Generic Issues on Sump Clogging

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Abstract

On July 28, 1992, strainers on the suction side of the ECCS pumps in Barsebäck NPP Unit 2 became partially plugged with mineral wool after a safety valve opened because steam impinged on the thermally-insulated equipment and released mineral wool. This event pointed out that the plugging of strainers after loss-of-coolant accidents was underestimated. The findings from this event led first to modifications in other BWRs but also to research activities for PWR sump designs.

Results of experiments at Karlstein and GKSS have shown that under realistic boundary conditions during LOCA released insulation material leads to a higher transportation rate in the sump and a larger deposition rate at the sump strainer and in the core than assumed before.

Based on the new knowledge a new statement on the „Requirements for the demonstration of effective emergency core cooling during loss-of-coolant accidents with release of insulation material and other substances" was issued by the German Reactor Safety Commission in July 2004.

Modifications of the insulation, the strainer size and the mesh size at the strainers were carried out in most of the German NPPs to improve the design for emergency core cooling during sump recirculation mode.

1 Introduction

On July 28, 1992, the Barsebäck Nuclear Power Plant Unit 2 was restarted after the annual outage. While the reactor was at 2 percent power and at 30 bar, a leaking pilot valve caused a stuck open safety valve. This valve discharged directly to the drywell. Steam from the open safety valve, impinging on thermally-insulated equipment, dislodged about 200 kg of metal-jacketed mineral wool. An estimated 100 kg of insulation material was washed into the suppression pool. Two of five strainers on the suction side of the ECCS pumps were in service and became partially plugged with mineral wool. Plugging caused pressure to decrease significantly behind the strainers and caused indications of cavitations in one pump about an hour after the event began. The operators successfully back-flushed the strainers and shut down the reactor without additional problems. In the safety analysis for Barsebäck, Unit 2, it was assumed that the strainers would not require back-flushing during the first 10 hours after a loss-of-coolant accident.

In 1993, at Perry Unit 1, two events occurred during which ECCS strainers became plugged with debris. On January 16, ECCS strainers were plugged with suppression pool particulate matter, and on April 14 an ECCS strainer was plugged with glass fiber from ventilation filters that had fallen into the suppression pool. On both occasions the affected ECCS strainers were deformed by excessive differential pressure created by strainer plugging.

On September 11, 1995 at Limerick Unit 1, following a manual scram due to a stuck open safety / relief valve, operators observed fluctuating flow and pump motor current in a loop of suppression pool cooling. The licensee later attributed these indications to a thin mat of fiber and sludge which had accumulated on the suction strainer.

The knowledge from these events and findings from research to resolve the BWR strainer clogging issue led to an enlargement of the strainers at German BWRs in the years 1993 and 1994. The findings from research to resolve the BWR strainer clogging issue have raised questions concerning the adequacy of PWR sump designs. The technical findings of research programs concerning PWRs during the last years demonstrated that the debris generated by a loss-of-coolant accident could be finer and more easily transportable.

Certain combinations of debris (mineral wool and particulate material) can result in a substantially greater head loss than an equivalent amount of either type of debris. In addition, chemical effects can increase head loss.

Based on these findings the German utilities performed a large experimental research program at Karlstein and GKSS in the year 2001. The RSK issued the statement "Requirements for the demonstration of effective emergency core cooling during loss-of-coolant accidents with release of insulation material and other substances" in 2004.

This paper describes the results of the experimental research program of the German utilities, the main aspects of the RSK statement, and the modifications of the strainers in the German PWRs.

2 Problem description

In the event of a loss-of-coolant accident inside the containment, energetic pressure waves and fluid jets would impinge upon materials in the vicinity of the break such as thermal insulation, coatings, concrete, corrosion products and dust /NRC 03/. Debris could also be generated through secondary mechanisms, such as severe post-accident conditions and flooding of the lower containment. In addition, debris can be created by the chemical reaction between chemically reactive ECC solutions used following a LOCA and the materials in the containment. These reactions may result in additional debris such as disbanded coatings and chemical precipitants being generated.

Through transport mechanisms such as entrainment in steam / water discharge from the break and washdown due to condensate flow in the containment, a fraction of the generated debris and other material in the containment would be transported to the containment sump. Subsequently, if the ECCS pumps are operating in sump recirculation flow, the debris suspended in the containment sump would begin to accumulate on the sump strainers or be transported through the ECC system and the primary coolant system to the core.

