as the need for future sensitivity analysis reflecting the importance of such conservatisms was eliminated.

2.3 Increase of mission time to 72 hours

As the analysis of functional safety should cover a mission time of 72 hours an extension of the 20 hours mission time that is considered in the baseline PSA model (PSA Level 1) of relevant components was necessary. The relevant mission time basic events included in the fault tree structure of the OBH function were identified in an iterative process starting with all mission time basic events and then deselect those component types for which an extended mission time didn't have to be considered. Examples of component types excluded from the extension of mission times are fuses, measurement devices and similar "electrical" components. The iteration started with more than 800 mission time basic events and at the end "only" 74 remained. The extension of the mission time was then made by using the macro language functionality in RiskSpectrum PSA to add a 52-hour component specific mission time basic event to all remaining basic events as shown in Figure 3.

Figure 3 Extension of mission time from 20 hours to 72 hours by adding 52 hours.

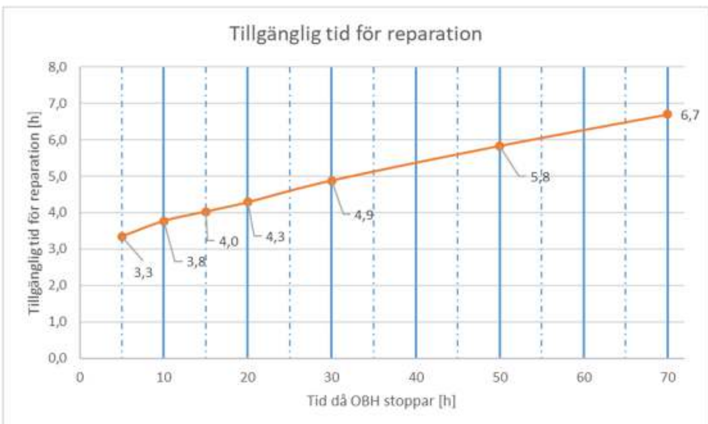


2.4 Modelling of repair of failed components

Since the analysis of functional safety was to span over a mission time of 72 hours, repair of failed components was considered. It shall be noted that this is not considered in the baseline PSA which meant that an analysis of available time for repair and necessary repair times was needed. The necessary repair time could be taken from the same data source as component failure data was taken from, in this case the T-Book. In the T-Book, both plant specific and generic repair times is provided for a number of component types. In order not to be optimistic, the longest of the two was used for the analysis. In addition, additional 2 hours was added to the repair time listed in the T-Book to in order to take into account that there may be extra time elements not considered in the T-Book, e.g., diagnosis time.

The other component was to assess how much time that were available for repair. For this, several MAAP runs were made for a general accident scenario after turbine trip. In those scenarios, the OBH function was defined as “running successfully” initially and it was “switched off” (failed) at a certain time point whereafter MAAP determined how long time it would take until core damage occurred, see **Figure 4**. Two different time intervals were then created, one representing failures within the first 20 hours (based on the mission time in the baseline PSA) and the other representing failures during the additional 52 hours (20+52=72 hours mission time in total). For the first time interval, the available time for repair was set to 4 hours and for the other time interval the available time for repair was set to 6 hours.

Figure 4 Available repair time (y axis) as a function of time when OBH fails (x axis).



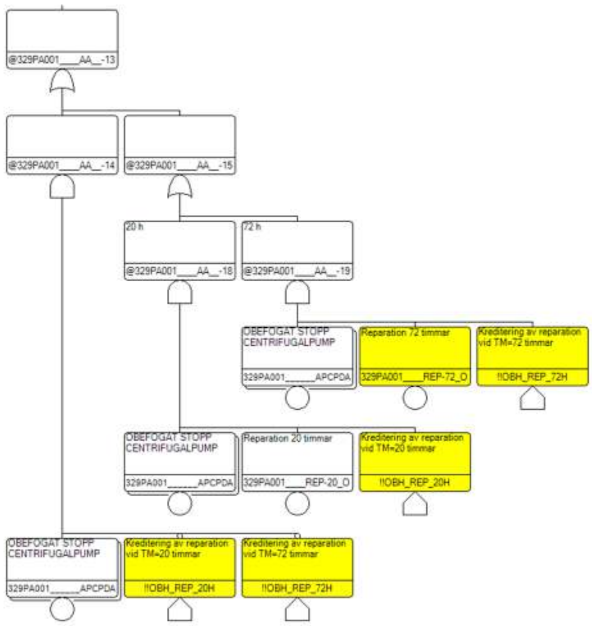
The likelihood of failed repair during each time interval was finally determined with formula (3) for those components for which repair was deemed possible. This was only done for components which failures contributed significantly to the functional safety of the OBH function, i.e., they showed up in the top cutsets.

