Transactions of the **14th International Conference on Structural Mechanics in Reactor Technology** (SMiRT 14), Lyon, France, August 17-22, 1997

PW/6

Numerical simulation of a BWR vessel lower head with penetration subjected to a postulated core damage accident

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ABSTRACT

To assess the safety and the integrity of nuclear power plants in operation, hypothetical accidental events are considered, which - on account of their low frequency of occurrence- do not belong to design accidents. In this context, a global finite element (FE) model of a German BWR RPV lower head and a control rod nozzle was developed. The melt down time estimations were obtained by FE calculations of the temperature distributions, which consider the influence of the complex heat transfer into the RPV lower head and control rod nozzle as well as phase changing of steel material.

1 INTRODUCTION

Many of the consequences of severe reactor accidents depend on the thermal hydraulic response of the RPV. In the event of a core meltdown accident in a BWR, the core debris may relocate into the bottom of the reactor vessel, where it could accumulate and begin to attack the lower head wall and control rod nozzle.

The aim of this research work was to improve the current understanding of the heat transfer from a molten pool to the reactor pressure vessel structures and the response of the structures under such conditions, [1], [2] and [3]. A part of this investigation was to adapt a properly and reliable working numerical analysis chain to determine temperature distribution and load carrying capacity of the considered components, and to evaluate their potential for initiating failure due to the melting of the control rod nozzle and /or RPV lower head. The estimation of the melt down time is relevant for accident management procedures.

These investigations have been carried out by means of finite-element (FE) computations. A structural mechanics and (FE) code [4] has been applied to study the behaviour of a typical German BWR RPV, specifically the vessel lower head and the control rod nozzle, during an hypothetical severe core melt accident. Specific developments have been made in order to solve the above mentioned problems.

2 Estimations of melt down time for different components

Investigations of the behaviour of structures of the reactor pressure vessel in severe accidents require knowledge on the energy transfer from the debris to the surrounding steel structures. In this context, a global finite element model of a corium molten pool in the reactor pressure vessel lower head and a control rod nozzle at the centre of the vessel was developed to simulate the heat transfer in a severe accident case.

The melt down time estimations for different components were obtained by FE thermal calculations which concern the relevant heat transfer into the RPV lower head and control rod nozzle. The estimation of the melt down time, if integrity of the structure is jeopardized, is relevant for accident management procedures.
This part presents finite element analytical models and calculations of the behaviour of the reactor pressure vessel lower head subjected to loads from a homogeneous distribution of corium.

2.1 FE discretisation, material properties and loading data

Essential data on geometry[4] and material properties of RPV structures of a German BWR were compiled and prepared for the use in the numerical calculations.
The FE-analyses have been performed using the GRS structural analysis chain based on the finite element programs ADINA, ADINA-T, ADINA-IN, ADINA-PLOT [5] and other pre- and post-processor programs. The FE thermal calculations were made using axisymmetric representations of the total RPV, molten pool and other structures. The model was mashed with 3407 isoparametric 4-node elements. The loading conditions were assumed tobe symmetric about the vertical axis.
The mesh of the two-dimensional continuum axisymmetric finite-element model of the RPV and the detail mesh of the lower head and control rod nozzle for determining time-dependent temperature distributions are given in Figure 2.1-1.

The RPV is fabricated of ferritic steel 22 NiMoCr 37 (similar to ASTM A 508 cl. 2). The cladding and the control rod nozzle are made of austenitic steel X10 Cr Ni Nb 18 9. Material data for this analysis are taken from several sources, e.g. [6] and [7]. The temperature-dependent thermal material data of ferritic steel 22 NiMoCr37 and austenitic steel X10 CrNiNb 189 are listed in Tables 2.1-1 and -2 respectively.

Table 2.1-1 Thermo-physical properties of ferritic steel 22 NiMoCr 37, temperature-dependent

Temperature [K]	293	373	473	573	673	773	973	1 273	1 573	1700	2 900
ρ [10^3Kg/m]	7.85	7.82	7.79	7.76	7.72	7.76	7.6	7.48	7.34	7.2	7.2
λ [W/mK]	44.5	44.9	44	41.9	39.1	36.4	30.6	25.8	25.5	26.5	26.5
c [J/kg K]	463	465	476	496	521	543	588	618	618	625	625

ρ: Density, λ: Thermal conductivity, c: Specific heat capacity

Table 2.1-2 Thermo-physical properties of austenitic steel X10 CrNiNb 18 9, emperature-dependent

Temperature [K]	293	373	473	573	673	773	973	1 273	1 573	1700	2 900
λ [W/mK]	14.7	15.8	17	18.4	19.8	20.9	232	25.2	26	26.1	26.1
c [J/kg K]	504	513	521	532	542	551	573	601	621	626	626
ρ [10^3Kg/m^3]	7.91	7.87	7.82	7.78	7.73	7.69	7.59	7.46	7.32	7.22	7.22

λ: Thermal conductivity, c: Specific heat capacity, ρ: Density

Information in Tables 2.1-1 and -2 indicates, that the solidus and liquidus temperatures of both steels is assumed to be about 1700 K.
The tensile properties of 22 NiMoCr 37 steel- not actually used in this part of analysis, but included for completeness- are listed in Table 2.1-3.