The accumulation of this suspended debris on the sump strainers can create an almost uniform covering on the strainer, which would tend to increase head loss across the strainer. If a sufficient amount of debris is accumulated on the strainer, the pressure loss across the debris would exceed the net positive suction head (NPSH) required to ensure successful operation of the ECCS pump in sump circulation mode. A loss of the NPSH margin for the ECCS pumps as a result of the accumulation of debris on the recirculation sump strainer could result in degraded pump performance and eventual pump failure.

Debris could also plug or wear components within the ECCS system. The effect may cause a component to degrade to the point where it may be unable to perform its designated function.

Debris can be accumulated at the grid spacers or at the IDF - foot of the fuel element. The effect may cause a reduction of the coolant flow through the core and a degradation of core cooling.

3 Results of the Karlstein and GKSS experimental research program

An experimental research program was performed by order of the German utilities/VGB in the year 2001 to verify and extend the knowledge of effective core cooling during a LOCA with a release of insulation material /FAN 03/.

Three experimental facilities were used to investigate the following items:

- fragmentation of insulation material under realistic LOCA conditions
- sedimentation and transportation of released insulation material in the sump
- deposition and penetration of insulation material at sump strainers
- pressure loss at the sump strainer
- deposition of insulation material and pressure loss at fuel elements

3.1 Fragmentation of insulation material under realistic LOCA conditions

Five large-scale fragmentation tests were performed for insulation cassettes with the mineral wool types MD2 (production year 1980 to 1982) and RTD2 (production year 1983) at Karlstein. The boundary condition in the blowdown vessel was a pressure of 110 bar. The vessel was filled with saturated water. The distance between the break orifice and the original insulation cassettes was 2 D of the orifice diameter (D). The calculated impact pressure was about 13 bar. A comparable impact pressure will be achieved for PWR boundary conditions for a distance of 3 D.

The test has shown that up to 86 % of the insulation material is released if the jet hits the superposed ends of the cassettes. The cassettes were not opened if the cassette was positioned at the opposite side of the impinged pipe. The insulation of one cassette was released at a distance of 15 D when it was hit at the inner side (equivalent to mat insulation).

The results of the fragmentation test are not completely covered by the NRC Cone model (Table 1) /GRS 05/.

Table 1 NRC Cone model release rates

	Distance	Release		
Region		Cassette-type insulation	Mat insulation	Conventional insulation
1	L < 3 D	100 %	100 %	100 %
2	3 D < L ≤ 7 D	50 %	100 %	100 %
3	7 D < L ≤ 30 D	0 %	0 %	100 %

The NRC Cone Model covers the test results for region 1. For PWR boundary conditions it is not demonstrated that the transition region from 1 to 2 is covered by the NRC Cone Model. The NRC Cone Model is not conservative for mat insulation in region 3.

3.2 Sedimentation and transportation of released insulation material in the sump

Five large scale tests were performed for sedimentation and transportation of released insulation material in the sump at GKSS.

The test facility was scaled 1: 4 (length and width 1 : 2, height 1 : 1) compared to a PWR. The sump was rectangular.

The insulation material used in the test was taken from the fragmentation tests. Only the insulation material was used, which was caught in the collecting cage. A large portion of the small fines of released insulation material was lost outside the collecting cage. In addition, the insulation material was first dried before it was added to the break flow. Therefore it is questionable if the insulation material used was really representative.

The fluid temperature of the break flow and the sump was 25 °C. The boron concentration was set to 0 ppm. A time interval of 2 minutes was necessary between the flood phase and the sump recirculation phase due to technical reasons at the test facility. These boundary conditions restrict the direct transfer of the experimental results to a real PWR.

The portion of insulation material that was found on the floor of the sump, was between 58 % and 75 % /GRS 05/. The transport rates to the sump strainer could not exactly be measured because some insulation material was not found (shrinkage) after the test in the test facility. Therefore the transportation rates were between 25 % and 42 % with consideration of the shrinkage and between 20 % und 38 % without consideration of the shrinkage. The highest transportation rates were found in the test with the combination of mineral wool and particulate material (crashed minileit).