$$Q_{rep} = e^{-T_a/MTTR} \tag{3}$$

Where:	Q_{rep}	Likelihood for failed repair
	T_a	Available time
	MTTR	Necessary time (Mean Time To Repair)

In **Figure 5** an example is provided showing how repair was modelled using house events to enable switch on and off the credit for repair.

Figure 5 Example of modelling of repair considering in which time period component failure occurred.



2.5 Model adaption for availability analysis

The purpose of the availability analysis was to determine the likelihood that the OBH function is not at a condition to fulfill its function at the onset of a demand, i.e., fail to start at time zero. To be able to use the same fault trees as for the analysis of functional safety the below described adaptions were needed.

Elimination of failure modes
For the purpose of only generating cutset that consists of failures that could occur at the onset of a scenario (time zero) all mission time basic events and category C operator action basis events were assigned a failure probability of zero.

Unavailability due to functional tests
As the time that a component might be unavailable during periodic testing is not considered (general simplification) in the Oskarshamn 3 PSA an investigation was made for those components that were modelled as periodically tested in the fault trees representing the OBF function. This was conducted by revisiting the Technical Specifications to get a clearer view on what tests that are being performed and how often in combination with information received from operators regarding the duration of the tests and if the tested components are available or not when the test is conducted. In several cases it

could be concluded that it was reasonable to assume unavailability during periodical testing could disregarded except for seven components. For those components the unavailability due to periodic testing was simply determined by calculating the proportion of the duration of all testes conducted of a reactor year and use this time fraction as a measure of component unavailability due to functional tests.

2.6 Modelling of ELAP scenario

As the OBH function was specifically designed to handle an ELAP scenario it was of interest to be able to study this scenario in particular. This was done by adding additional boundary conditions to the loss of offsite power (LOOP – loss of 400 kV grid) initiating event which set the below components to a failed state:

- Diesel generators except the one dedicated for the OBH function
- Gas turbines
- 130 kV grid
- Return of 400 kV grid

2.7 Outage specific aspects

Analysis of refueling outage had of course to take outage specific aspects into account, including the fact that system configuration and success criteria for the OBH function were different compared to power operation.

Otherwise, a similar exercise to identify conservatisms in the outage PSA was conducted in the same manner as for power operation in the baseline PSA, see section 2.2. Besides those measures taken for the baseline PSA the only additional measure that had to be taken for outage conditions was adjustment of the human error probability (HEP) for one operator action.

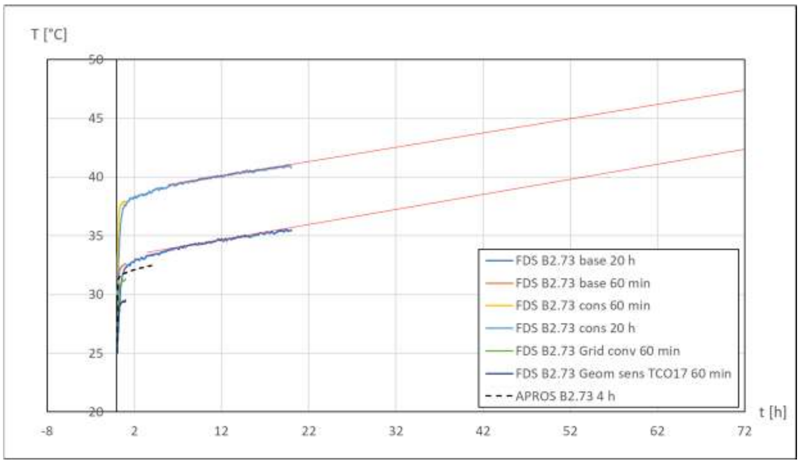
It had also to be investigated if any additional mission time basic events had to be assigned the additional 52-hour mission time to be able to analyze a mission time of 72 hours. It was concluded that those adjustments that had been made for power operation also covered the needs for refueling outage, see section 2.3

2.8 Other general assumptions and simplifications

The bullet list below lists the most important assumptions and simplifications in the analyses that were performed.

