STEAM EXPLOSIONS AND THEIR RELEVANCE FOR PROBABILISTIC RISK ASSESSMENT

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1. Introduction

There is some disagreement about the role of steam explosions in probabilistic risk assessment. Former risk studies /1,2/ assume and impute with a certain probability that a steam explosion could damage the containment during a severe accident. In this case an early radioactive release with severe consequences would occur.

In the meantime there is - thanks to experimental and theoretical efforts - at least agreement in the International Nuclear Safety Community that the risk from steam explosions was originally overestimated by several orders of magnitude. These conclusions are still based on hypothetical assumptions for a hypothetical event, and one should really argue how reasonable it is to treat the sequences and phenomena of a hypothetical accident in a physically often unrealistic way.

In the following an attempt is made to draw a conclusion, whether a steam explosion can or cannot endanger the integrity of the containment and/or the reactor pressure vessel of a pressurized water reactor. The deliberations are based on three reports /3,4,5/ being recently published, or being in the process of publishing in the Federal Republic of Germany. As far as special design criteria are concerned, the conclusions may mainly or only be relevant for German PWR's.

2. Status of Knowledge

Worldwide numerous experimental and theoretical research activities are under way to study the phenomena and the consequences of steam explosions. Here only a few of them, being mainly important for risk deliberations, shall be briefly discussed.

The experiments performed can be roughly subdivided in four categories, depending on the aim of the study, namely in experiments looking for

- melt water contact in the pressure vessel,
- melt water contact outside of the pressure vessel,
- fundamental aspects,
- influence of system pressure.

Here only a few newer experiments shall be discussed; olders are very well reviewed in /6/.

The Sandia-PITS-Experiments /7-10/ had the aim to get a better understanding about explosions with larger masses of melt. The lessons learned from these experiments were:

- With increasing melt mass no trigger is necessary to initiate the steam explosion. It usually starts 0,5 to 3 s after the beginning of pouring in.
- In many cases the interaction started before the total mass of melt was in the water tank.
- The efficiency of the explosion is decreasing with the diameter of the fragmented particles.
- The maximum efficiency found in the experiments was 1,34%; however, with 90% of all experiments the efficiency was lower than 0,5%. With hot or boiling water an efficiency of only 0,3% was reached.

This series of experiments was the basis for ongoing studies which were better instrumented. The FITS-Experiments, also performed at Sandia, had the intention to study a variety of influencing parameters /11-15/.

These research activities showed that:

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- Steam explosions occur not only with molten metal and thermit but also with CORIUM.
- The self-ignition at ambient pressure is only depending on the melt mass; with CORIUM about 4 kg.
- With melt falling into water the position where self-ignition starts may vary, sometimes it was observed already at the surface or on a vertical wall; latest, however, at the bottom of the water vessel.
- At higher pressures steam explosions are suppressed unless a triggering mechanism is used.

In the Federal Republic of Germany KWU performed a series of steam explosion experiments to study the interaction between water and melt during the so-called "fourth phase" of a core melt down process. In this phase, due to the penetration of a wall in the pressure vessel-cavern , water is flowing over the melt. The experiments showed that as long as the water level above the melt is not too high, a steady evaporation of the water without steam explosions will usually occur with the melt surface being liquid. With increasing water level the melt starts to freeze at its surface with periodically violent eruptions, followed by strong evaporations which, however, are no steam explosions /16/. A similar experience was made by the author of this paper himself /17,18/ in experiments, where in addition gas was blown through the melt to imitate the H_2-production during the interaction between melt and concrete. Also in this case only sudden evaporations but no steam explosions were observed. A similar kind of flooding experiments were also performed at Sandia, however, with small amounts of melt /19/. Here one can argue, whether due to the small amount of melt or due to the flooding process no steam explosion occured without a triggering mechanism.

Newer experiments within the FITS-series, also with flooding the water over the melt, showed a very violent and eruptive evaporation rather than a steam explosion. The conditions in these experiments, however, were not quite comparable with the reactor situation because the temperature of the melt would not be as high as 3000°C as it was in the experiments.

A special scenario discussed in the United States is the imputation that melt is blown out under high pressure through a hole of the pressure vessel into a water reservoir. This situation is physically impossible with German pressurized water reactors because there is no water in the cavern below and around the pressure vessel. The melt jet would only hit a thick concrete wall.

