PREVENTION OF HEAVY MISSILES DURING SEVERE PWR ACCIDENTS

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ABSTRACT

For future pressurized water reactors, which should be designed against core melt down accidents, missiles generated inside the containment present a severe problem for its integrity. The masses and geometries of the missiles as well as their velocities may vary to a great extend. Therefore, a reliable proof of the containment integrity is very difficult.

To overcome this problem the potential sources of missiles are discussed. In section 5 it is concluded that the generation of heavy missiles must be prevented. Steam explosions must not damage the reactor vessel head. Thus fragments of the head cannot become missiles endangering the containment shell. Furthermore, during a melt through failure of the reactor vessel under high pressure the resulting forces must not catapult the whole vessel against the containment shell. Only missiles caused by hydrogen explosions might be tolerable, but shielding structures which protect the containment shell might be required. Here further investigations are necessary.

Finally, measures are described showing that the generation of heavy missiles can indeed be prevented. In section 6 investigations are explained which will confirm the strength of the reactor vessel head. In section 7 a device is discussed keeping the fragments of a failing reactor vessel at its place.

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1. THE SAFETY CONCEPT AND THE ROLE OF MISSILE IMPACT

For future pressurized water reactors it is not sufficient to show that core melt down accidents are very unlikely. In Germany it will be demanded that in addition

core meltdown accidents must not be able to impair the reactor containment,

so that severe consequences outside the plant can be excluded [1-4]. Consequently, the evacuation of people and a temporary loss of land need not be discussed any longer; and the understanding and acceptance of the low probability for a core meltdown accident, which has turned out to be a difficult hurdle for some people, is no longer an indispensable element of the safety concept. In other words: *the probabilistic approach is replaced by a deterministic point of view.*

For experts extended safety requirements may provide just a further reduction of risk which is not absolutely necessary when risks of other human activities are taken into account. Nevertheless, the requirements are reasonable if one considers that the number of nuclear plants will increase and that the costs expected for the discussed improvements are moderate.

However, for concerned people, who hardly have the opportunity to check risk assessments in detail, the additional requirement may be of great help in appreciating that nuclear reactors do not present an undue safety problem. Also, it should be kept in mind that it is not only scientists who finally decide about the future of nuclear power [5].

To comply with this general aim, the most unfavorable containment loadings caused by core melt down accidents must be considered. These loadings include the impact of missiles stemming from dynamic events and fracture processes which accompany the accident. The missile problem requires special attention, since the masses, shapes and velocities of missiles vary to a great extend such that the specification of worst cases is quite difficult.

2. MISSILES CAUSED BY STEAM EXPLOSIONS

During the core melt down accident large masses of molten fuel (and other core material) may fall down into a water pool remaining in the lower head of the reactor vessel. If the lower head has been already molten through, the fuel may fall down into some water collected in the reactor vessel cavern. In both cases steam explosions may occur accelerating molten fuel slugs upwards against the reactor vessel head [6, 7]. If the head or its bolts failed heavy fragments could be hurled against the containment shell (Fig. 1).

The masses of the molten fuel slugs have been estimated up to 80 000 kg. Their velocities are not known yet, but for safety proofs figures around 150 m/s are under discussion [7, 8]. Then, the resulting momentum is around 12 MNs and the kinetic energy is about 1000 MJ. The masses, velocities and energies of missiles caused by a failing reactor vessel head might reach the same orders of magnitude. The transfer of kinetic into potential energy before the containment shell is hit can be neglected for the high velocities discussed here.

For comparison the energy needed to deform one square meter of a steel containment shell of 40 mm thickness such that the average strain reaches 20 % is only about 4 MJ. For a piece of shell undergoing such a loading significant leakages are likely. Therefore, it can be concluded that missiles caused by a steam explosion damaging the reactor vessel would strongly endanger the containment integrity.