- The availability of the OBH function was only analyzed for power operation.
- No specific analyses were made for low power modes of operation (only power operation and outage period covered).
- Parametric uncertainties were considered in the same manner as in the baseline PSA model.
- In terms of prolonged mission time (from 20 to 72 hours) and the related system requirements on support systems a linear interpolation was made, see **Figure 6** for room cooling where the requirement is that the room temperature must stay below 50 degrees Celsius. Based on this, a general assumption was made that existing system requirements for 20 hours mission time was also sufficient for 72 hours mission time.
- As the analyses performed were based on faut tree analysis no positive credit was taken from sequence based (event tree) conditions such as pro-longed time to perform operator actions in specific sequences.

Figure 6 Linear interpolation of system requirements for room cooling



3 ANALYSIS & RESULTS

3.1 Functional safety

The results from the analysis of functional safety are displayed in **Figure 7** and **Figure 8**. The parametric uncertainty analysis for power operation gave that the 95th percentile for the LOCA scenario is approximately 97% while other initiating events had their 95th percentile close to 99% when repair was considered. For the outage period, the 95th percentiles were calculated to approximately 97% for the first phase and 99% for the other phases.

Figure 7 Functional safety, 72 hours mission time – power operation

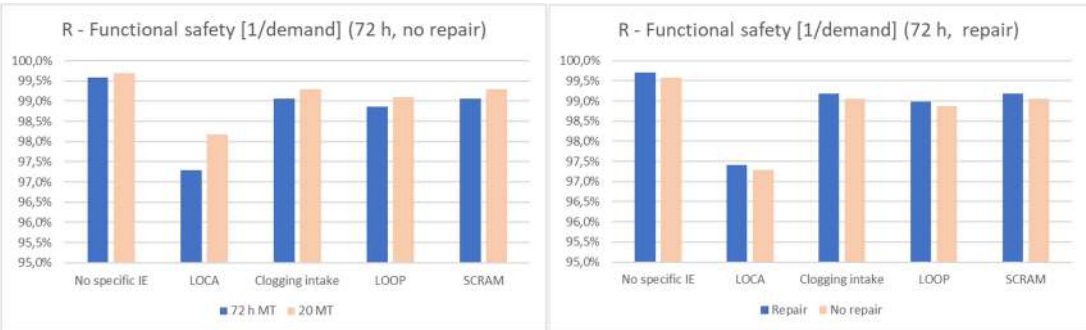
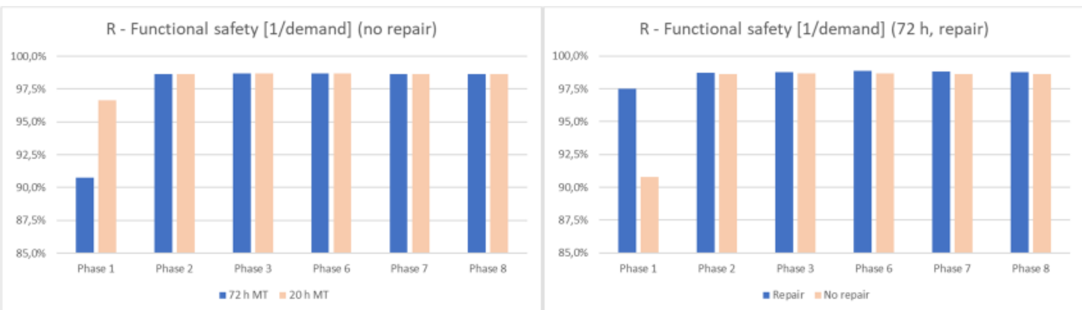


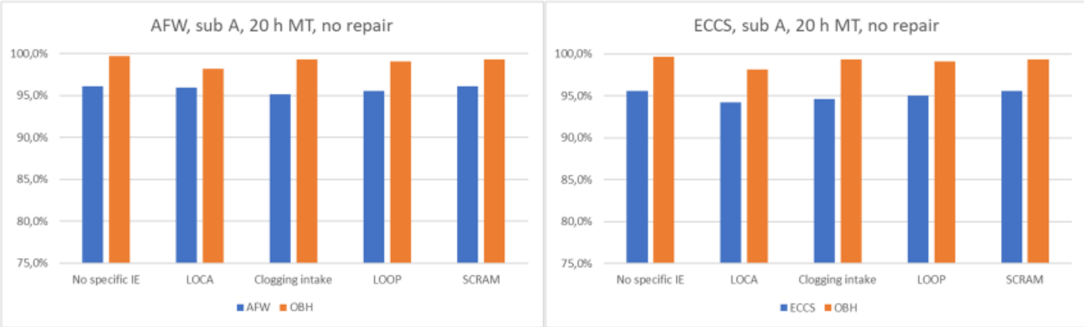
Figure 8 Functional safety, 72 hours mission time – outage