The influence of the system pressure and, by this, the influence of a high pressure atmosphere in the reactor pressure vessel was researched in a series of experiments performed at EURATOM Ispra /20,21/. From these experiments the general conclusive statement can be drawn that with system pressures higher than 2 MPa, steam explosions could only be initiated with very strong detonative triggers. This, in general, is also confirmed by the MFTF-experiments /22/, even with some of the test results apparently being not in agreement. Here one has to be aware of the fact that the cover of the MFTF-vessel hits the bottom of the vessel, which acts as a trigger for the steam explosion.

3. The Steam Explosion During and After a Catastrohpical Failure of the Core

There is a large number of partially highly sophisticated theories describing the phenomena in connection with steam explosions and trying to extrapolate from experiments the mechanical action on reactor components and, by this, the possible or not possible damage due to steam explosions. It would by far break up the frame of this short report to discuss them with all their benefits and draw-backs. Therefore, briefly only one theory -comprehensively described in /23/- shall be mentioned, the so-called "detonation theory". Comparisons with a THERMIR-experiment /24/ showed good agreement with respect to the pressure-time-behaviour, as well as to the expansion of the shock-front. The theory also shows that above a system pressure of 2 MPa no detonation wave can develop and that in case of a CORIUM-water-system no detonation situation could be predicted in which the maximum pressure of the wave-front was larger than the layout pressure of the pressure vessel. However, one has to be aware of the fact that also this theory - as all other theories - starts from the assumption that the melt is homogeneously mixed with the water before the detonation is initiated. To do this premixing additional forces - i.e. momentum forces from jet flow - have to be available. Risk studies concerning the impact of steam explosions very often also assume that the premixing and pre-fragmentation is a given situation and do not spend many thoughts whether such a situation is physically possible for a large amount of melt.

All theories, however, agree that the following eight conditions have to be simultaneously fulfilled to enable the development of a large steam explosion with serious consequences:

1) There must be a sufficient and as good as possible homogeneous premixing between melt particles and water, which stays long enough with a large amount of melt.

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2) During this premixing period the steam explosion must not start too late, otherwise the premixed and pre-fragmented particles would cool and freeze due to film boiling.

3) In the experiments the delay-time after a steam explosion started was always below 3 s, which means that the pre-fragmentation and premixing has to be completed for a large amount of melt within this period. This needs extremely high momentum- or viscous-forces for the mixing process.

4) The heat transfer area between melt and water must be extremely large for a catastrophic steam explosion, which is only possible if the molten material in a second step undergoes a fine-fragmentation resulting in particle diameters in the order of 10^3-10^6 m.

5) These microscopically fragmented particles of the melt must have very close liquid contact with the water, which is only possible if each of the fragments is surrounded by a small volume of water, approximately equal to its own volume, and if all fragments are homogeneously distributed in the water. This microscopic fragmentation has to occur in an extremely short period - a few milliseconds - and this for a large amount of melt.

6) The liquid contact between melt and water must be long enough without any boiling phenomenon at the interface, in order to transfer enough energy for the subsequent steam explosion.

7) The melt water mixture must be completely homogeneous because any discontinuity would deflect, retard or damp the shock-wave, which would result in a strong reduction of the steam explosion impact and would rather produce several small steam explosions instead of a large one.

8) There must be not only enough melt available but also enough water,which during several sequences of a core melt process is not the case, and if it is the case, there is not enough momentum force to premix melt and water.

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All these eight conditions have to be fulfilled to make a large steam explosion possible.

We have now to discuss what happens in the reactor and what pathes of severe accident sequences do we have to follow up. Experiments showed that steam explosions in the pressure vessel above a pressure of 2 MPa must not be taken in account at all and that also in the region of 0,5 to 2 MPa a steam explosion is only possible if a strong trigger exists. Finally the melt can come in contact with water if the concrete wall of the biological shield around the pressure vessel fails. However, then we have the situation of flooding water above the melt. So we have to take in account three pathes:

- Low pressure path: self-ignition of a steam explosion if the melt from the core flows or falls into the water in the lower plenum.
- High pressure path: in case of a small leak or a station black-out there must be a trigger with enough energy to start the steam explosion.
- Containment situation: the interaction between melt and flooding water after damaging the concrete wall of the biological shield has to be taken in account.

