POST-FUKUSHIMA EXTENSION OF THE SAFETY MARGINS IN NPPs: MODELING, IMPLEMENTATION AND INSIGHTS FROM A PSA PERSPECTIVE

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Given the post-Fukushima safety demonstrations and analysis conducted by NPP Goesgen-Daeniken, which were performed based on new aggravated hazard assumptions, it became clear that the previous, relatively high safety margins, especially those related to seismic hazard and flooding, have been exhausted. Consequently, a need for enhancement, retrofitting measures has been implicated with the goal for re-establishing the formerly high safety margins. This paper addresses, from a PSA standpoint, the extension of the special emergency safety functions which are foreseen to be implemented in the course of the following 3-5 years at KKG. The qualitative implementation of the foreseen adaptations in the plant's PSA model and the related methodology therefore are discussed. The quantitative impact of the foreseen changes, seen as a reduction of the core damage frequency and the large early release frequency are presented.

I. INTRODUCTION

The NPP Goesgen-Daeniken (KKG) is a 3-loop KWU PWR 1035 MWe single-unit NPP that started with commercial operation in 1979. As part of the analysis and assessment regarding the accident at Fukushima in March 2011, a program for extension of the functional capabilities of the special emergency safety system was set up.

According to the ENSI Guideline A06[1], the need for enhancements is to be evaluated using the plant-specific PSA. Retrofitting measures should be implemented, where appropriate, when the average CDF is higher than 1E-5 / yr or the risk profile is not balanced (i.e. in cases where one IE category contributes to more than 60% of the CDF and this contribution is higher than 6E-6 / yr). This second criteria are met in KKG PSA risk profile by the seismic IE group. Thus, there is a need for retrofitting to reduce the seismically-induced risk. On the other hand, another ENSI guideline G02[2] – to be published – purports that it should be ensured, via implementation of new enhancement measures, that the occurrence of very improbable events combining multiple failures of the primary safety- and special emergency safety systems will not imply severe core damage. The bunkered special emergency safety systems are meant to cope against extended accident conditions of station blackout (SBO), which at KKG implies the loss of the primary emergency diesel generators (EDGs). Fixed installed equipment should be favoured before the mobile emergency equipment and should be designed in such a way that it the plant would be brought in a safe state and autarkic kept in this state for 72 hrs[3].

This paper addresses five of the foreseen extensions of the special emergency safety functions are modelled and analysed with the plant's PSA model: *i.) Automatization of the process of partial cool-down via the main steam relief valves*; *ii.) Installation of two new special emergency HP safety pumps*; *iii.) Automatic and seismically-induced reactor trip from the ZX*; *iv.) Extension of the battery capacity*; *v.) Installation of passive isolation valves for the instrumentation lines penetrations of the containment*.

II. METHODOLOGY

The main emergency safety system at KKG is designed as a 3+1 safety system train system. The trains are separated among each other, and each of the trains is equipped with a separate EDGs. The emergency core cooling system (ECCS) is designed as 4x100% redundant safety system. There is an additional 2x100% redundant bunkered emergency safety system (special emergency feedwater system, special ECCS, residual heat removal (RHR) system), called the special emergency safety system, or simply the ZX-system. It comprises two additional special EDGs. Hence, the primary and the special emergency safety systems are, already by design, covering a wide range of accidents such that for many of the accident scenarios at KKG 6 x 100% redundancy of emergency safety systems (24 h mission time) can be guaranteed.

As discussed in the introduction, there is need for enhancement of the spectrum of accidents that can be coped by the ZX-system at KKG such that the bunkered special emergency safety systems would be able to cope against extended accident conditions of SBO (loss of the primary emergency DGs). In that direction, an upgrade, i.e. enhancement of the functions of the ZX-system is foreseen in several parallel measures. The plant's PSA model is adopted as a basis for the modelling of the planned measures. It is an Event Tree linking approach PSA model, develop with the RISKMAN™ software[4].

Five of these measures[3, 5] are subject of this paper. Due to the page number limitation of this paper, the specifics of each of the measures are discussed in the continuation in general.

