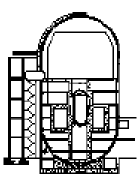
SWR 1000: US-NRC/Framatome-ANP GmbH Meeting
Erlangen, Germany, 23-26.06.2003

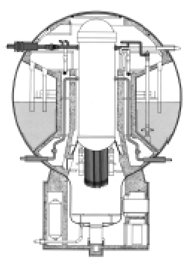
Evolution of Framatome ANP's BWR Technology

- Kahl
- Gundremmingen A
- Lingen (1st Fine Motion CRD - 1968)



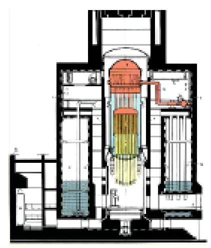
Full pressure containment - 61

- Würgassen
- Brunsbüttel (1st Internal recirc pump - 1977)
- Philippsburg 1
- Isar 1
- Tullnerfeld
- Krümmel

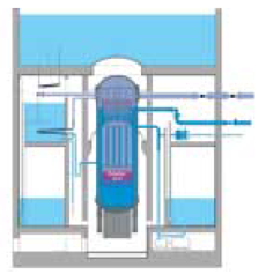


Product Line 69

- Gundremmingen B/C (3 train RHR & prestressed concrete containment - 1984/85)



Product Line 72



SWR 1000

Motivation for selecting the external cooling as SWR 1000 severe accident management strategy

by

Nikolay Ivanov Kolev, Dr.-Ing. habil.,
Department Manager Multi-Phase Flow
Framatome Advanced Nuclear Power NGPS1,
P.O. Box 3220,
D-91058 Erlangen,
Germany

Tel. +49 9131 189-63 40,
Fax.+49 9131 189-70 18,
e-mail: Nikolay.Kolev@framatome-anp.de

1. The effect of scale

Consider a typical water-cooled nuclear reactor vessel with diameter D_v = 4.42m. The semi-spherical lower head has a radius R_{LH} = 2.21m. The vessel is submerged in water. Consider molten debris inside the lower head with a mass of 112t with a metallic layer of $M_{m,0}$ = 10.7t atop the oxide layer. The relocation of this debris happens τ_{rel} = 2h after SCRAM of the reactor for reasons that are not important here. The initial thermal power of the reactor is assumed to be 3400MW. Inside the debris there are no submerged structures, $M_{m,sub}$ = 0t. Above the reactor there are $M_{m,\max}$ = 40t structures that can melt and move down due to absorbing radiation heat. The process starts with already-molten metal $M_{m,0}$ =10.7t being atop 112t oxide. The oxide height at the axis is $L_{LH,ox}$ = 1.695m. The initial thickness of the metal is δL_m = 0.2m. We assume that c_2 = 0.3 part of the energy radiated upwards from the molten pool is consumed by melting the structures as long as they are available. The other part of the radiation energy is dissipated in the vessel and also removed by external cooling. Next, we will analyze different effects on the maximum heat flux into the external water using the method published in [1].

1.1 The effect of vessel diameter

Here we simply vary the diameter of the vessel, keeping all other conditions constant, in order to see the effect on the maximum external heat flux. For cases 1 to 6, the semi-spherical lower head has the same diameter as the vessel.