In order to be able to judge if the calculated functional safety of the OBH function is meeting what can be expected a comparison was made with the functional safety of the emergency feedwater system (EFW) and the emergency core cooling system (ECCS). As the OBH function in principle is a one train system the comparison was made against only one train in AFW and ECCS respectively.

This comparison is presented in **Figure 9** and from this it could be concluded that the functional safety of the OBH system is similar or better than for one train of AWF and ECCS.

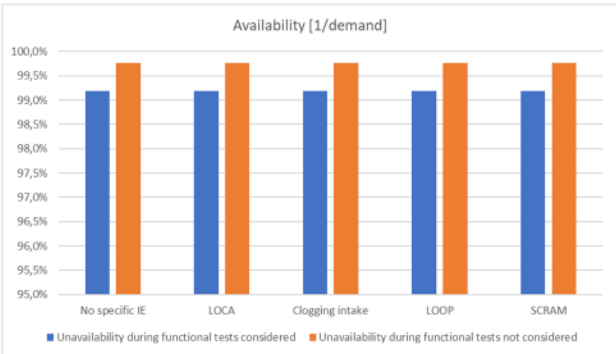
Figure 9 Functional safety, comparison with one train in AFW and ECCS, 20 h mission time – power operation



3.2 Availability analysis

The results from the availability analyses are provided in **Figure 10** and it can be concluded that the availability is not dependent on initiating event, and it is greater than 98,5% (95th percentile) even if component unavailability due to functional tests is considered.

Figure 10 Availability of the OBH function – power operation



3.3 Special cases

In **Figure 11** and **Figure 12** the results from some special analyses cases are shown, the first being the functional safety when also the conditions from the availability analysis are considered, i.e., component unavailability due to functional tests. The second case is comparison between the ELAP scenario, see section 2.6, with loss of off-site power.

Figure 11 Functional safety considering component unavailability due to functional tests – power operation

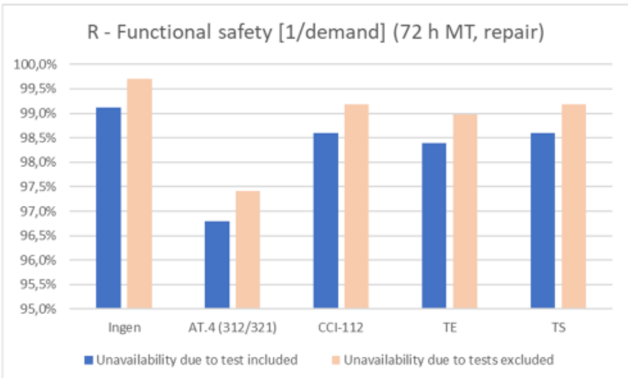
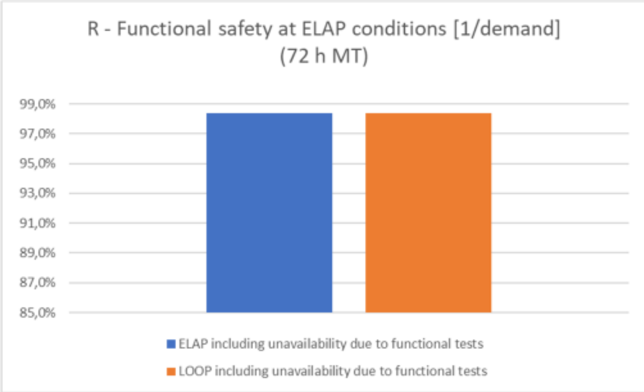


Figure 12 Functional safety during ELAP scenario – power operation



4 CONCLUSION

The conducted analyses have demonstrated that the functional safety for the OBH function is similar, or even better, compared to one train in the AFW and ECCS systems respectively and it has also demonstrated that the OBH function is well suited to handle an ELAP scenario. The analyses have thereby provided a good basis for OKG to conclude that the reliability of the OBH function (including its availability and functional safety) should be as high as can be expected.