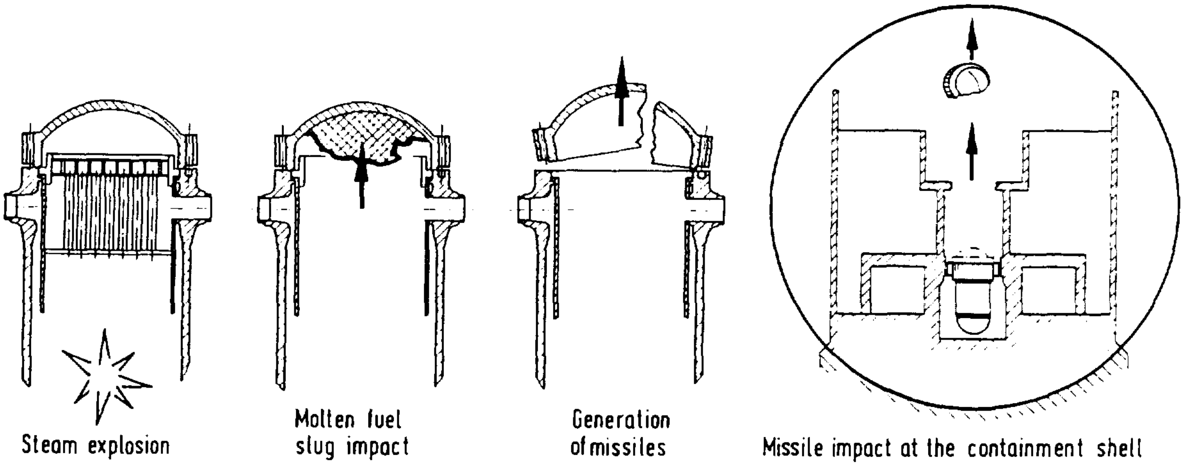

Fig. 1: Heavy fragments of the pressure vessel might be hurled against the containment shell as a consequence of a steam explosion. It must be shown that this event does not occur.

Even the energy dissipation by protective structures located inside the containment in a certain distance from the containment shell would hardly be sufficient. Assume, for instance, that the protective structures would consist of concrete beams having a width b and a thickness h. Under missile loading the beams would undergo bending exceeding the yield limit σ_y and forming a plastic hinge able to transfer a bending moment of

$$M = \frac{3}{2}\sigma_y \frac{bh^2}{6} .$$

Assume furthermore that the plastic hinge allows a bending angle α before the beam collapses and the bending moment vanishes. Then the dissipated energy is roughly

$$E = M\,\alpha .$$

For heavy beams with $b = 5$ m and $h = 2$ m, with an average yield stress $\sigma_y = 60$ MPa and a relatively high bending angle $\alpha = 0.1$ (5.7°) the dissipated energy amounts to

$$E = 30\,\mathrm{MJ} .$$

This is much smaller than the kinetic energy of the missiles discussed above (Fig. 2).

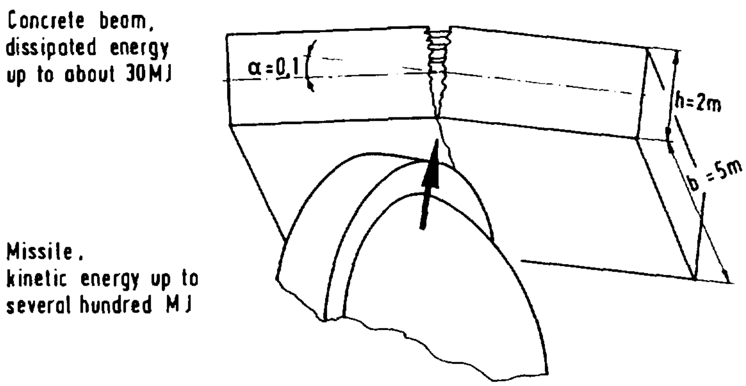

Fig. 2: The energy which can be dissipated by the protective structure is much smaller than the energy of missiles caused by a steam explosion

If, however, the reactor vessel head does not fail, the momentum of the molten fuel slug is transfered to the whole vessel. Due to its large mass its velocity is quite moderate. Therefore, the vessel does not reach the dome of the containment shell.

