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PWR LOWER HEAD RUPTURE AT HIGH SYSTEM PRESSURE: ANALYSIS OF THRUST LOAD ON PRESSURE VESSEL DURING BLOWDOWN

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1. INTRODUCTION

In a hypothetical severe accident at a nuclear power plant it is conceivable that the reactor core melts down, while the primary system pressure remains on a high level (17 MPa). If accident management measures fail, the molten corium relocates into the lower plenum, several hours after the accident initiating event, and comes in direct contact with large portions of the lower head of the pressure vessel. The melt subjects the inner surface of the vessel wall to high temperatures (1700 K). As the temperature increases through the thickness of the wall, the strength of the steel is dramatically reduced, until the cooler outer portions of the vessel wall can no longer withstand the high internal pressure. That ultimately leads to a rupture of the lower head causing a violent blowdown. The discharge of a mixture of water, steam, and corium debris exerts a thrust load on the pressure vessel in upward direction extremely demanding the supporting structure of the pressure vessel. If this load cannot be carried by the supporting structure, the vessel could move upwards crashing through the reactor cavity covering and endangering the containment hull. The blowdown is accompanied by a heavy pressure build-up in the reactor cavity putting a strong strain on the cavity walls. The situation is schematically shown in Figure 1. Further, the cavity pressure increases the load on the vessel support ring, which presents a considerable area to the pressure.

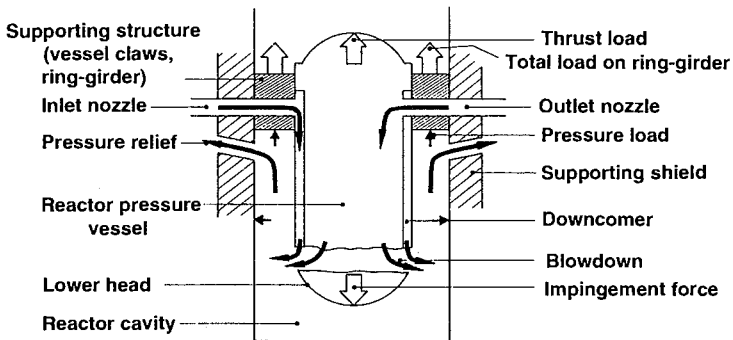


Fig.1: Reaction forces during a pressure vessel blowdown

The high pressure failure of the vessel is being studied within a new R&D activity at KfK investigating ultimate containment loads as a result of severe accidents not getting under control. The activity is related to an initiative of Eibl, Hennies and Kessler [1], who proposed a new containment concept for large (1300 MW (e)) next generation pressurized water reactors. The concept is aimed at passive mechanisms that can safely confine core-melt accidents, whatever remote their likelihood might be. In contrast to other approaches, the concept demands a deterministic exclusion of large radioactivity releases and disastrous impacts from severe nuclear accidents to man and environment.

The paper deals with the estimation of hydraulic loads during blowdown of the failed reactor pressure vessel. The information obtained provides a force-function input for structural dynamics analyses for a new core-melt resistant containment design. The analysis based on calculations with the light water reactor transient analysis thermal-hydraulics computer code RELAP5/MOD3 [3] is more detailed than the analytic approach in the German risk study (phase B) [2].

2. METHOD

During blowdown dynamic hydraulic forces are exerted on the vessel. The only mechanism for exerting forces on a fluid container are the forces on the wetted surface of the wall including the fluid static pressure and the friction between the surface and the fluid. This reaction force is

$$\vec{F} = \int_W p \vec{n} dS + \int_W \vec{\tau} dS$$

W is the wetted wall surface, p is the static pressure acting over the wetted surface, \vec{n} is the unit vector normal to the surface, $\vec{\tau}$ is the shear stress tensor of the fluid at the surface, and dS is a surface element. The expression can be evaluated by performing the two spatial integrations. However, their evaluation may be difficult. The spatial integrals are terms in the conservation-of-momentum equation. Therefore, the calculation of the transient hydraulic force on the vessel is accomplished more easily by evaluating the remaining terms of the momentum equation.