3.3 Deposition and penetration of insulation material at the sump strainers

The mesh size of the strainers in the GKSS test facility was 9 x 9 mm. The size of the strainers varied between 1.5 m^2 and 5.5 m^2. Today the PWR-typical strainer size scaled to GKSS is about 5.5 m^2. The deposition of the insulation at the strainers was between 10 % and 32 % with consideration of the shrinkage related to the transported insulation in the sump and between 12 % and 45 % without consideration of the shrinkage /GRS 05/. The higher value for the deposition of insulation at strainers was measured for tests with a small strainer size. The accumulation at the strainers for a reactor-typical strainer size was between 10 % and 15 %. Today the mesh sizes of the sump strainers are 3 x 3 mm in almost all German PWRs. Therefore the data of the GKSS tests cannot be used for deposition or penetration of insulation at the strainers for sump strainer designs in German PWRs.

3.4 Pressure loss at the sump strainer

The evaluation of the pressure losses at the sump strainers for the GKSS test was difficult because always more than one parameter was changed between the different tests. Therefore it was difficult to quantify the dependencies on different parameters. The following dependencies could be identified /GRS 05/:

– the pressure loss increases almost linear with the thickness of the deposited insulation layer
– the pressure loss increases with the flow velocity with an exponent of about 1.15
– the specific pressure loss decreases with increasing flow velocity during the deposition process
– the combination of mineral wool with particulate material (minileit) leads to a strong increase of the specific pressure loss

All data from the GKSS tests were generated for a mesh size of 9 x 9 mm. An additional strainer with a mesh size of 2 x 2 mm was installed behind the sump strainer. The specific pressure loss for the smaller mesh size was much larger. This result gives only an identification of a possible dependence of the specific pressure loss on the mesh size because the measurement device at this strainer was no qualified. The data from the GKSS test for a mesh size of 9 x 9 mm cannot directly be transferred to the actual strainers in German PWRs with a mesh size of 3 x 3 mm.

3.5 Pressure loss at deposited insulation in fuel bundles

Seven fuel bundle tests were performed for the insulation materials MD2 and RTD2 at GKSS. A shortened fuel bundle dummy with three grid spacers was used for the tests. The following parameters were varied during the test:

– flow direction in fuel element
– flow direction of fuel element foot
– amount of insulation material in the test circuit
– type of insulation
– boron concentration

– flow velocity during deposition of insulation

– fluid temperature during deposition of insulation

The following dependencies can be derived from the bundle tests /GRS 05/:

– the pressure loss increases linear with the thickness of the insulation

– the pressure loss increases with the flow velocity with an exponent of 1.2

– the pressure loss is directly proportional to the viscosity of the sump water (temperature dependence)

– the pressure loss increases with boron concentration (2200 ppm compared to 0 ppm→ 15 % to 30 % increase)

– the specific pressure loss decreases with the increase of the flow velocity and fluid temperature (doubling of the velocity and temperature increase from 30 °C to 80 °C leads to a 40 % lower specific pressure loss)

– large deposition at the IDF – foot, no deposition at the standard foot

– no significant dependence of the specific pressure loss on the location of the deposition

– strong dependence of the pressure loss on the type of insulation material and the production year (figure 1)

– flow stagnation or slight flow reversal lead to a drop of the deposited insulation at the IDF – foot. A large flow reversal is necessary at grid spacers.

Based on the above-described dependencies, the measured pressure losses were normalised (Table 2). The normalised specific pressure losses are almost identical.

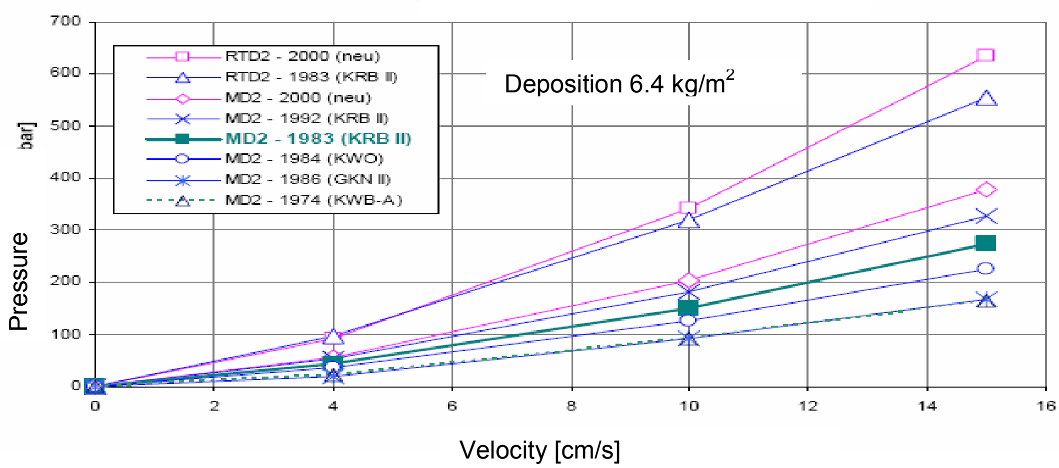

Figure 1 Dependence of pressure loss on type of insulation material and production year