3. UPWARD ACCELERATION OF THE WHOLE REACTOR VESSEL CAUSED BY A MELT THROUGH FAILURE OF ITS LOWER HEAD UNDER HIGH INTERNAL PRESSURE

Depending on the initial events the core melt down accident may start with the reactor vessel loaded by the operating pressure of about 160 bar. If no measures are taken to reduce this pressure, the melt through failure of the reactor vessel lower head may cause very strong dynamic forces catapulting the whole reactor vessel upwards like a rocket (Fig. 3).

According to the actual knowledge it cannot be ruled out that during this process the lower head will be completely torn off. For this case maximum dynamic forces up to 300 MN occur [9]. The time history of these forces F(t) is shown in Fig. 4.

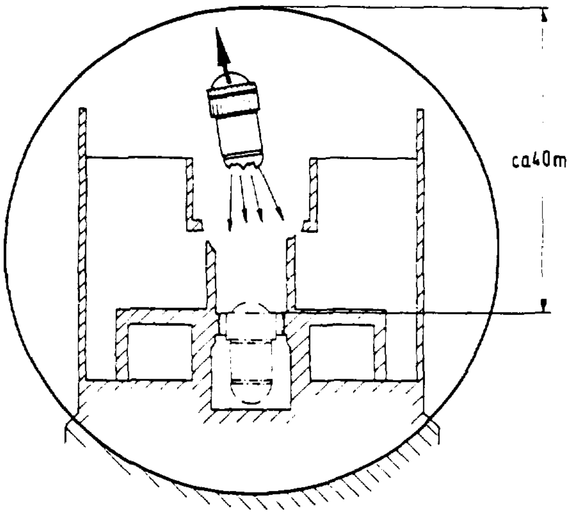

Fig. 3: The whole reactor vessel might be hurled against the containment shell as a consequence of a melt through failure under high internal pressure. This event must not occur.

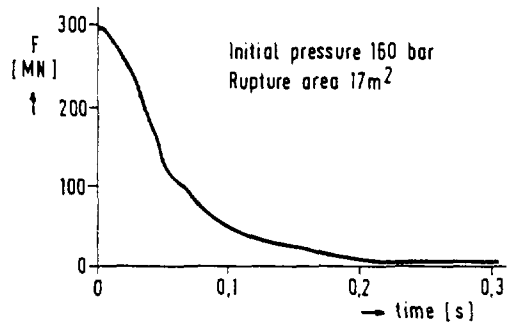

Fig. 4: Force F acting at the reactor vessel after a melt through failure under high internal pressure; figure taken from [9].

It exceeds the strength of the actual reactor vessel clampings considerably. If no adequate design changes are made, the clamping can be neglected and the momentum of the upward moving vessel can be assessed

$$I = \int F(t)\, dt .$$

Using the time history of Fig. 4 one obtaines

$$I = 20\ \text{MNs} .$$

For a reactor vessel mass of 500 000 kg, the upward velocity is

$$v = 40\ \text{m/s}$$

and the kinetic energy is

$$E_1 = 400\ \mathrm{MJ}.$$

In a vertical distance of about 40 m the reactor vessel hits the containment shell. After substraction of the corresponding potential energy, the kinetic energy left is reduced to

$$E_2 = 200\ \mathrm{MJ}.$$

This is again much more than the energy needed to damage the containment shell. It is even more than the energy which can be dissipated by the heavy protectice structures discussed in the last section.