Table 2.1-3 Tensile properties of ferritic steel 22 NiMoCr 37, temperature-dependent

Temperature [K]	293	373	473	573	673	773	973	1 273	1 573	1700	2 900
E [GPa]	210	206	200	189	175	160	114	28	13	7.3	7.3
$R_{P0.2}$ [MPa]	319	318	308	293	271	241	130	23	11	0.1	0.12
R_M [MPa]	584	584	574	556	509	423	179	35	20	0.12	0.1
A_5 [%]	15	15	16	18	21	24	19	13	5.2	4.5	4.5
A_{gl} [%]	8	7.3	6.4	5.5	4.9	4.5	5.9	5.9	4.4	3	3
ν [-]	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3

E: Young's modulus, $R_{p0.2}$: Yield strength at temperature, R_M : Ultimate strength at temperature
A_5 : Fracture strain, A_{gl}: Strain at ultimate strength, ν: Poisson's ratio

It is to be noted, that in contrast to mechanical material parameters there were almost no data above 1000 K available for material properties of physical parameters. For heat transport analyses therefore, extrapolations of these data have been used, see **Table 2.1-1** and **-2**, which introduce some uncertainties in the prediction of failure times due to melting.

The initial and loading conditions- as they might occur during a severe accident including core relocation- considered in the FE calculations are given in Table 2.1-4.

Table 2.1-4 Initial and loading conditions applied in the FE analysis

RPV:	
Initial temperature of RPV	548 K
Temperature of RPV-surroundings	323 K
Heat transfer coefficient RPV/surroundings	2 W/m^2 K
(constant in time)	
RPV internal pressure (constant in time)	8 [MPa]
Molten pool:	
Initial temperature of corium:	2700 K
Maximum temperature of corium:	2900 K
Decay heat generation in corium:	133 W/Kg
Maximum height of corium pool above the bottom of RPV	600 mm

For further considerations we suppose that the corium pool temperature exceeds the melting temperature of the RPV and control rod nozzle steel and hence a part or the total of the thickness of the structures in contact with the corium will melt.

2.2 Results of thermal response calculations, Melt down time

Based on the axisymmetric model, FE simulation was run over a period of 13500 s after the core relocation. Time-dependent temperature distributions from the debris/vessel interaction until the maximum calculation time have been performed, Figure 2.2-1 and -2.

For the FE investigations, some new mathematical methods were developed, concerning, e.g. radiation through a narrow gap of a control rod nozzle, internal heat production in corium (simulation of decay heat generation) and phase changing of steel material (solidus to liquidus and vice versus).
Further information concerning the melting duration has been derived on the basis of reaching melting temperature of steel structures (1700 K solidus-liquidus), see Table 2.2-1 and Figure 2.2-3.

Concerning the failure time due to melting of control rod nozzle and -internals, the melting time is associated with the coolant flow (i.e. water) and heat transfer within the various regions of the nozzle internals.

A simplified analysis program MLTCCRFT was developed at GRS to estimate failure times of a lower head arising from various possible failure mechanisms -such as melt-through, plastic collapse, exceedance of ultimate strength, and creep failure. For further validation of the performance of the thermal analysis of this simplified analysis program, comparison was made with the results of the finite element model. The melt down time obtained by MLTCCRFT deviates from the FE-result by less than 5% (Table 2.2 -1); both results are in good agreement.

Table 2.2-1 : Melt down time estimations for different components

Steel components	Internal coolant flow	Estimation time min.
Stand pipe (thickness 4.25 mm)	available	>52
	not available	3.4
Control rod nozzle (thickness 15 mm)	available	11
	not available	9.7
Control rod drive housing (thickness 16 mm)	available	21.3
	not available	13.4
Control rod nozzle and internals (thickness 75 mm)	available	>52
	not available	19.7
RPV lower head (thickness 236 mm)	ADINA	223
	MLTCCRFT	213

3 CONCLUSIONS

The purpose of the current study was to provide a framework for evaluation of the thermal attack of the BWR vessel lower head and the control rod nozzle by a corium pool accumulated in the lower plenum and to improve the understanding of the phenomena involved.
A thermal transient FE model analysis has been developed for the molten pool behaviour and thermal attack of the lower head. The model has been described and the main part of the analysis results have been reported here. Based on the axisymmetric model, FE simulations were run over a period of 13500 s after the core relocation. Time-dependent temperature distributions from the debris/vessel interaction up to the maximum calculation time have been performed.
The results indicate that the FE mesh and the boundary conditions of the model were sufficient to describe the thermal response of the structure.