II.A. Measure 1 (M1)[3, 5]: Automatization of the process of partial cool-down via the main steam relief valves

The purpose of this modification is to reduce the number of challenges of the steam generator safety valves (SGSV) and to avoid opening of first pressurizer safety valve. This will be done by implementation of automatic signals for opening of steam generators (SG) relief valves (SGRVs) and subsequent unit cooldown. Reaching the pre-set parameters will cause relief valves opening and cooling down. During class 3 accidents, the primary side pressure should not exceed 1.3 of design pressure and secondary side pressure should be sufficiently limited. This task is performed by SGSVs mounted on each SG. To avoid opening of first pressurizer safety valve and/or SGSV the control of SGRV should be extended. This will reduce the frequency of challenges of both pressurizer and SGSVs and respectively it will reduce the probability of these valves to remain spuriously opened.

Currently the steam dump in case of failure of turbine bypass to the condenser is accomplished through SGSV. Then the cooldown speed of 100K/h or 45K/h is set manually from the main control room (MCR) or 10K/h from the second, emergency control console in the ZX-building. The cooldown process of the plant could be interrupted any time. A stuck-open atmospheric dump or relief valve can be isolated, whereas a stuck-open safety valve cannot be isolated.

The foreseen changes are related to the automatization of the partial and complete cooldown process. The partial cooldown means cooldown of the corresponding SG with 100K/h from MFW pressure 82bar to 74bar. The steam release is provided by SGRV and it is used in cases where main heat sink by turbine bypass is not available or main steam isolation valve is closed. With the implementation of this measure, this automatic cooldown can be initiated from the ZX building or by MCR. The complete cooldown is similar to the partial with the difference that the cooldown process with 100K/h is carried on till 1bar pressure is reached. The steam dump again is the preformed by the SGRV. The automatic cooldown signals from ZX building override the manual signal (partial cooldown with 100K/h overrides manually induced cooldown with 100K/h).

II.B. Measure 2 (M2)[3, 5]: Installation of two new special emergency HP safety pumps

The purpose of this modification is to widen the range of LOCA accidents that can be coped in extreme conditions. Namely, currently there is no option at KKG for LOCA compensation in case of SBO (failure of the 4 EDGs). In other words, the existing high pressure injection pumps (HPIP) of the ECCS system are not backed by the special EDGs.

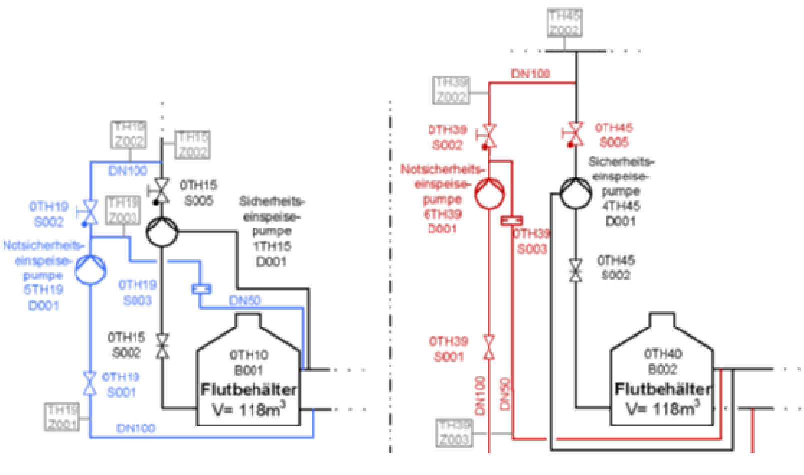

Fig. 1. Affected systems (left) and direct cause category (right).

Therefore, this measure foresees the installation of two new HPIPs, referred to with their abbreviation NSEP further in the text, which will be backed by the two special EDGs so that they would provide high pressure injection and compensate in the early phases of small LOCA scenario overlapping with SBO conditions. The required new high pressure injection pumps NSEP should be integrated into the existing trains TH10 and TH30 of the ECCS. According to the developed concept the high pressure injection with the NSEP starts shortly after the incident start. Normally the NSEP are turned off. The total water amount in the tanks is 944 m³ (4 flooding tank pairs). Since the NSEP be suction side connected to the flooding container of strands TH10 and TH30 and NNKP to the flooding container of strands TH10 and TH30, a maximum of 708 m3 (3 flooding tank pairs) available. The low-pressure injection is carried out with the existing emergency low pressure pumps (NCP) of the strands TH10 and TH30. Figure 1 presents, as an example, the integration of one of the NSEP pumps in train TH10.