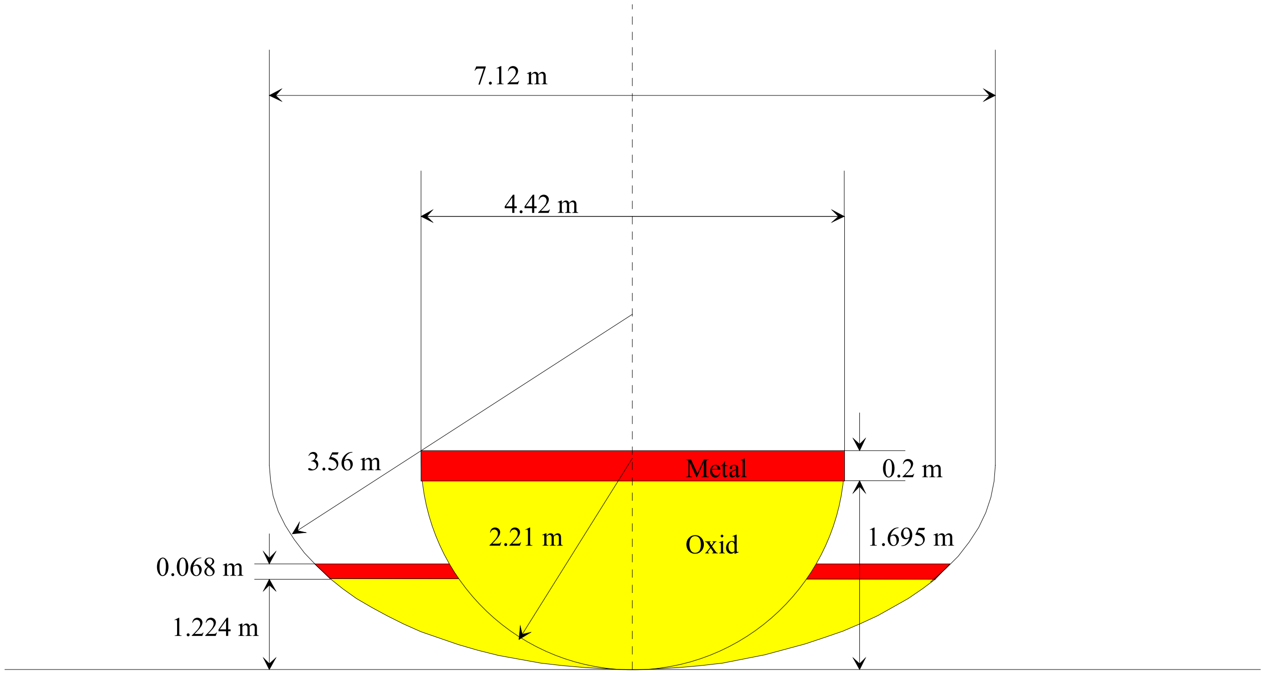


Fig. 1. Effect of the vessel size with semispherical lower head on the external cooling for typical 3400 MWt water-cooled reactors

Conclusion 1: For the cases in which the maximum heat flux is in the metal layer (cases 1-6) there is no strong effect from the change of the size of the vessel. This changes if the maximum heat flux is inside the oxide pool do to the large amount of metal atop the oxide.

Table 1. Effect of the vessel diameter on the maximum external heat flux

No	τ_{rel} h	D_v m	R_{LH} m	$L_{LH,ox}$ m	δL_m m	$F_{ox,up}$ m^2	$F_{ox,da}$ m^2	c_1	c_2	$M_{m,0}$ t	$M_{m,sub}$ t	$M_{m,\max}$ t	$\dot{q}''_{\max}$ MW/m^2	$\delta_{LH,\min}$
1	2	4.42	$D_v/2$	1.695	0.2	14.51	23.53	0	0.3	10.7	0	40	**2.153**	0.025
2	2	5	$D_v/2$	1.542	0.171	16.75	24.22	0	0.3	10.7	0	40	**2.111**	0.025
3	2	5.5	$D_v/2$	1.443	0.156	18.39	24.93	0	0.3	10.7	0	40	**2.076**	0.025
4	2	6	$D_v/2$	1.362	0.144	19.84	25.67	0	0.3	10.7	0	40	**2.045**	0.025
5	2	6.5	$D_v/2$	1.295	0.134	21.17	26.44	0	0.3	10.7	0	40	**2.032**	0.025
6	2	7.12	$D_v/2$	1.224	0.068	22.68	27.38	0	0.3	10.7	0	40	**1.404**	0.037
7	2	7.12	4.46	1.073	0.107	26.45	30.07	0	0.3	10.7	0	40	**1.378**	0.037
8	8	7.12	4.46	1.073	0.107	26.45	30.07	0	0.3	10.7	0	40	**0.817**	0.062

1.2 The effect of the lower head radius

Now we introduce case 7 in which only the lower head radius is increased to the radius of the SWR 1000. This increases the lower head heat transfer surface from the oxide pool and reduces the maximum heat flux by 36% with respect to case 1.