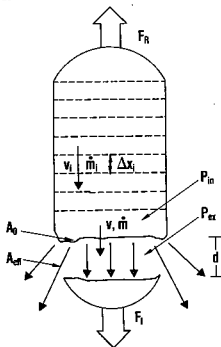


Fig.2: Thrust force on the vessel

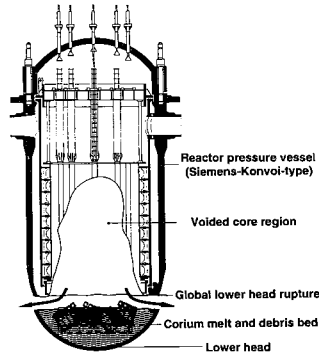


Fig.3: Failure of the lower head

In a one-dimensional approximation, which is pre-determined by the used RELAP5 code, the reaction or thrust force can be obtained by substitution of the above expression into the momentum equation yielding:

$$F_R = - \left\{ \frac{d}{dt} \sum_i \Delta x_i \dot{m}_i + (p_{in} - p_{ex}) A_0 + \dot{m} |v| \right\}$$

for the discussed vessel open on one side. For simplicity, the gravity force can be neglected. Figure 2 illustrates the meaning of the introduced quantities. A_0 is the cross-sectional area of the rupture, A_{eff} is the effective flow area, i. e. the cylindrical area between the body of the vessel and the moving lower head, \dot{m} is the blowdown mass flow rate, \dot{m}_i is the mass flow rate in the i -th node. p_{in} and p_{ex} are the pressures upstream and downstream the rupture surface, respectively. v and v_i are the fluid velocities at the rupture surface and in the i -th node, respectively. Δx_i is the length of the i -th node. i is the node number in the nodalization scheme for the vessel.

The above equation is recorded in a simplified form for a homogeneous fluid. However, the actually performed calculation evaluates two-phase terms. The wave force, which describes the first term on the right side of the equation, represents the time rate of change of the total momentum of the fluid in the container vanishing at steady flow. The next term represents the pressure force acting at the fluid discharge plane. The last term represents the spatial acceleration of the momentum efflux at the discharge plane. The sum of the last two terms is the so-called blowdown force, F_B , which is equal to the impingement force of the fluid jet striking and accelerating downwards the lower head. Since the lower head intersects only part of the jet area, the jet load on the missile is estimated by:

$$F_l = A_0/(A_{eff} + A_0)F_B$$

The effective flow area A_{eff} is obtained from the equation of motion of the accelerated lower head missile:

$$\frac{d^2}{dt^2} A_{eff} = \frac{2\pi R}{M} F_l$$

R is the radius of the cross-sectional area A_0 and M is the mass of the lower head.

The used RELAP5 code produces the thermalhydraulic information needed for the above approximate calculation of the thrust force, and permits owing to its control system the feedback of the effective flow area to the force accelerating the lower head and increasing the effective flow area. Further, the control system of RELAP5 can be used for the entire evaluation being fitted in along with the main computing job.

3. MODEL

In a previous paper [4] the author presented a highly simplified analysis only including the pressure vessel and the reactor cavity (16 control volumes). The present analysis uses a finer nodalization (100 control volumes) and includes all the primary system piping with a volume of 440 m³. Considering a Siemens Konvoi plant Figure 4 shows the primary coolant system and the corresponding nodalization for a RELAP5 calculation. The four loops are put together to a single loop in the model. All those parts of the modelled system, which can be regarded as undamaged, especially in the pressure vessel, are provided with the operational properties. Because of the rapidity of the event, the model can do without a decay heat source in the corium melt and heat conducting structures. The nodalization of the reactor cavity as part of the containment is shown in Figure 5. The two systems are connected by the rupture opening (node no. 224).

As the lower head in the considered Siemens design has no guide tube penetrations, it is assumed that the lower head is heated up uniformly by the melt pool. Conclusively, a global circumferential rupture a little beneath the pool top

level is assumed, as shown in Figure 3. The reference case is characterized as follows. The height of the separated lower head is 1.5 m corresponding to a circumferential rupture on the level at the bottom of the lower core support structure. From this results a cross-sectional area A_0 of 16.96 m², and a mass M of the lower head filled with corium debris of $1.5 \cdot 10^5$ kg.