II.C. Measure 3 (M3)[3, 5]: Automatic and seismically-induced reactor trip from the ZX

II.C.1. Automatic reactor trip from ZX-building

Currently, there is option for manual actuation of the reactor trip from the “secured area”, i.e. the ZX-building. The idea, foreseen with this measure, is to extend this manual actuation with an additional option for automatic initialization of the reactor trip from the ZX-building. Consequently, along the already existing high level of protection given the available automatic reactor trip from the “unsecured area” (ZE-building), there will be a provision for automatic reactor trip of the plant directly from the ZX-building also in case of relatively rare-events that are to be coped with by the special emergency safety systems. Given the automatic reactor trip from the ZX-building, new criteria/limit values will be installed such that small LOCAs and secondary side leakages would be possible to cope with. These criteria / limit values are already available within the reactor protection system (RPS) logic. Currently, they are processed either in the ZE- or the ZX-building. All the contacts from the “unsecured area” are being currently interconnected for the initialization of reactor trip. The triggering of the automatic reactor trip from the ZX-building is foreseen to take place when one of the following limit values will be reached: Pressure drop MFW line > 4 bar/min; MFW line pressure > 82 bar; SG Level < 9.0 m; PZR Level < 2.2 m; PZR Level > 9.3 m; Primary pressure > 162 bar; Difference pressure containment versus atmosphere > 30 mbar; Rotational speed of 2 of 3 MCP < 94 % nominal. The above-mentioned criteria / limit values are already available in the ZE-building and being used for the automatic triggering of the reactor trip. These criteria are now foreseen to be additionally used for the automatic reactor trip triggering from the ZX-building as well.

II.C.2. Seismic power limitation (seismic reactor shut-down)

An additional function for automatic reactor power limitation (reactor shut-down) in case of PGA (horizontal/vertical) of ca. 0.02 g should be implemented in order to enhance the shutdown capability of the plant. This additional function of so-called seismic reactor shut-down should be performed via the existing control rods insertion function (Samtel-STEW, STEW-RESA). The response of the function implicates turbine trip as well. For the purpose of generating the earthquake signals, which will be connected to the already existing shut-down logic as explained above, 8 new earthquake detectors will be installed in the annulus building. The limiting value is set such that already by very small peak ground accelerations (PGA) of ca. 0.02 g the insertion of all the control rods instantaneously will be triggered before safety-relevant equipment is impacted by relatively higher seismic accelerations that would follow. Similarly as in the case of automatic reactor trip triggered from the RPS (and implemented via the 6-contact -system) also here, in this case of seismic reactor shut-down, a turbine trip will be consequently implicated. Also, in case of an automatic reactor trip triggering from the RPS and because of the coupling of the signals from the RPS, this second automatic seismic shut-down path will be used as a diversified option (vis-à-vis the 6-contact-system reactor trip path) to de-energize the coils of the control rods drives.

II.D. Measure 4 (M4)[3, 5]: Extension of the battery capacity

This measure is intended to increase the capacity of the DC batteries in the ZX building so as to ensure: Emergency power supply of the instrumentation for a time period of T>3 days without charging the batteries; Minimum 4-fold switching over (manipulation) of all valves, which in emergency situation, accompanied by failure of both the special EDGs, are required for implementation of measures on makeup water supply for the spent fuel storage pool and the refueling water storage tank; Minimum 2-fold switching over of all motor driven valves (1-st and 2-nd closing) with the purpose of primary and secondary side isolation.

To implement the purposes of this measure, the existing system of 24V batteries is replaced by a system of 220V batteries. Respectively, a completely new concept for power supply is developed as shown in Figure 2. The new DC system includes 220V DC buses (FH52 and FH62), 220-V batteries (FH55 and FH65) and current rectifiers for charging (FH51 and FH61). For 220V DC bus (FH52 and FH62), as before the power supply from 380V sections (FM и FL) is provided by the current rectifiers (FH51 and FH61). During the first 24 hours, the FR71 bus power supply (power supplying the measuring equipment) is provided from the system of the new 220V batteries, line 5 and 6. After voltage drop below the minimal voltage, the FR71 bus is power supplied from the new system for 24V batteries from line 7, providing the electricity for the emergency instrumentation for at least 48 hours.