The question, whether a steam explosion can endanger or damage the pressure vessel can be attacked from two sides:
First one can argue, what is - under pessimistic assumptions - the maximum amount of melt which could interact with the water in the lower plenum during a core melt down and can the pressure vessel withstand the impact of this reaction?
The second possibility is to look for the maximum allowable mechanical load onto the pressure vessel, and then to ask what would be the corresponding mass of melt to produce this mechanical impact?
Both ways were gone in German studies.

Körber /3/ studied the maximum mass of melt which could flow into the water of the lower plenum until a steam explosion occurs and which would be available for the melt-water-interaction.

He took in account the freezing of originally molten material in lower parts of the core and made deliberations, how stable a crust or a frozen layer above the lower fuel element endboxes could be,before it would be penetrated by the melt lake.
He also calculated the down-flow velocity after opening of the crust and assumed that a hole suddenly opens which has the cross section of 2 fuel elements.

How difficult it is to keep only a few hundred kg of hot CORIUM-melt in a vessel, is well known by all experimentalists doing research in core melt down and in steam explosions. In spite of this experience it is often assumed that several tons of liquid melt could be collected above a frozen layer and that this frozen layer would then fail over its total cross section. This is physically impossible; the melt will,furthermore,continuously flow through the lower endboxes into the water, due to its low viscosity. A continuous flow of melt into the lower plenum would result in a mass flow rate of approximately 100 kg/s. However, Körber /3/ in his study made pessimistic assumptions and, based on strength and stress calculations /25,26/ under high temperature, as well as looking to the failure mode of the core, he predicts with the assumption of re-freezing and crust formation, with pessimistic assumptions a maximum melt flow into the water of 1700 kg/s.

From the experiments it is well known that the ignition of the steam explosion with large melt masses starts automatically usually after the first contact of the melt with the water, however, latest when the melt hits the bottom of the pressure vessel. Taking this in account, Körber /3/ comes to a maximum mass of melt of 2000 kg, which could react in a steam explosion. Here it has to be emphasized that, in addition to the availability of this mass of melt, all eight conditions mentioned before have to be fulfilled.

The mass of melt which could react with the water is also a function of the mass of water being present in the lower plenum. With decreasing water level in the lower plenum, even with very large amount of melt being available, only a part of it could react.

In Fig.1 the dependency of the reacting melt mass on the water level in the lower plenum is shown. In addition, one has to realize that the lower plenum is not an empty volume, where the shock waves of a starting steam explosion could expand unprevented. There is a structure supporting the core in the lower plenum, as shown in Fig.2. This supporting device in German PWR's guarantees that the core structure and, by this, the frozen layer cannot break down at once, because it is still cooled by water until the steam explosion starts. The supporting device, however, also is conducting heat from the lower fuel element endboxes into the water, which produces boiling and so the falling down melt would not find an ideal water pool, as it is the case in the experiments, but a foaming two-phase mixture which is much less favourable for steam explosions.

Wagler and co-workers /4/ went the other way in a recent study. They looked for the maximum allowable mechanical load on the pressure vessel of a 1300 MW German PWR. They took in account most of the experiments performed in the last years, started from very pessimistic assumptions and most favourable conditions for the steam explosion. Based on these pessimistic assumptions they found that the pressure vessel of the above mentioned reactor could withstand a steam explosion, where 50000 kg melt would interact with water at once, without being damaged. Under less pessimistic assumptions the allowable amount of melt reacting with water would increase remarkably, as shown in Fig.3, which is taken from /4/.

The study by Wagler and co-workers /4/ is based on the newly developed computer code KODEX. 50000 kg melt reacting with water in a steam explosion are far away from any imaginable physical possibilities.

After melting through the reactor pressure vessel, the melt does not come in contact with water immediately. This only takes place after the failure of the biological shield due to melt-concrete-interaction. Studies /5/ showed that the increasing volume, which is a consequence of the failure of the biological shield, helps

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to reduce the pressure wave of a potentially arising steam explosion. The containment would not be dangered in any case.