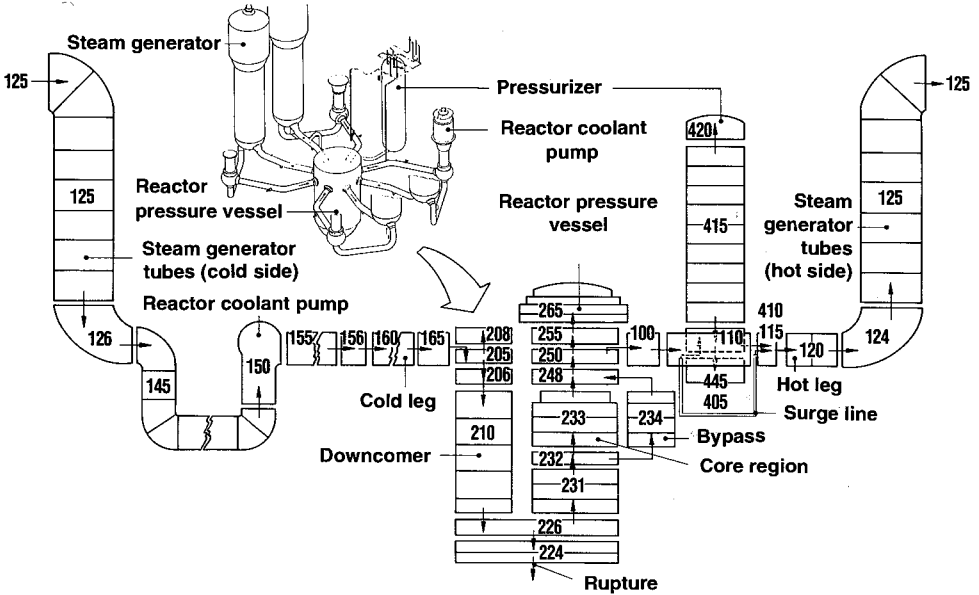


Fig.4: Nodalization of the primary coolant system for RELAP5 calculation

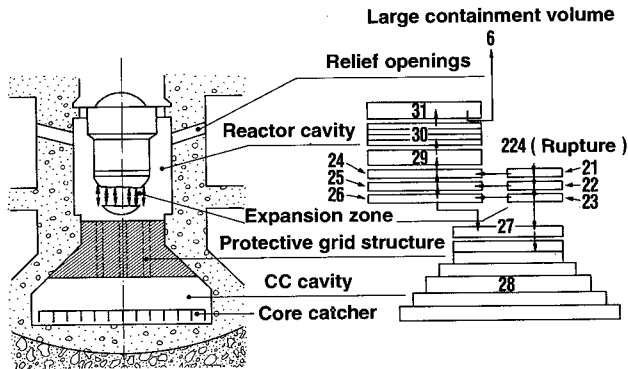


Fig.5: Nodalization of the containment for RELAP5 calculation

The distance between the bottom edge of the intact pressure vessel and the top edge of the protective grid structure is 0.6 m which makes a maximum effective flow area A_{eff} of 9.42 m². The relief openings, which connect the upper reactor cavity to the large containment volume, have a cross-sectional area of 4 m². The RELAP5 calculation starts at the moment, when the lower head just is torn off and free to be accelerated downwards. The initial state of the fluid is saturated steam at 17.4 MPa.

The described model has some insufficiencies. Undoubtedly, it is important to take into consideration the ejection of portions of melt and debris together with

the vapour. This is left up to a later investigation. Another simplification is the one-dimensional treatment neglecting influences of transverse flows in the region between the vessel body and the lower head. Further, the model is confronted by some uncertainties, which could up to now not be cleared up. The uncertainties concern the mode and timing of relocation of corium debris into the lower plenum, the amount of remaining water in the lower plenum, as well as the mode and timing of lower head failure.

4. RESULTS

Figure 6 shows for the reference case the calculated thrust force acting on the pressure vessel including the three contributing forces according to the above thrust force equation. The total thrust force is dominated by the pressure force, which has its maximum of 300 MN at the beginning, because the pressure difference is the greatest at the beginning of blowdown.