4. MISSILES CAUSED BY HYDROGEN EXPLOSION

As a consequence of a core melt down accident hydrogen may be released into the containment atmosphere. If no measures are taken to reduce the hydrogen accumulation, it may explode causing strong pressure waves propagating through the containment atmosphere [10]. These waves will also pass structural elements surrounded by the containment atmosphere. Consequently, during this process pressure differences will act at these elements. In addition, the flowing gas behind the wave front will exert drag forces on the elements. Therefore, structural elements which are not properly fixed will be accelerated. In this way they might become missiles (Fig. 5).

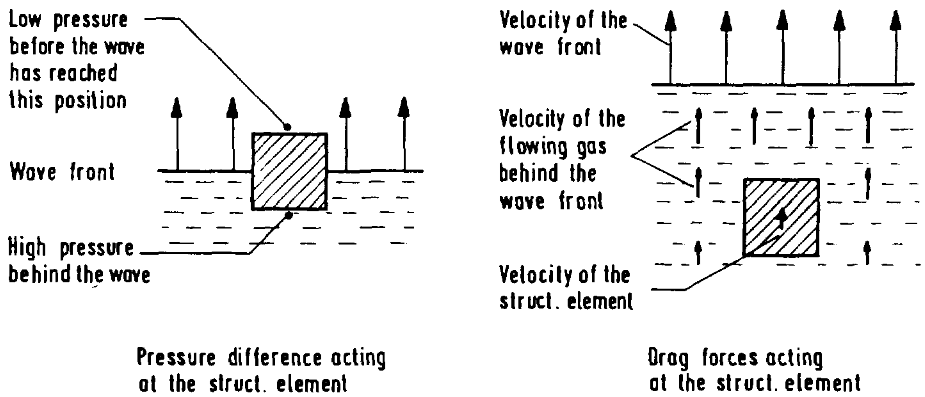

Fig. 5: Structural elements which are not properly fixed may be accelerated by passing pressure waves caused by hydrogen explosion.

However, the driving forces last only for very short times. Since the velocity of the wave is always larger than the velocity of the flowing gas which again is larger than the velocity of the structural element, the wave will be reflected at the containment wall and will come back before the structural element has reached the containment wall. Now the acceleration of the structural element will be reversed. Due to three dimensional effects of the processes the superposition of acceleration and deceleration must not cancel the movement of the element completely. But it is likely that the velocity will be considerably reduced before the element is able to hit the containment wall. In conclusion, the velocity of missiles caused by hydrogen explosions is expected to be moderate.

The problem may be more severe, if the hydrogen explosion occurs in a compartment with small openings. Then the pressures may act for longer time and if a compartment breaks fragments of the walls may become missiles with higher velocities.

5. CONSEQUENCES FOR THE PLANT DESIGN

According to section 2 the protection of the containment shell against missiles caused by steam explosions breaking the reactor vessel head would be very difficult. Concrete shielding of 2 m thickness inside the containment shell would hardly be sufficient. Therefore, it is required that

the vessel head must withstand the dynamic loading caused by a steam explosion.

Then missiles caused by steam explosion do no longer question the containment integrity. Investigations of the load carrying capacity of the reactor vessel head are be described afterwards.

According to section 3 also the protection against the impact of the whole reactor vessel accelerated by a melt through failure under high internal pressure would be almost impossible. Therefore, it is required that either

the pressure in the reactor vessel must be sufficiently reduced before the melt through failure occurs; this solution would require only minor changes, but the necessity of active measures may be critized,

or

the hole in the reactor vessel caused by the melt through failure can be shown to be always much smaller than the cross-section of the vessel; such a proof would be quite difficult, even after appropriate changes of the geometry of the vessel,

or

the clamping of the vessel must be improved significantly; this solution would require much stronger and space consuming designs,

or

the accelerated reactor vessel must be catched by a missile retention device.

Strictily speaking, these measures must not prevent any upward movement of the reactor vessel completely. It would be sufficient when its initial kinetic energy were smaller than the consumption of potential energy before the vessel reaches the containment shell - this means, when its initial velocity were smaller than about 25 m/s. Therefore, some of the above measures which are difficult to realize when the reactor vessel must be kept at its place may be quite suitable when only its initial velocity must be reduced. For instance, the improvement of the vessel clamping should also be evaluated under this point of view. The same is true for the missile retention device which will be discussed in more detail afterwards.