One could now argue that there may be a failure of the core and of the frozen layer in a pressure range between o,5 and 2 MPa, due to any highly unprobable reason. Here we first have to realize that the accumulators feeding in emergency core cooling water open at 2,8 MPa (German PWR) or 4,4 MPa (US-PWR) respectively. This means that the core was cooled down before it can start again to heat up and to melt. This heating process is rather slow because only the decay-heat is available. In this slow process heat conduction and radiation will evaporate the water in the lower plenum, and if the core finally would fail, there is almost no water present in the lower plenum. However, even if we assume a steam explosion in this pressure range, it would not damage the pressure vessel. Certainly the elastic reserves of the pressure vessel are smaller at this elevated pressure, however, the plasticity of the pressure vessel structure is increased due to the higher temperature. Therefore, even with this higher system pressure the pressure vessel could withstand approximately the same interacting core melt as with the lower system pressure. This is also valid for higher system pressures up to approximately 10 MPa.

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4. Consequences for Future Actions

A detailed survey of the international literature and also studies performed in our country showed that the integrity of the pressure vessel or of the containment structure of a modern German pressurized water reactor would not be endangered due to a steam explosion. This statement is valid without raising a loan, from probabilistic studies or from deliberations, with what probability which course of any severe accident may occur. So in risk studies steam explosions leading to an early contamination of the environment should not play any role for future.

Another question is whether research activities in steam explosions should be continued or not. There are several phenomena of great general interest connected with steam explosions, which are up to now not well or almost not understood. Steam explosions are not only a matter of nuclear safety, they can occur and occurred in foundries, in paper factories, and they may also happen with handling liquid methan or any other deeply frozen fluid. The emphasis of these tests, however, should be put on the understanding of the mechanisms and not so much on demonstrating the powerfulness of artificially scaled up and initiated steam explosions.

In nuclear safety the habit developed that it has always to be proved with what probability or improbability a sequence of a severe accident can occur. Perhaps it would be sometimes wise to turn around the question and to ask how it is imaginable that a hypothetical sequence of a severe accident leading to a catastrophical failure could be verified, if one would get the task to do it. I think, everybody would be overcharged if he would get the task to bring several tons of hot melt homogeneously and simultaneously to react in a powerful steam explosion.