Table 2 Normalization of measured pressure losses

Test	Boron ppm	V cm/s	T °C	deposition kg/m^2	V-deposition °C	T-deposition °C	foot typ	ΔP measured m bar	ΔP_{norm} m bar
1	0	6	30	1.69 (spacer)	3.4	30	IDF	69	43
3	0	5.75	31	0.9 (foot)	3.4	30	IDF	38	47
4a	2200	5.7	30	1.15 (foot)	3.4	30	IDF	54	40
4b	2200	5.8	80	1.6 (foot)	3.4	30	IDF	38	43
5	2200	5.7	34	2.24 (foot)	6.8	80	IDF	63	43
7	2200	5.9	50	1.8 (spacer)	6.8	50	IDF	39	43
ΔP_{norm}	Related to a deposition of 1 kg/m^2, v = 5 cm/s, T = 30 °C, Bor = 2200 ppm (adaption factor 1.31 (test 4b to 1)), V_{dep} = 3.4 cm/s, T_{dep}. = 30 °C (adaption factor 1.69 (test 4b to 5))								

4 Analytical investigations

4.1 Transport inside the containment

The transport methods are first the entrainment of released insulation material with the water phase (larger fines) to the sump and containment internals below the break position and with the steam phase (minor fines) into the containment. COCOSYS analyses have shown that the minor fines entrained by steam are deposited on the floor (59 %) and on the sump (3 %) due to sedimentation and on the wall (38 %) due to condensation /GRS05/. COCOSYS calculated drainage rates up to 20 kg/s into the sump due to condensation of steam. The insulation, deposited on floors and walls, can partly be washed down to the sump by the drainage rate. But the extent of the washdown cannot be quantified.

4.2 Determination of the available NPSH of the ECCS pumps

The available NPSH of the ECCS pumps depends on the water level of the sump and on the subcooling of the sump water. Analyses with the coupled code ATHLET/COCOSYS were performed for a 0.1 F cold-leg and a surge line break in a PWR with licensing boundary condition /GRS 05/ and best-estimate thermohydraulic models. A special water convection model was developed for the sump in COCOSYS derived from CFX analysis results to determine the sump temperature at the inlet of the ECCS suction line. The subcooling of the sump water was calculated at about 20 K at the start of ECCS sump circulation mode (see figure 2). This subcooling shows a large safety margin for the NPSH of the ECCS pumps compared to values, if the RSK guidelines are applied (assumption of saturation temperature in the sump).