Taking into account section 4, protection of the containment shell against missiles with moderate velocities stemming from hydrogen explosions seems to be possible. However, more detailed investigations are needed to evaluate the velocity which can be reached by such missiles. To avoid missiles with higher velocities, the inner containment structures must be such that the pressurization and the collapse of individual compartments cannot occur. On the other hand also the sensitivity of the particular containment walls under missile loading has to be studied. Of course, the dynamic interaction with shielding structures has to be included.

6. INVESTIGATION OF THE SLUG IMPACT STRENGTH OF THE REACTOR VESSEL HEAD

Assessments carried out recently suggest that rather strong molten fuel slug impacts can be carried by the vessel head. For slug masses up to 80 000 kg tolerable velocities between 150 and 210 m/s are mentioned [8]. This means, steam explosions causing such impacts cannot be a source for missiles endangering the containment shell.

However, it is quite difficult to provide reliable proofs of the slug impact strength of the reactor vessel head. If the upper internal structures underneath the vessel head are neglected, computational models can be applied to describe the impact problem. Exploratory computations show that some basic phenomena of the liquid-structure impact are not fully understood; different computational models yield different results. Therefore, experiments would be necessary to clear up this problem. In any way the results will depend very much on the assumed slug shape. If the slug fits into the reactor vessel head very well, the load peaks are very high. This presents quite a problem, since in safety investigations such extreme cases must be considered. In addition, due to the neglected upper internal structures, the slug impact strength of the head will be underestimated.

If the upper internal structures are included, the liquid-structure impact process is much more difficult. As indicated by several assessments, the internal structures will be heavily damaged during the impact [6, 8]. Therefore, the development of appropriate computational models is almost impossible, and their results will be very questionable. On the other hand, the interaction of the liquid slug with the failing upper internal structures is quite important. Now it can be expected that the slug shape does not influence the results very much, which is essential for safety investigations. In addition, the interaction dissipates kinetic energy and smoothes the impact process, i.e. it increases the duration Δt of the impact. Consequently, the interaction with the upper internal structures increases the momentum I which can be transfered from the slug to the vessel head before failure occurs.

$$I = \int_{\Delta t} F(t)\, dt .$$

Note, that F(t) is the impact forces versus time t, and that the maximum impact force is given by the strength of the bolts, for instance. The problem is illustrated in Fig. 6.