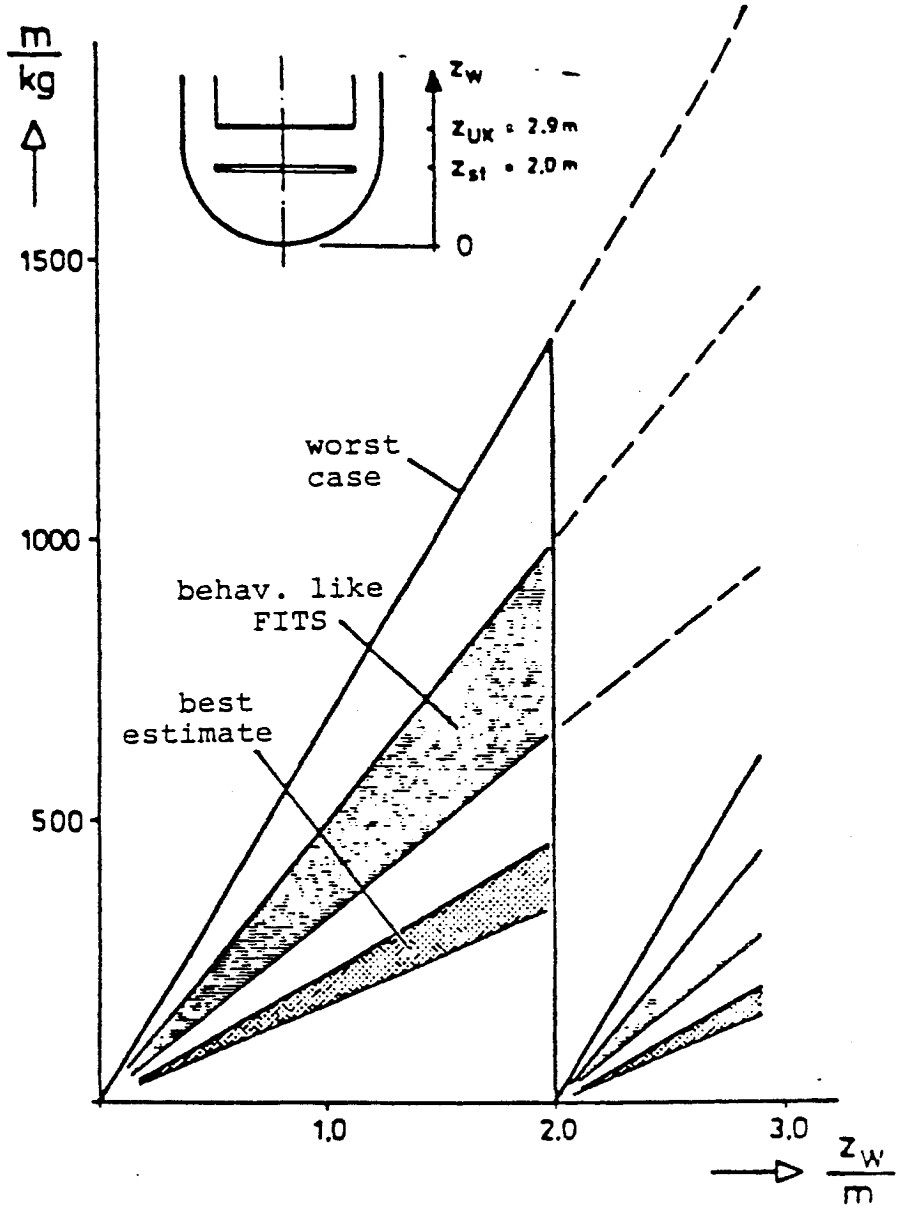

Fig.1: Mass of melt available for steam explosion during core melt down depending on water level Z_w in lower plenum /3/