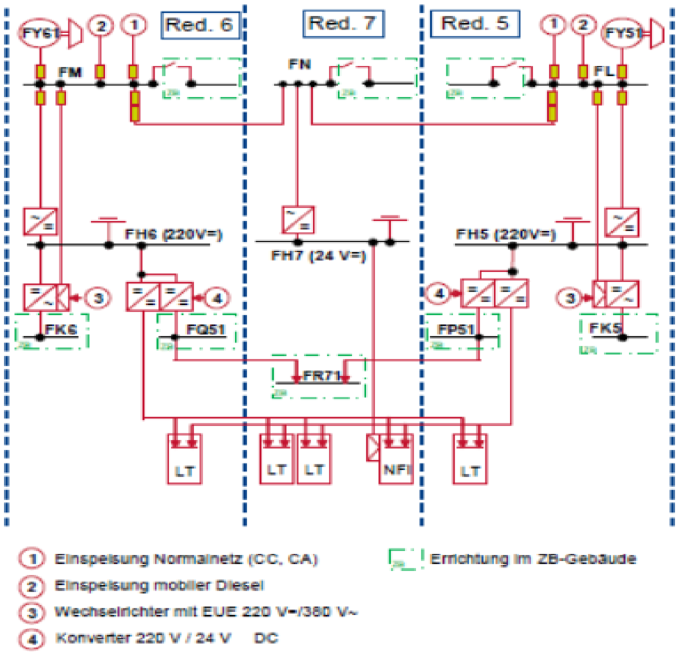

Fig. 2. Power supply diagram after implementation of the new batteries.

II.E. Measure 5 (M5)[3, 5]: Installation of passive isolation valves for the instrumentation lines penetrations of the containment

The purpose of this measure is to minimize passively containment bypass leakage from the primary and secondary circuit. The measure relates to small measuring lines DN15 and DN10. The measurement lines in pressurized reactor are constructed in such a way that although the system is integrated within the containment, the transmitters are located outside the containment. By this arrangement, the electrical parts are protected against the immediate effects of leakage incidents. The case of an annulus leakage from a measuring line from the primary circuit leads to the infringement of the two barriers against activity release, namely:

- Primary side, and
- Containment.

The above said as well as given the objective for minimizing the humidity and temperature distribution in the annulus, infers the fact that a fast and reliable limitation of leak flow should be pursued. This can be realized by implementation of a technical solution with passively acting leak stop valves (LSV). From the other side it is ensured that inadvertent common cause closure of passive isolation valves is practically impossible. This can be achieved by a combination of qualification and issuing requirements and a full routine testing of the functionally relevant parts. If necessary, it is possible to provide a small remaining bypass current in shut-off valve to keep the measurement even in the event of incorrect closure. By using a completely passive device, which does not require any external power supply and without any control, a fault closure due to failures in a control level can be excluded from the outset.

The described hereinafter leakage stop valves valve (Figure 3) are a possible solution proposed for rapid and reliable limiting leakage flow. The pressure difference across the valve seat is an additional trigger criterion. The isolation valves are to be used mainly in differential pressure lines (measurement lines DN15 and DN10) that are connected to high-energy components inside the containment. Since the operating temperature of these systems is usually considerably higher than the room temperature, it can be used for leak detection and triggering the closure of the valves. The basic idea of the proposed new LSV is based on the response of the valve already in cases with minor leakages. As leakage indicator here is the changing medium temperature in leak-induced flow through the valve. Moreover, in order to isolate even in cold medium states (in startup or shutting-down) and to achieve passive leakage barrier, the pressure difference provided with leak-related medium throughput on the valve seat is as an additional trigger criteria.

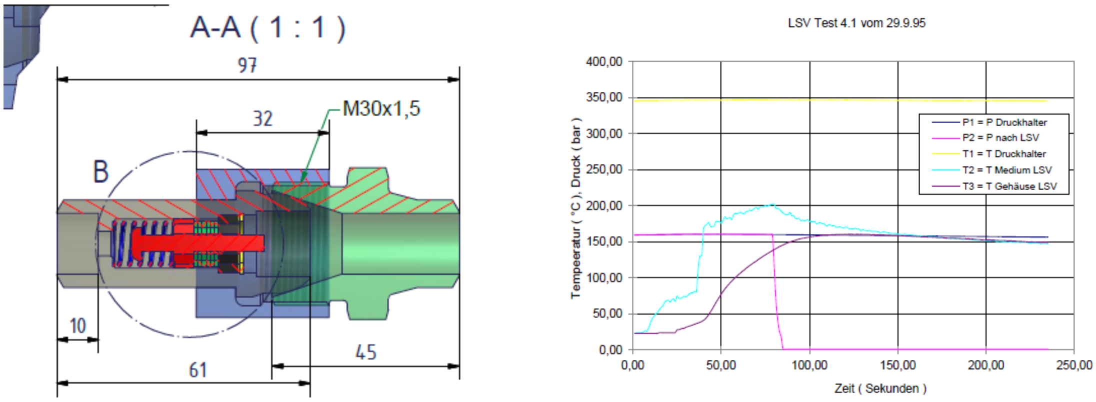

Fig. 3. Passive LSV (left); Measured parameters during a test run of a LSV.