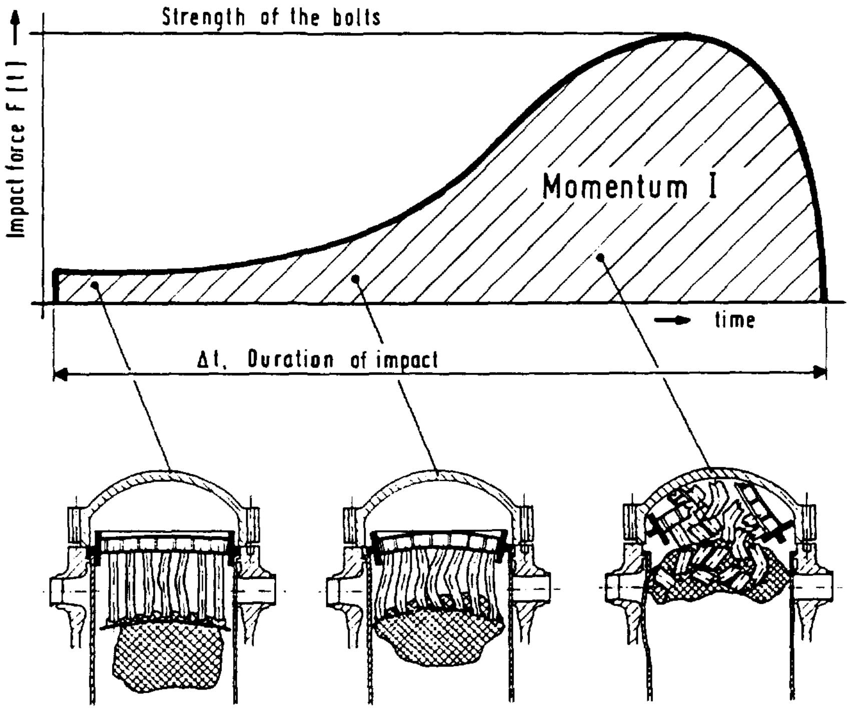

Fig. 6: Force transfered during the slug interaction with the upper internal structures and the impact with the head. The curve shows only the qualitative behavior.

To elude the computational difficulties, the impact problem will be investigated by the model experiments BERDA (Beanspruchung des Reaktordruckbehälters bei einer Dampfexplosion) where the impact process will be simulated in a smaller scale such that the expences are acceptable. To assure similarity between full and small scale some dimensionless quantities must be identical. They can be obtained using the relevant basic equations describing the problem [11].

The test facility for the model experiments BERDA is shown in Fig. 7. The structural model is scaled down by factor 10. It consists only of the upper part of the reactor pressure vessel including the vessel head with its bolts and the upper internal structures, with the grid plate, the guide tubes and support columns, the upper support grid and the upper part of the core barrel. In order to simulate the molten fuel slug a liquid of the same density will be used. It will be accelerated upwards to a predefined velocity using a pneumatic drive mechanism. During the acceleration phase the liquid is contained in a crucible which is able to withstand the acceleration forces. Before the liquid reaches the model the crucible will be decelerated by a crash material while the upward movement of the liquid slug continues until penetration into the upper internal structures and impact at the vessel head occurs. The maximum mass of the slug is 80 kg, corresponding to 80 000 kg in full scale. The maximum slug velocity is 130 m/s, corresponding to about the same velocity in full scale.

Care has been taken for sufficient instrumentations. The slug velocity and the slug shape will be measured before the slug impact. Resulting pressures, forces, strains and accelerations of the structures will be recorded during the test as a function of time. Permanent deformations and the amount of fracturing can be determined in great detail after the test.

Using the similarity relations the results can be directly transfered to full scale; for instance, the strains in the model are the same as the strains in full scale. Especially, slug velocities which the model can withstand will also be tolerable for the real pressure vessel.

7. DESCRIPTION OF A CAGE TYPE OF MISSILE RETENTION DEVICE FOR A BURSTING REACTOR VESSEL

A proposal for the device is shown in Fig. 8a. It is designed against sudden vessel failure caused by cracks propagating in circumferential and axial direction as well. More details are given in [12]. Of course, if such a device were introduced, the investigation of the slug impact strength at the vessel head would be of lower priority.

It is important to note, that there is a gap of 0.5 m between the reactor vessel and any surrounding structure, so that access to the reactor vessel is possible. Upon failure of the reactor vessel under high pressure the fragments are accelerated across this gap to high velocities before they impact the missile retention device. This consists of individual rings and axial bars which are made of a high strength ductile steel, and which are designed to undergo considerable uniaxial plastic elongations under the impact. Thus the high kinetic energy of the vessel fragments will be dissipated in these elements without threatening the containment shell.

The innermost concrete structure fixes the rings and carries the dead weight. (Alternatively, the rings could be attached directly to the axial bars.) Appropriate radial openings in the concrete structure along the circumference will distribute the escaping steam more symmetrically. For refuelling first the nuts of the bars have to be detached prior to removing the upper traverse. Then the refuelling conditions are similar to those in the present plants.

The elements of the missile retention device form a closed system. Major unbalanced forces due to jets escaping from the failing reactor vessel, and which might catapult the system away, cannot occur.Therefore, heavy clamping of the missile retention device is not required.