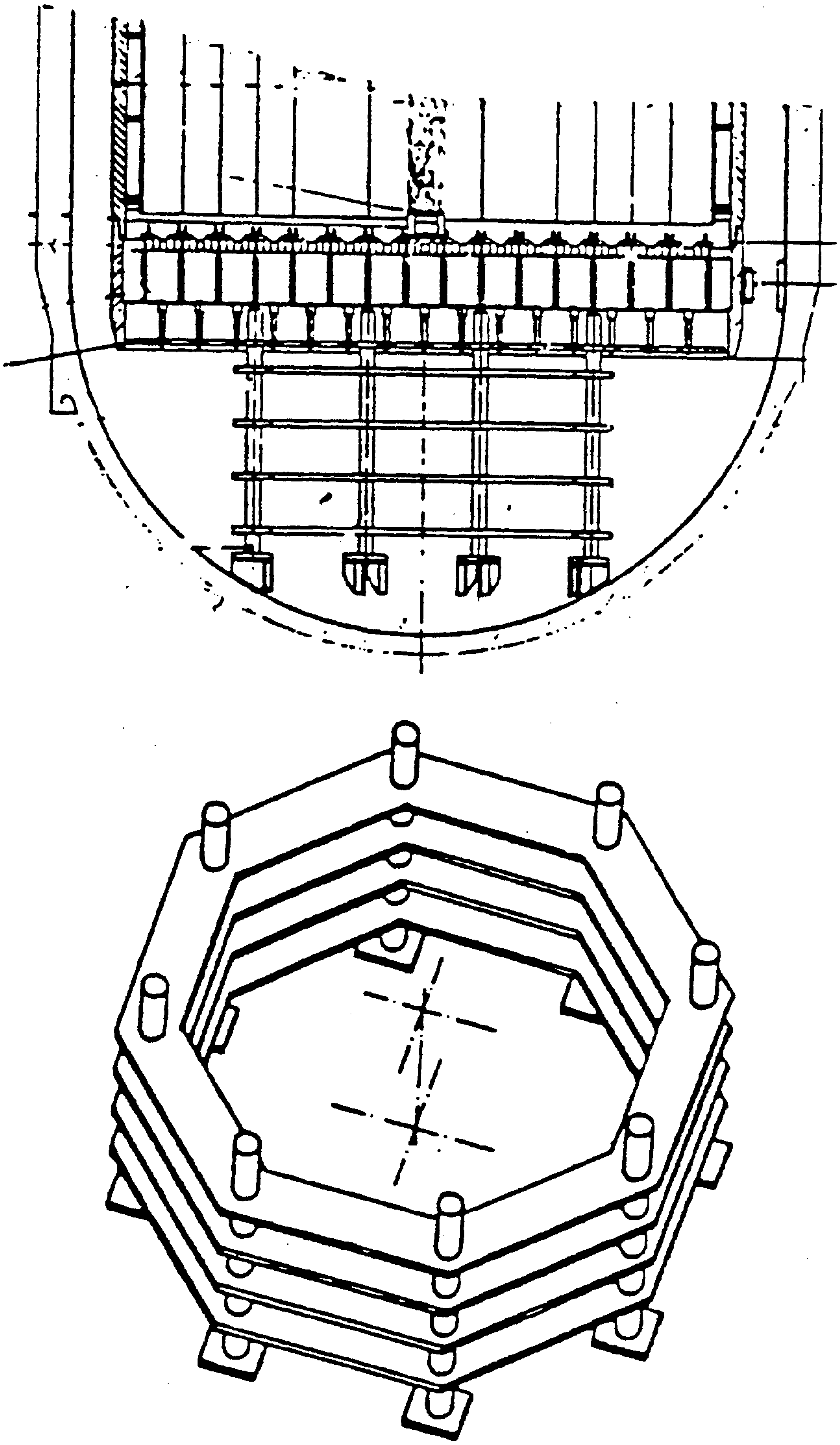

Fig.2: Core support structure of a German 1300 MW PWR

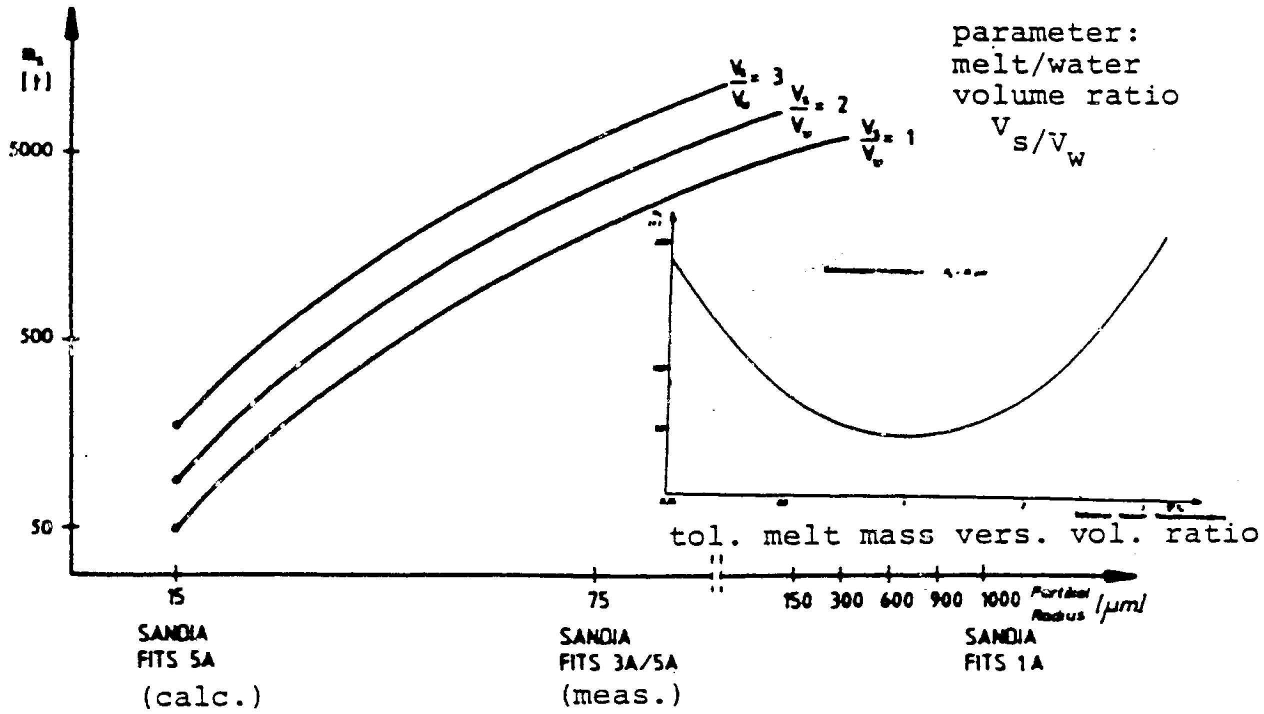

Fig.3: Tolerable melt mass for steam explosion in the pressure vessel of the German 1300 MW design (low pressure core failure case)