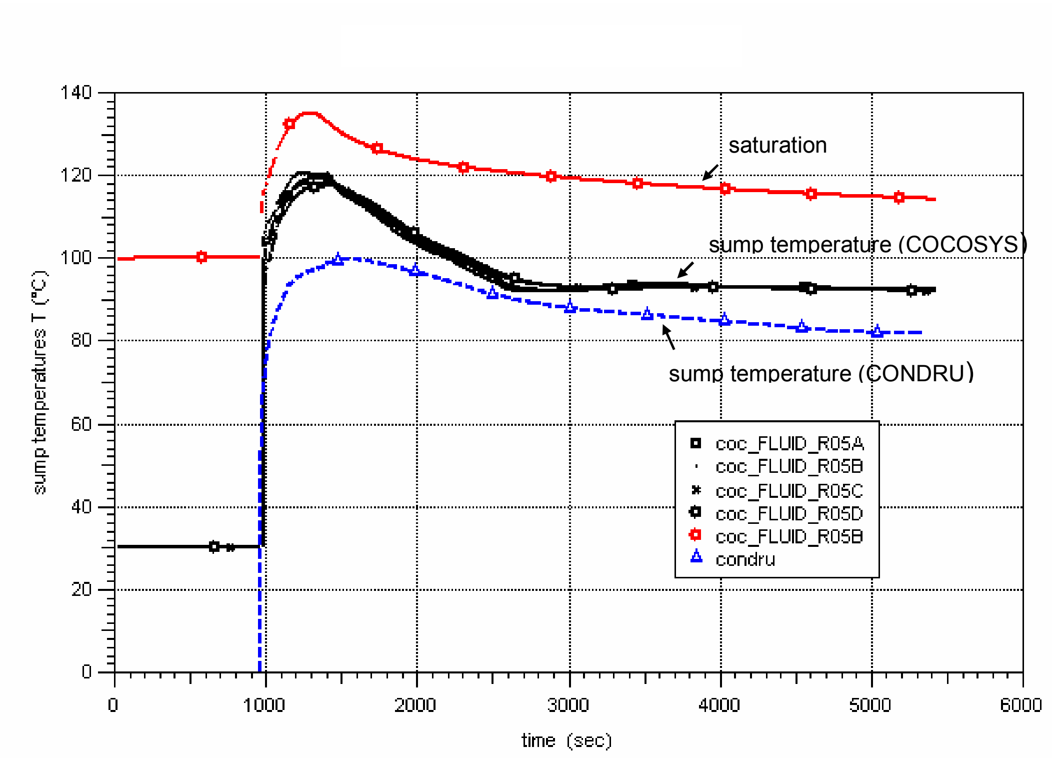

Figure 2 Sump temperatures during a surge line break in a PWR

4.3 Determination of pressure loss in the core

The coolant mass flow through the core is dependent on the open flow paths between the ECCS injection points and the break location. Two phases have to be distinguished /GRS 05/:

– if primary pressure is below secondary pressure, the ECCS mass flow can flow only through the core and the core bypass (injection opposite the break) or directly to the break (injection on break side)

– if primary pressure is above secondary pressure, the ECCS mass flow can flow through the core, core bypass and the steam generator U-tubes or directly to the break.

The core mass flow is strongly reduced if the flow paths through the steam generator U-tubes are open. Therefore the fluid temperatures at the core outlet (for a surge line break) strongly jump to a higher value after the flow through the U-tubes has started (see Figure 3).

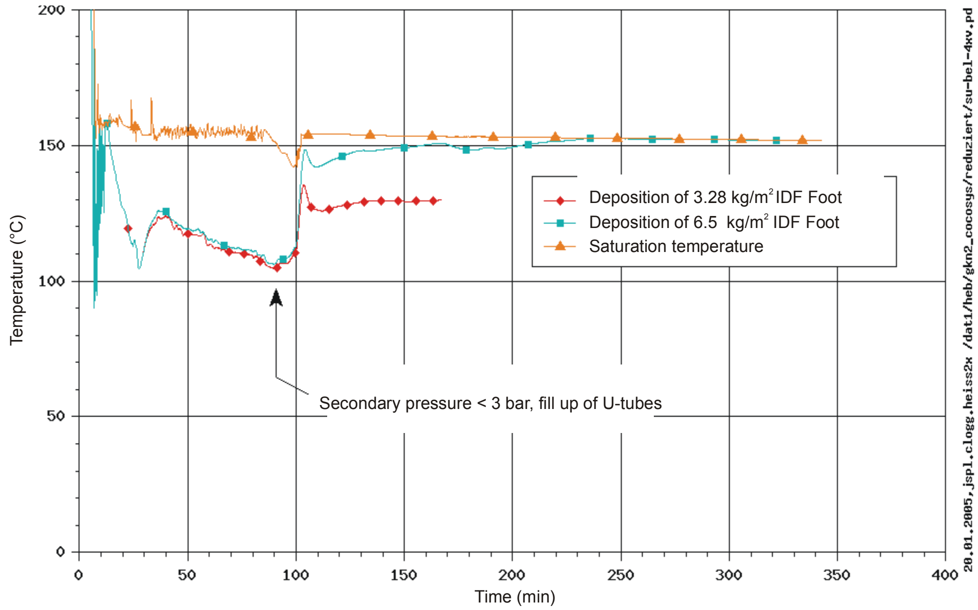

Figure 3 Fluid temperatures at the core exit for a surge line break

Saturation temperatures are calculated for a deposition of 6.5 kg/m^2 at the IDF foot and of 1.9 kg/m^2 at the first grid spacer. The latter value corresponds to a deposition of 19 kg at the first grid spacer for a PWR. The specific pressure loss for the deposition was taken for MD2 from the GKSS bundle test (chapter 3.5).