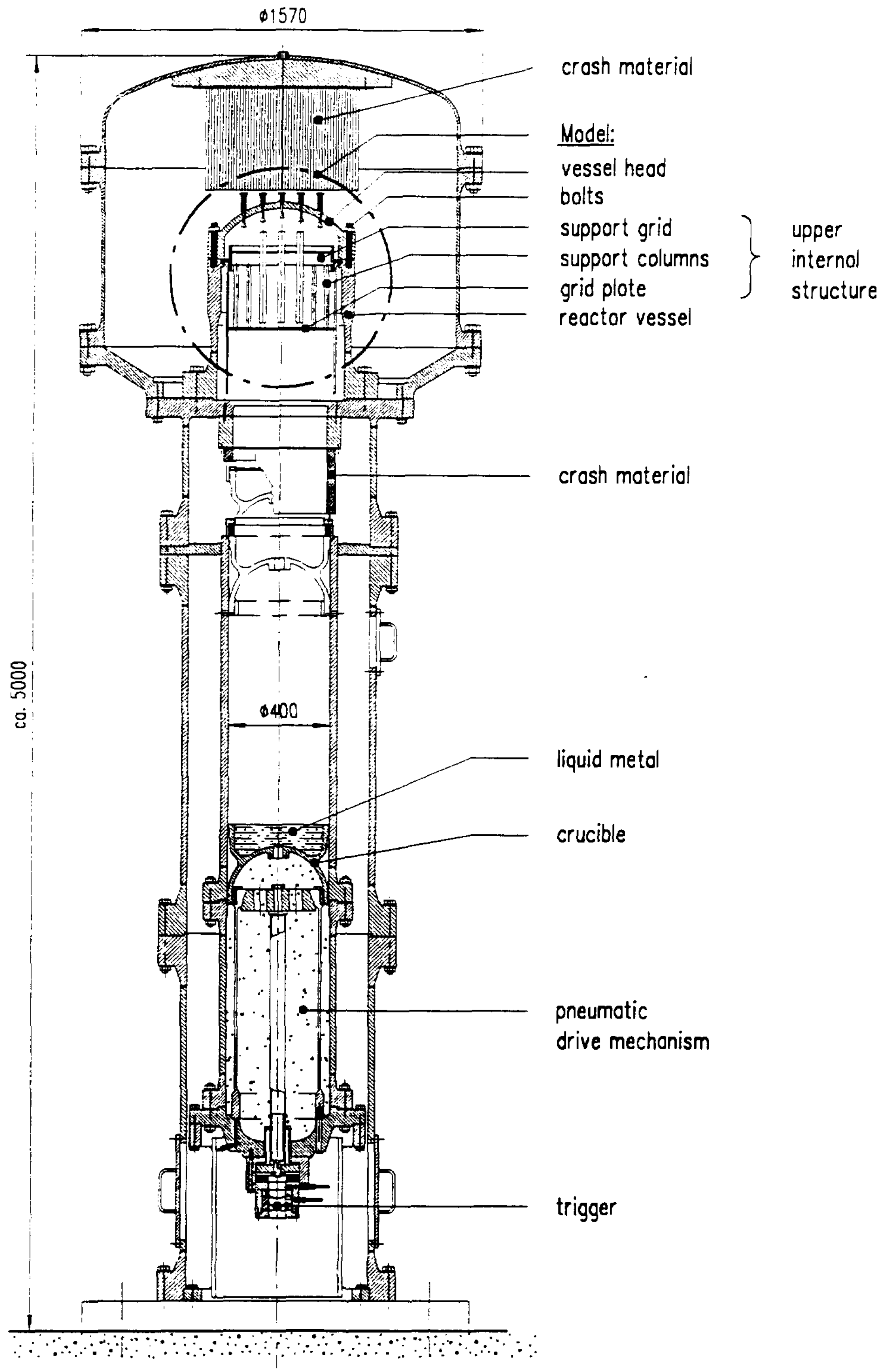

Fig. 7: Test facility for the model experiments BERDA; the model is scaled down by 1:10.