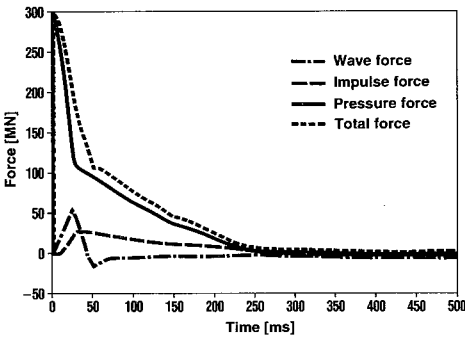


Fig.6: Thrust force history

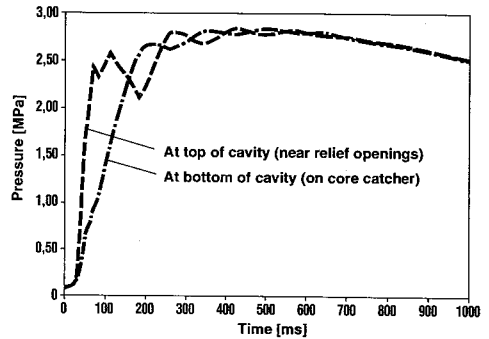


Fig.7: Pressure history

The wave force and the impulse force reach their maximum of 50 MN and 25 MN, respectively, within 25 ms. This time period of 25 ms is a characteristic value for this analysis in two different respects. On the one hand, the pressure wave requires about 25 ms to run from the rupture surface to the top of the vessel. This behavior is well expressed by the shape of the wave force curve. On the other hand, 25 ms approximately is the opening time of the cylindric flow area to its maximum influencing strongly the pressure distribution in the expansion region between vessel body and lower head. This fact results in a sharp bend of the curves of the impulse force and the pressure force. The total thrust force decreases rapidly of an order of magnitude within 200 ms.

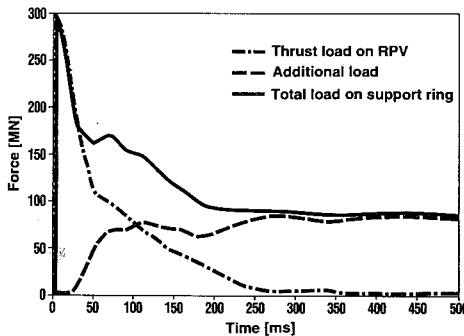


Fig.8: Hydraulic load acting on the vessel support ring

The maximum of the thrust force depends strongly on both the break size and the internal pressure. The thrust force equation indicates that the pressure force is proportional to the pressure difference and the cross-sectional area of the break. Therefore, neglecting the other contributions the thrust is nearly proportional to the internal pressure and the break size. The lower head strikes the protective grid with a kinetic energy of 130 MJ.

The pressure build-up in the reactor cavity is shown in Figure 7 for two locations, at the bottom of the core catcher cavity and at the top of the reactor cavity just below the support ring. After an equalization period of only 200 ms due to the large flow area (20 m^2) in the protective grid between the two cavities, the cavity pressure reaches a value of 2.8 MPa lasting for several seconds. As a consequence of the high pressure level in the cavity an additional load on the support ring of nearly 75 MN is continuing for several seconds, what can be seen in Figure 8. The total load acting on the support frame remain on a high level of about 80 MN for several seconds. From the previous explanations follow that the discussed load on the supporting structures is a hydraulic load. The response of the structures depending on the structural properties might amplify the effective load. However, this fact is a subject of the forthcoming structural dynamics analysis.

5. CONCLUSIONS

The considered Siemens pressure vessel supporting frame consisting of several vessel claws, a support ring, and a support in the shield can withstand a vertical upward directed load of only 50 MN [2]. Therefore, the absorption of a peak load of 300 MN and a continuing load of 80 MN by the vessel supporting frame, and its transmission into the foundation would require a considerable enlargement of the load-bearing cross-sectional areas of reinforced concrete and other structures surrounding the pressure vessel. That seems to be feasible, however, the increase of the load-bearing capacity of the vessel claws comes up against limiting structural factors. Even the doubling of the number of claws with extreme enlargement of the claws could increase the capacity only to 150 MN [5]. Among possible passive precautions a strong protective covering above the pressure vessel absorbing the remaining thrust impact of a torn off vessel body seems to be the best structural improvement imaginable to keep back any missile within the reactor cavity. Other presently discussed passive or active measures which are to prevent a high system pressure or a large circumferential vessel break are welcome but cannot replace a precaution like the above which constitutes an ultimatum.

6. REFERENCES

1. HENNIES, H. H., KESSLER, G., EIBL, J., 1989, "Improved Containment Concept for Future Pressurized Water Reactors," 5th Internat. Conf. Emerging Nuclear Energy Systems (ICENES '89), Karlsruhe.
2. Gesellschaft für Reaktorsicherheit (GRS), 1989, Deutsche Risikostudie Kernkraftwerke Phase B.
3. CARLSON, K. E.; ALLISON, C. M. et al., 1990, RELAP5/MOD3 Code Manual (4 Volumes), NUREG/CR-5535, EG&G Idaho, Inc.
4. JACOBS, G. J., 1991, "Loads Acting during Reactor Pressure Vessel Blow-down at High Pressure," Seventh proceedings of nuclear thermal hydraulics, American Nuclear Society, pp. 57-63.
5. Siemens A G, 1992, Unpublished communication.