Figure 4 presents an example of the foreseen points of installation of the LSVs in the first loop.

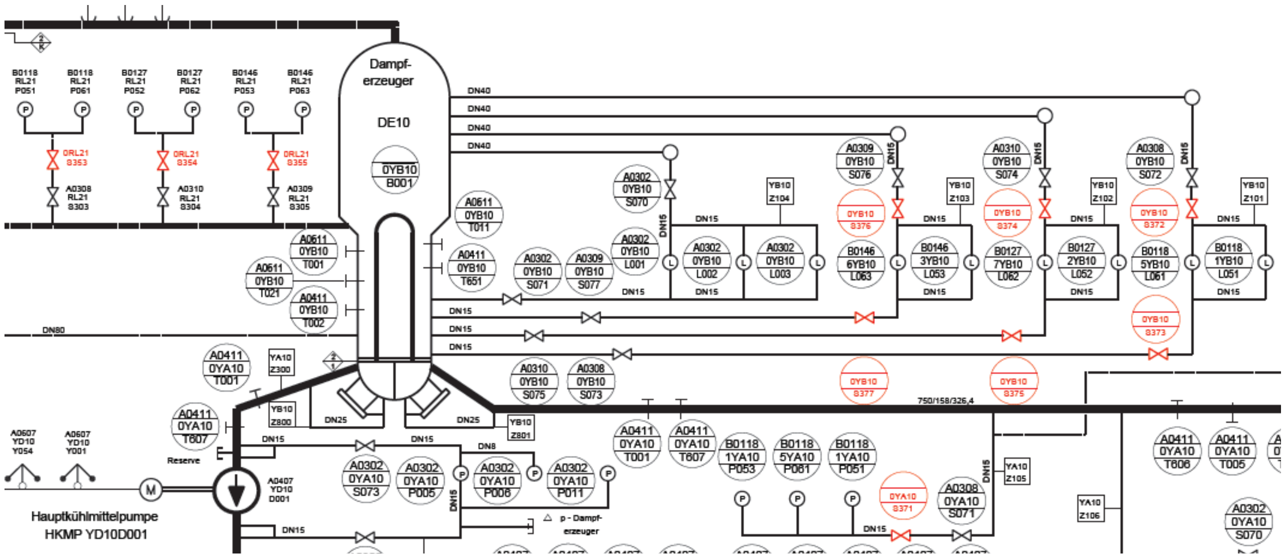

Fig. 4. Installation points of the LSVs for the Loop 1 measurement penetration lines.

III. ANALYSIS AND RESULTS

All the five measures are separately modelled in the base model GPSA15[6]. The modelling encompasses changes in the data (failure distributions), changes/adaptation of existing system or sub-system fault trees (FT), creation of new FTs as well adaptation of some of the event trees (ET). The effects of implementation of each of the five measures on the plant risk (Level 1 & 2 PSA) are briefly discussed, quantitatively and qualitatively. Due to the page number limitation of this paper, only selected results are presented. Also, the summarized effect of all 5 measures is presented.

Table I and Table II present the summarized results, in terms of impact on CDF and LERF respectively, of the implementation of each of the five measures separately as well as the combined effect of all of the measures integrated together in the PSA model.