Another aim of this project was to investigate the limits of the present available analytical methods in the FE code, regarding the energy transfer from debris to the surrounding steel structures, and if necessary, to improve it.
With respect to this objective some new mathematical methods have been developed and implemented into the FE code, concerning, e.g. radiation through a narrow gap of a control rod nozzle, internal heat production in corium (simulation of decay heat generation) and phase changing of steel material (solidus to liquidus and vice versus). Sofar the efficiency of the analysis code was improved and demonstrated.

ACKNOWLEDGEMENT

The authors thank the German Minister for Education, Science, Research and Technology (BMBF) for supporting this work.

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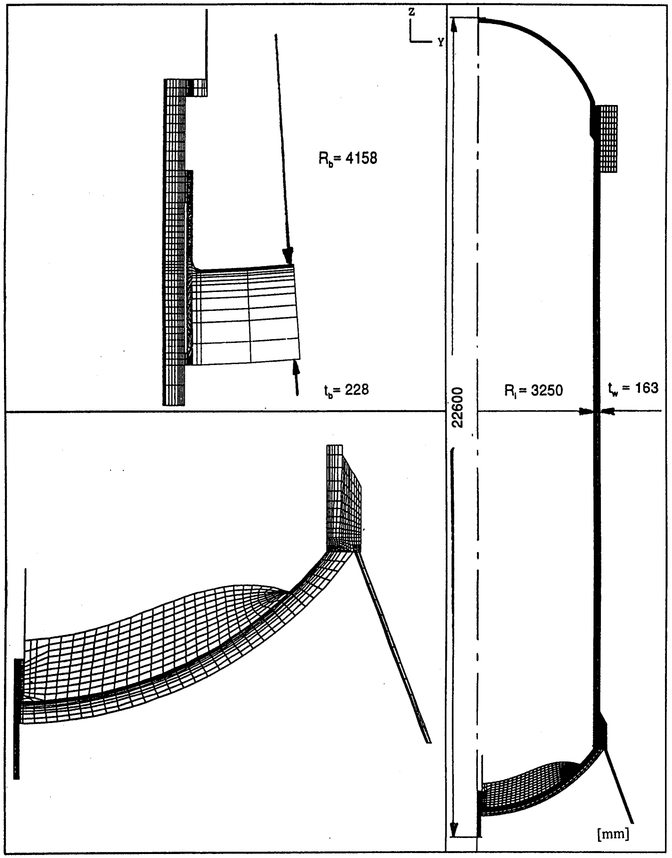

Figure 2.1-1 Mesh of two-dimensional continuum axisymmetric finite-element model of RPV and detail mesh of lower head and a control rod nozzle.

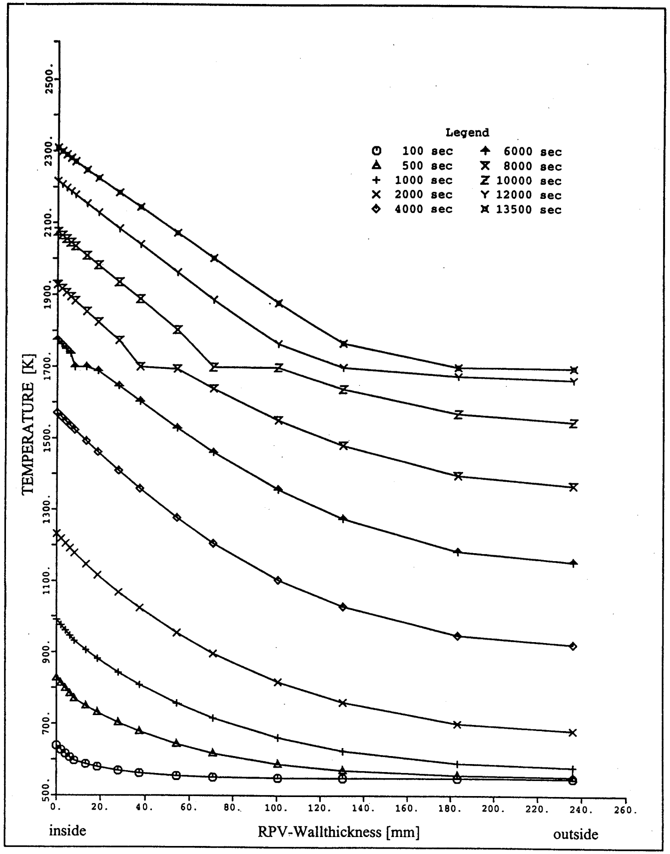

Figure 2.2-1 Temperature distribution associated with the debris/vessel interaction over a period of 13500 seconds after debris relocation