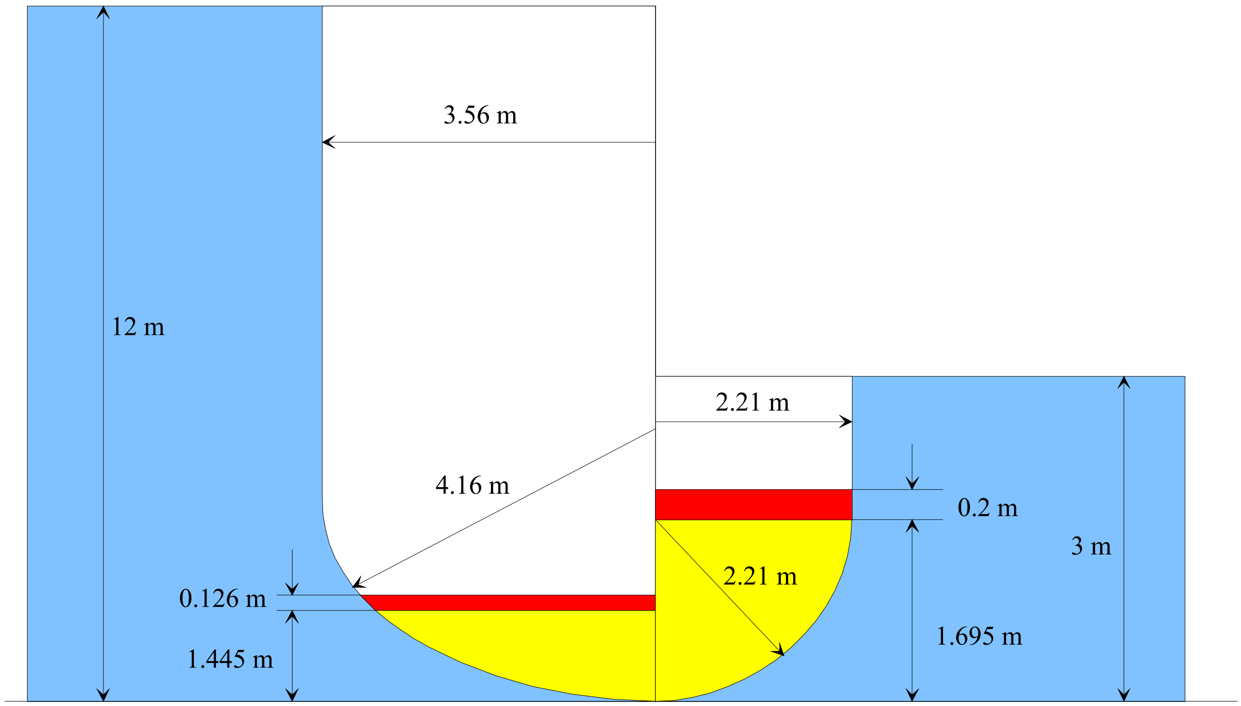


Fig. 2. Left: SWR 1000 vessel without the structural penetrations with total amount of oxide debris - initial state for the analysis; Right: Typical PWR-vessel for comparison

Conclusion 2: Increasing the lower head radius reduces the maximum heat flux at the vessel wall and therefore influences the process positively.

1.3 The effect of the relocation time

Due to the large water inventory in the SWR, relocation of melt into the lower head during severe accidents happens much later than in the case of PWRs. Consider the differences between cases 7 and 8. The only difference in these two cases is that the assumed time of the melt relocation into the lower head is increased from 2 to 8h after SCRAM. This results in about 41% lower head flux in case 8 compared to case 7.

Conclusion 3: Increasing the delay time of the melt relocation reduces the maximum heat flux into the coolant - an effect that is intuitively expected.

1.4 The effect of the mass of the internal structures

A significant difference between BWRs and PWRs of the same power level is that the first contains a considerable amount of internal structures. The SWR 1000 has about 700t internal structures. About 400t of this is below the upper core plate, including the plate itself. About 200t of structures such as control rod drives, instrumentation pipes, lower core plate, etc. are below the core region. The structures submerged into the melt first have to melt until the oxide pool starts to increase its temperature significantly above the steel melting temperature. The hanging structures absorbing radiation energy and melting have a similar effect and therefore increase and cool the upper metallic layer. This is manifested in the SWR 1000 case shown in Table 1. It results in a significant reduction of the maximum heat flux - an effect again that is intuitively expected.