5 RSK statement for demonstration of effective emergency core cooling during LOCA

The new RSK statement on the „Requirements for the demonstration of effective emergency core cooling during loss-of-coolant accidents with release of insulation material and other substances" was issued at the 374. Meeting of the RSK on 22 July 2004 /RSK 04/.

5.1 Assessment criteria

The general criterion for the safety-related assessment of the release of insulation material during a loss-of-coolant accident is the ensurance of sufficient core cooling. For this purpose it has to be demonstrated for each plant that

- the amount of the insulation material deposited inside the core remains below the amount at which sufficient core cooling is no longer guaranteed
- the supporting structures and the sump strainer can carry the load resulting from the pressure differences due to the deposition of insulation material

– No cavitation occurs in the residual-heat removal pumps that will lead to an inadmissible reduction in flow rate.

5.2 Basic principles

The RSK recommendation follows several principles:

- The recommendations can be applied to PWRs, partially to BWRs
- The recommendation concerns the evidence for design basis accidents. In addition, accident management measures are recommended.
- The present findings mainly rely on experiments and do not allow a fully analytical treatment of the topic.
- The procedure recommended is to take into account any existing uncertainties with a view to achieving an enveloping overall result.
- The measures to be provided for the control of design basis accidents have to be thus devised that no accident management measures are required by design.
- Accident management measures have to be developed for beyond design accidents
- The size of sump strainers and the mesh size have to be designed in such a way that any possible inadmissibly high pressure loss could only occur at the sump strainers. For this case, accident management measures have to be provided to limit or reduce pressure loss.

5.3 Steps for the demonstration of effective emergency core cooling

The following steps have to be demonstrated for effective core cooling during a LOCA with release of insulation material:

– Leak location: Those leaks have to be selected which lead to the most adverse conditions at the sump strainer or in the core

– Release of insulation: The calculation of the amount of insulation material released has to be determined according the NRC cone model (chapter 3.1) with the additional assumption that the cassette regions outside the jet attributed to region 2, if in region 1 or 2 the cassette was hit by the jet.

– Transport within the containment: Based on the Barsebäck event, 50 % of the released insulation reaches the sump.

– Transport in the sump water: Based on the GKSS tests, 20 % and 40 % of the insulation material MD2 is assumed for the transport to the strainer. For other insulation or combinations of insulation, the transport rates have to be determined by experiments.

– Head loss across sump strainer: The specific pressure losses have to be determined by experiments. The following deposition rates have to be assumed for the determination of pressure loss:

    - Large mesh size: measured deposition plus 50 % of penetration
    - Small mesh sizes: the entire transportable material

– Penetration through sump strainer: The penetration has to be determined plant-specifically in a conservative way.
– Pump suction head: The pump suction head could be determined in two ways:
  - with atmospheric pressure
  - conservative calculation of containment pressure and sump temperature with validated codes
– Pressure drop inside the core: It is assumed that all materials which penetrate through the sump strainer are transported to the pressure vessel. The deposition in the core is either conservatively determined by experiments or assumed to be the whole penetrated material. Core cooling is calculated with qualified thermohydraulic codes.

In addition, the residual-heat removal system components, the long-term behaviour, the housekeeping in the plant, and accident management procedure had to be considered.

5.4 Open items

Following items are not yet resolved:

– Influence of jet shifts on the release of debris for a pipe break
– Fragmentation of mobilised debris
– Transport behaviour of debris (mineral wool other than MD2 80/82 as well as of other substances) in the sump and the consequences on head loss and penetration of the sump screens
– Influence of the “thin bed effect” on head loss across the screen
– Long-term behaviour, especially corrosion due to boric acid
– Functional performance of components in RHR mode
– Effectiveness of special Accident Management measures
– Applicability of RSK-2004 recommendations to BWR

6 Plant modification

Based on the new RSK statement and the experimental and analytical results, modifications of the insulation and at the sump strainers were performed in the German PWRs. In almost all PWRs the mesh size of the sump strainers was reduced to 3 mm x 3 mm, so that the inadmissibly high pressure loss could only occur at the sump strainer. The strainer sizes were partly increased to reduce the pressure loss over the deposition on the sump strainer. The insulation material was homogenised to reduce mixed released insulation and to get clear boundary conditions for the demonstration of a suitable sump design for effective emergency cooling during a LOCA. The plant modifications are described in the following Tables 3 and 4.