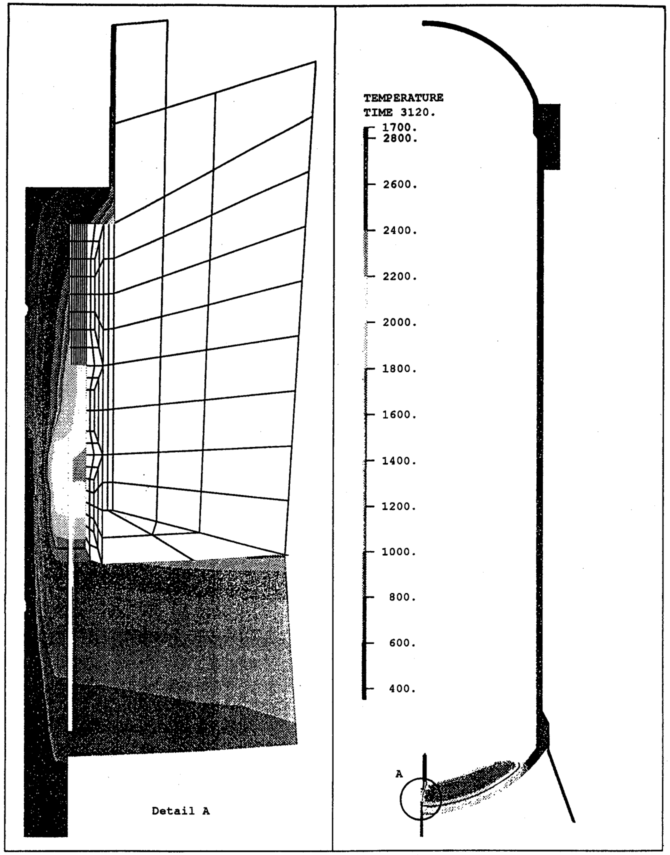

Figure 2.2-2 Global temperature distribution of RPV and control rod nozzle at 3120 seconds after debris relocation

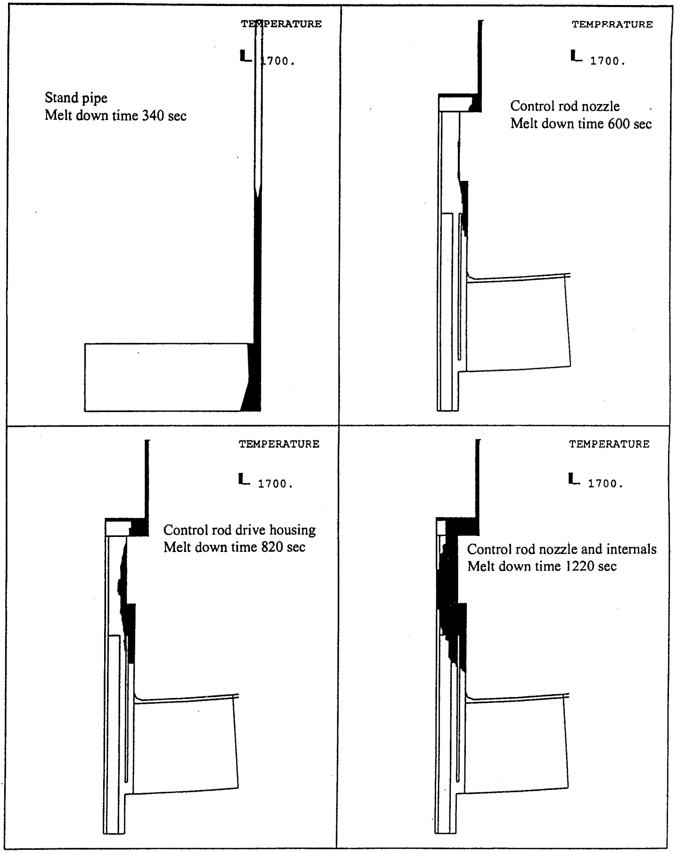

Figure 2.2-3 Melt down time estimations for different components