TABLE I. Impact of plant modifications on CDF

Initiating Event Category (Group)	Existing results – base model		All measures		Measure 1	Measure 2	Measure 3	Measure 4	Measure 5
	CDF [yr^{-1}], Mean	% of Grand Total(Mean)	CDF [yr^{-1}], Mean	% of Grand Total (Mean)	CDF [yr^{-1}], Mean	CDF [yr^{-1}], Mean	CDF [yr^{-1}], Mean	CDF [yr^{-1}], Mean	CDF [yr^{-1}], Mean
LOCAs	6.14E-07	3.7%	2.21E-07	1.7%	3.29E-07	5.89E-07	6.14E-07	6.14E-07	4.98E-07
SGTRs	2.14E-08	0.1%	3.21E-09	0.0%	3.22E-09	2.11E-08	2.14E-08	2.14E-08	2.18E-08
Transients	1.19E-08	0.1%	9.28E-09	0.1%	1.19E-08	1.19E-08	1.19E-08	1.18E-08	1.19E-08
Internal Event (Total)	**6.47E-07**	**3.9%**	**2.34E-07**	**1.8%**	**3.44E-07**	**6.22E-07**	**6.47E-07**	**6.47E-07**	**5.32E-07**
Fire	1.52E-06	9.2%	1.22E-06	9.5%	1.52E-06	1.51E-06	1.52E-06	1.41E-06	1.52E-06
Internal Flooding Events	5.51E-10	0.0%	5.20E-10	0.0%	5.50E-10	5.48E-10	5.51E-10	5.49E-10	5.51E-10
Internal Plant Hazard Events (Total)	**1.52E-06**	**9.2%**	**1.22E-06**	**9.5%**	**1.52E-06**	**1.52E-06**	**1.52E-06**	**1.42E-06**	**1.52E-06**
Seismic Event	1.22E-05	74.5%	9.40E-06	73.4%	1.22E-05	1.22E-05	1.14E-05	1.22E-05	1.05E-05
External Wind and Tornadoes	1.83E-06	11.1%	1.77E-06	13.8%	1.83E-06	1.83E-06	1.83E-06	1.72E-06	1.83E-06
External Flood	7.27E-08	0.4%	6.89E-08	0.5%	7.27E-08	7.27E-08	7.27E-08	6.86E-08	7.27E-08
Aircraft Crash	1.17E-07	0.7%	1.16E-07	0.9%	1.16E-07	1.17E-07	1.17E-07	1.16E-07	1.17E-07
Cooling Water Intake Plugging	7.81E-10	0.0%	7.23E-10	0.0%	7.80E-10	7.81E-10	7.80E-10	7.54E-10	7.80E-10
External Event (Total)	**1.43E-05**	**86.8%**	**1.14E-05**	**88.6%**	**1.42E-05**	**1.43E-05**	**1.34E-05**	**1.41E-05**	**1.25E-05**
ATWS	4.64E-06	28.2%	4.33E-06	33.8%	4.64E-06	4.64E-06	4.34E-06	4.64E-06	4.64E-06
Core Damage Arrest	4.38E-07	2.7%	3.91E-07	3.1%	3.34E-07	4.13E-07	4.38E-07	4.37E-07	4.05E-07
CDF (Grand Total)	**1.64E-05**	**100%**	**1.28E-05**	**100%**	**1.60E-05**	**1.64E-05**	**1.56E-05**	**1.62E-05**	**1.45E-05**
Reduction [%]	**/**	**/**	**22 %**	**/**	**2.4 %**	**0.15 %**	**5.2 %**	**1.5 %**	**11.5 %**