Table 3 Plant Modifications (part 1)

	Strainer size		Mesh size		Insulation material	Limitation of sump water temperature
Plant	**old (m^2)**	**new (m^2)**	**old (mm)**	**new (mm)**	**--**	
PWR 1	4.9	20	9 x 9	3 x 3	---	> 60
PWR 2	2 x 5.5	2 x 11	9 x 9	3 x 3	exchange microtherm →MD2	> 60
PWR 3	4 x 2	26.4	9 x 9	8.5 x 8.5	exchange minileit →MDK	------
PWR 4	4 x 7 (6.8 – 7.22)	--	8 x 8	3 x 3	reduction in insulation material mix	------
PWR 5	2 x 21	2 x 24	9 x 9	3 x 3	exchange microporous → mineral wool	------
PWR 6	4 x 8.3	--	9 x 9	3 x 3	reduction of RTD2	------
PWR 7	4 x 11	--	9 x 9	3 x 3	exchange minileit →MD2	------
PWR 8	29	--	9 x 9	3 x 3	---	------
PWR 9	2 x 20	--	9 x 9	3 x 3	exchange micro porous →mineral wool	------
PWR 10	4 x 11	--	9 x 9	3 x 3	---	------
PWR 11	4 x 11	--	9 x 9	3 x 3	exchange RTD → MDK	------

Table 4 Plant Modifications (part 2)

	Strainer size		**Mesh size**		**Insulation material**	**Limitation of sump water temperature**
Plant	**old (m^2)**	**new (m^2)**	**old (mm)**	**new (mm)**	**--**	
BWR 1	4.8 for TH, TK in KK 4.5 in the sump	--	Ø 4 3 x 3	---------	exchange microporous →mineral wool	------
BWR 2	2.2 for TH, TK in KK 1.9 for TH, TK in the sump	--	Ø 10 Ø 2.5	---------	reduction of minileit	------
BWR 3	3 x 5.3	--	Ø 5	--------	exchange microporous →mineral wool	------

The modification in the plants was mainly based on the Karlstein and GKSS experiments. The RSK statement demands plant-specific experiments for the plant specific design of the insulation material and strainers. These experiments are running. The results of these experiments have to show whether the assumptions used for the demonstration of effective emergency core cooling based on the Karlstein and GKSS experiments have been conservative. If this is the case, the new design of the insulation material and strainers will fulfil the RSK recommendations.

7 Conclusions

Results of the experiments at Karlstein and GKSS have shown that under realistic boundary conditions, insulation material released during LOCA leads to a higher transportation rate in the sump and a larger deposition rate at the sump strainers and in the core than assumed before. The mixture of mineral wool and microporous material leads to a strong increase of the specific pressure loss through deposited insulation material.

Based on the new knowledge, a new statement on the „Requirements for the demonstration of effective emergency core cooling during loss-of-coolant accidents with the release of insulation material and other substances" was released by the Reactor Safety Commission in July 2004.

The portion of microporous material in the insulation and the mesh size of the strainers were reduced in almost all PWRs. In some PWRs the strainer size was increased.

Ongoing experiments have to prove that the plant-specific assumptions for the specific pressure losses of deposited insulation material and for the transport, deposition and penetration rates are conservative.

Literature

/FANP 03/ G. Seeberger, Experimenteller Nachweis der gesicherten Sumpfansaugung nach einem Kühlmittelverluststörfall bei KWU-Druckwasserreaktoren, FANP NGES1/2002/de/0210, November 2003

/GRS 05/ W. Pointner, et al, Beeinflussung der Kernnotkühlung durch freigesetzte Materialien bei Kühlmittelverluststörfällen, GRS-A-3282, Juni 2005

/NRC 03/ NRC Generic letter 2003, Potential Impact of Debris Blockage on Emergency Recirculation During Design Basic Accidents at Pressurized Water Reactor

/RSK 04/ RSK, Anlage 2 zum Ergebnisprotokoll der 374. Sitzung der Reaktorsicherheitskommission vom 22.7.2004, „Anforderungen an den Nachweis der Notkühlwirksamkeit bei Kühlmittelverluststörfällen mit Freisetzung von Isoliermaterial und anderen Stoffen, Juli 2004"