Conclusion 4: Internal structures penetrating the debris or immediately above them during severe accidents (a) consume a significant amount of the decay energy, (b) rapidly increase the metallic layer atop the oxide pool and, therefore, significantly reduce the maximum heat flux into the coolant.

2. Effect on the external collapsed water level

Consider now the effect of the collapsed level on the external-cooling concept.

2.1 Resulting forces on the vessel wall

Consider two cases; the first a typical 1000MWe PWR with a collapsed flooding level of about 2 to 3 m compared with the SWR 1000 vessel with collapsed flooding level of 12m. Table 2 summarizes the forces acting on the lower head - at the horizontal cross section at about the oxide level.

Table 2. Forces acting on the lower head at the horizontal cross section at about the oxide level

	Typical 1000 MW PWR	SWR 1000
Collapsed flooding level in m	2 - 3	12
Dead weight:		
lower head + debris in MN	1.9	4.87 (assuming 400 t debris + 98 t lower head)
Buoyancy force in MN	0.8	4.5
Resulting force in MN	1.1	0.37
Yield strength for carbon steel at 900K in MPa	350	350
Minimum required wall thickness in mm	0.22 (if no DNB?)	0.0459 (far below DNB)

The buoyancy force in the case of SWR 1000 is so high that, even assuming 400t of derbies + 100t lower head, the resulting force is about one third of those of the typical PWR. Assuming that there is part of the vessel wall thickness at the level considered that has a temperature below 900K resulting in a 350MPa yield strength for carbon steel, we obtain in the first case a sufficient wall thickness of 0.22mm if there is no DNB and in the second case 0.0449mm. We see also the superposition of the effect of the larger diameter giving about 1.6 times larger circle perimeter (about 4.8 times reduction - from: 0.22/0.0459 = 4.8).

Conclusion 5: The large external water level considerably reduces the effective forces acting on the vessel wall at the horizontal cross section at about the oxide level.

2.2 Pressure difference over the lower head

Over the period of the melt relocation, the long term external hydrostatic pressure is larger then the long term internal hydrostatic pressure until the debris reaches a state of more the 1.2m liquid level measured from the lowest point of the vessel. For a typical PWR with 3m external collapsed water level, this mark is 30cm - reached with a small portion of the total debris, as intuitively deduced from Fig. 2. For the SWR 1000, over the long term melt stabilization process, the external hydrostatic pressure over the predominant portion of the lower head is larger then the internal hydrostatic pressure. Therefore, if one postulates an opening that is not sealed by crusts, the water will penetrate from outside into the melt resulting in a very effective melt-cooling mode called the "COMET concept". This concept was investigated over many years in the Karlsruhe Research Center in Germany and has been proven to operate properly. The inside hydrostatic pressure over the lowest portion of the SWR 1000 vessel is slightly larger then the outside hydrostatic pressure. This portion is covered with a very thick crust (14cm in the case of SWR1000) due to the very low heat fluxes in this region. Therefore, any cracks are sealed by the crusts and melt release is impossible.

Conclusion 6: Large external water collapse level hinders melt release outside the vessel for a predominant part of the lower head. At those places where the internal hydrostatic pressure is higher, the crust is so thick that it safely seals any imaginable cracks in the lower head.

With all these six conclusions in mind, we immediately recognize the potential of BWRs to arrest the melt inside the vessel during severe accidents. But let us elaborate more carefully all aspects of this potential in [2].

References

1. Kolev NI (1996) External cooling of PWR reactor vessel during severe accident, *Kerntechnik, 61 (1996) 2-3, pp-67-76*. In abbreviated form in Proc. ICONE-4, *The Fourth International Conf. on Nucl. Engineering*, New Orleans, March, 8-12, 1996, USA
2. Kolev NI (2003) External cooling - the SWR 1000 severe accident management strategy, SWR 1000: US-NRC/Framatome-ANP GmbH Meeting, Erlangen, Germany, 23-26.06.2003