TABLE II. Impact of plant modifications on LERF

Initiating Event Category (Group)	Existing results – base model		All measures		Measure 1	Measure 2	Measure 3	Measure 4	Measure 5
	LERF [yr^{-1}], Mean	% of Grand Total	LERF [yr^{-1}], Mean	% of Grand Total (Mean)	LERF [yr^{-1}], Mean	LERF[yr^{-1}], Mean	LERF[yr^{-1}], Mean	LERF [yr^{-1}], Mean	LERF [yr^{-1}], Mean
LOCAs	7.88E-09	0%	1.72E-09	0%	3.26E-09	7.81E-09	7.88E-09	7.87E-09	5.96E-09
SGTRs	2.02E-08	1%	1.94E-09	0%	1.93E-09	2.01E-08	2.02E-08	2.01E-08	2.02E-08
Transients	7.14E-10	0%	2.23E-10	0%	7.13E-10	7.04E-10	7.14E-10	7.09E-10	7.14E-10
Internal Event (Total)	**2.88E-08**	**1%**	**3.88E-09**	**0%**	**5.91E-09**	**2.86E-08**	**2.87E-08**	**2.87E-08**	**2.683E-08**
Fire	6.25E-07	17%	4.21E-07	14%	6.23E-07	6.24E-07	6.24E-07	6.19E-07	6.28E-07
Internal Flooding Events	1.16E-11	0%	7.03E-12	0%	1.16E-11	1.14E-11	1.16E-11	1.13E-11	1.16E-11
Internal Plant Hazard Events (Total)	**6.25E-07**	**17%**	**4.21E-07**	**14%**	**6.23E-07**	**6.24E-07**	**6.24E-07**	**6.19E-07**	**6.28E-07**
Seismic Event	2.89E-06	80%	2.43E-06	82%	2.89E-06	2.89E-06	2.57E-06	2.89E-06	2.73E-06
External Wind and Tornadoes	7.93E-08	2%	8.20E-08	3%	7.93E-08	7.93E-08	7.93E-08	4.07E-08	7.93E-08
External Flood	3.08E-09	0%	2.95E-09	0%	3.08E-09	3.08E-09	3.08E-09	1.56E-09	3.08E-09
Aircraft Crash	5.15E-09	0%	3.32E-08	1%	5.08E-09	5.15E-09	5.14E-09	5.13E-09	5.14E-09
Cooling Water Intake Plugging	2.85E-11	0%	2.36E-11	0%	2.85E-11	2.85E-11	2.85E-11	1.87E-11	2.85E-11
External Event (Total)	**2.98E-06**	**82%**	**2.55E-06**	**86%**	**2.98E-06**	**2.98E-06**	**2.66E-06**	**2.94E-06**	**2.82E-06**
ATWS	1.89E-06	52%	1.61E-06	54%	1.89E-06	1.89E-06	1.59E-06	1.89E-06	1.90E-06
LERF (Grand Total)	**3.64E-06**	**100%**	**2.98E-06**	**100%**	**3.60E-06**	**3.63E-06**	**3.31E-06**	**3.59E-06**	**3.47E-06**
Reduction [%]	**/**	**/**	**18 %**	**/**	**0.85 %**	**≈ 0 %**	**9.0 %**	**1.4 %**	**4.5 %**

As it can be derived from Table I, the overall reduction of the CDF for internal events is 4.13E-07 /y, which corresponds to 64% reduction of the CDF for this category of IEs (Figure 5). The overall reduction of the CDF for the internal plant hazard events is 2.96E-07 /y, which corresponds to 19% reduction of the CDF for this category of initiating events (Figure 5).

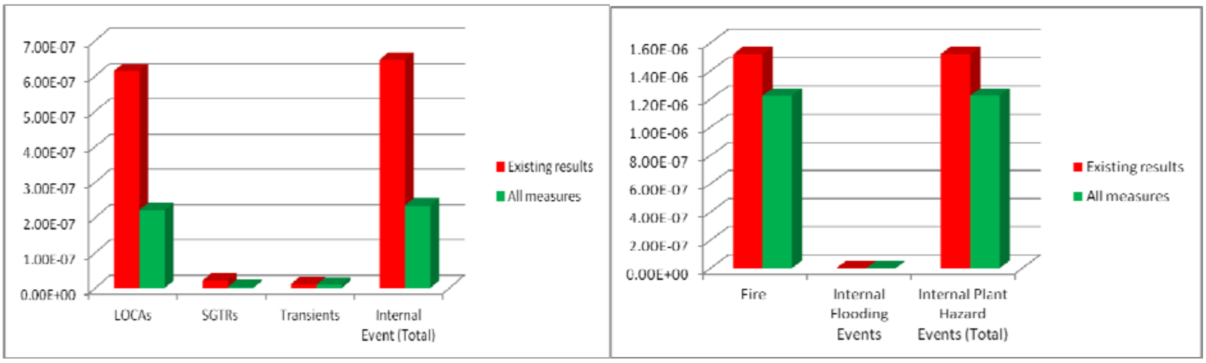

Fig. 5. Impact of plant modifications on CDF for internal events (left) and for internal plant hazard events (right).

As it can be derived from Table I, the overall reduction of the CDF for external events is 2.91E-06 /y, which corresponds to 20% reduction of the CDF for this category of initiating events. (Figure 6).

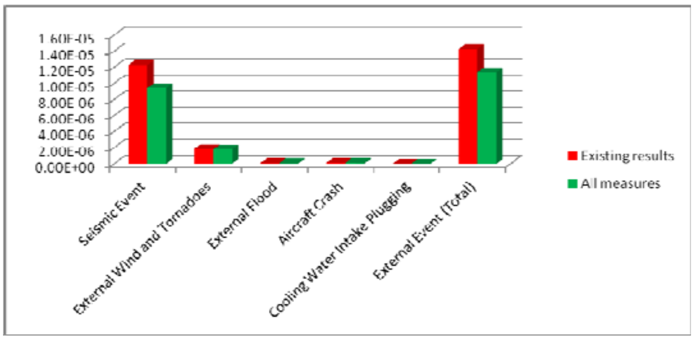

Fig. 6. Impact of plant modifications on CDF for external events.