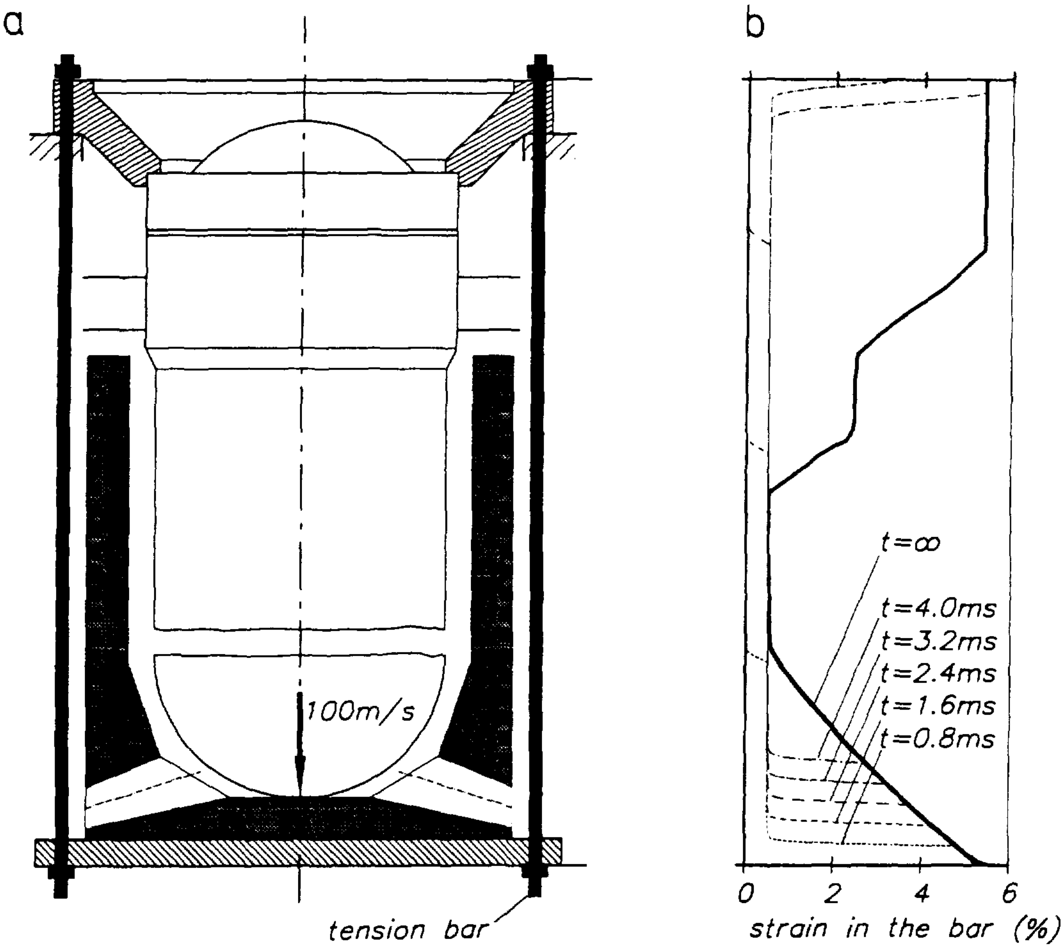

Fig. 8: The missile retention device forms a closed system

Attention must be paid to the strain distributions along the rings and axial bars. Due to wave propagation effects the distributions can be very irregular. Fig. 8b shows the distribution along the axial bar for different times t after an impact of the broken lower head. In the elastic region up to a strain of about 0.5 % the wave propagation is fast. In the plastic region, i.e. for strains above 0.5 % the propagation is considerably slower. The accumulated strain distribution is shown by the bold curve. It varies between 0.5 and almost 6 %.

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