Figure 7 shows the % reduction of LERF for separate initiating events. The most considerable reduction of LERF is observed for initiating events with primary leak (first of all for primary to secondary leaks). This result is mainly due to the implementation of Measure 1. Measure 1 contributes to the reduction of the contribution of the remaining initiating events with small and medium primary leak.

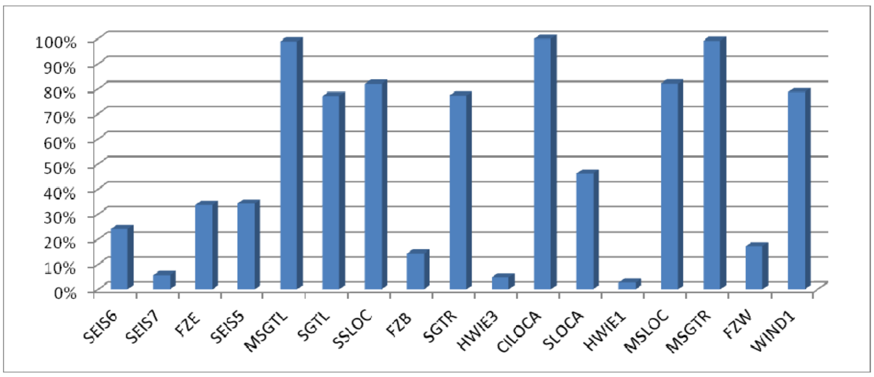

Fig. 7. LERF reduction for different initiating events.

IV. CONCLUSIONS

This paper is related to the enhancements and retrofitting measures that have been implicated given the post-Fukushima safety demonstrations and analysis conducted by KKG. The goal of these enhancements is the re-establishing of the formerly high safety margins. The special emergency (bunkered) safety system is the subject to the above-mentioned enhancements. A spectrum of measures was suggested, accepted and a work report was compiled. Due to the page number limitation of this paper, five of the measures are briefly addressed. The plant's PSA model is used as a basis for the modelling and analysis of the planned measures. The quantitative impacts of the foreseen changes, seen as a reduction of the core damage frequency and the large early release frequency are presented and discussed.

The largest reduction of CDF is registered for M5 (just above 11%), Measure M3 (just above 5%) and Measure M1 (ca. 2.5%). The integrated effect of all measures provides a reduction of CDF by 22%. Actually, the result is determined by the seismic impacts for PGA niveaus over 0.6g. It should be noted that the Measures M5 and M3 have the greatest overall reduction, as they directly affect the contribution of the seismic events. In practice, the complete risk reduction, expressed in terms of CDF, corresponds to the reduction of the contribution of the seismic events. The higher decrease observed for M5 is due to the impact of the measure on the category with internal initiating events as well. In practice, all measures have influence on the CDF from internal events, which determines the substantial decrease of the CDF for this category – 64% decrease. Measure M1 determines to the greatest extent the CDF reduction for this category. The result for Measure M1 confirms the fact that the automation of the performance of the individual safety functions is obviously critical for the overall safety enhancement. **T**he overall reduction of the CDF for the internal plant hazard events is ca. 19% CDF for this category of initiating events. The overall reduction of the CDF for external events is ca. 20% of the CDF for this category of initiating events.

In terms of the LERF, practically the same trends as for the CDF results are observed. This is expected in view of the fact that the measures as a whole are intended to increase the unit's capabilities to react to the relevant type of initiating events in order to reduce the core damage probability. The largest reduction is registered for the Measure M3 (about 9%), while for Measure M5 about 4.5% is observed. Again, the main reason for the observed effect is the direct effect on the contribution of the seismic events, which at the existing risk profile is of essential significance. The effect of Measures M1 and M4 is within the frames of 1% reduction of LERF. The integrated effect of all measures provides reduction of LERF by 18%. Despite of the relatively small absolute reduction of LERF, actually, the biggest percentage reduction of LERF for the individual categories of initiating events is observed for the internal initiating events (86%) and for the internal plant hazard events (33%). The reduction of LERF from external events is 14%, and they are basically due to the reduction of the contribution of the seismic impacts.

ACKNOWLEDGMENTS

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