Analyses of Containment Loading by Hydrogen Burning During Hypothetical Core Meltdown Accidents

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Summary

The possibility of occurance of violent hydrogen burning during a LWR meltdown accident and its consequences to containment atmosphere conditions are discussed. Two accident sequences with low and high system pressure during the in-vessel-melt phase of a meltdown accident are considered. In both sequences only deflagration, but no detonation may become possible, presuming homogeneity of the containment atmosphere. In a low pressure szenario the pressure increase due to deflagration will not reach the failure pressure of the containment, if combustion takes place when the flammability limit is reached. For the special situation of a rapid release of steam and hydrogen after a high-pressure failure of a reactor pressure vessel, calculations with a multicompartment code show that the possibility for hydrogen burning does not exist. Thus, an additional augmentation of the steam spike as a consequence of the failure of the pressure vessel cannot occur.

1. Introduction

In risk analyses, it is of central interest to know whether and if so when, a containment functioning as the final barrier against fission product release into the environment, will fail due to the events during a meltdown accident.

The behaviour of the containment atmosphere during a meltdown accident with respect to pressure and temperature is mainly determined by the release of steam, volatile decay heat sources and gases like carbondioxid (CO_2), carbonmonoxid (CO) and hydrogen (H_2). Of special interest is the behaviour of H_2, which can be generated to a large amount by different metal-water reactions (esp. Zr - H_2O) during the in-vessel- and ex-vessel-melt phases of an accident.

Hydrogen may influence containment atmosphere conditions in several ways: If it does not burn it contributes to the pressure of containment atmosphere by its partial pressure. When generated it may burn continuously releasing the heat of reaction. Finally it may burn violently, i.e. it may deflagrate or detonate, if certain values of H_2 - enrichment are exceeded.

Best estimate core meltdown analyses for a large 1300 MWe PWR containment of german design show that without violent H_2 burning overpressurization of the containment shell has to be expected not before about four days after start of the accident.

With respect to the potential for the generation of a large amount of H_2 during a meltdown accident, the possibility of violent H_2 - burning during an accident with core meltdown and its consequences to containment atmosphere conditions were analysed. In the following results are discussed for two accident sequences.

2. Accident Sequences

Analyses presented in this paper are performed for

- Loss-of-coolant-accident (LOCA) caused by a large break in the primary circuit, and complete failure of all low pressure recirculation systems /1/.
- Emergency power case and complete failure of the auxiliary power supply.

The first case may be regarded as characteristic for accidents with core meltdown under low system pressure ("low pressure case"), the second for meltdown under high pressure ("high pressure case").

3. Codes

In-vessel-melt- and ex-vessel-melt-calculations have been performed by using the codes MARCH (for core heatup) and KAVERN (melt-condrete interaction).

Pressure and temperature of the containment atmosphere as well as the thermal load of containment structures have been analysed by the code CONDRU. CONDRU was used as a single-compartment model. It considers all mass and energy transports (including fission products) into the containment atmosphere. H_2 -burning is simulated in CONDRU by adding the equivalent energy to the atmosphere, taking into account the change of composition of the atmosphere due to the chemical reaction.

Additionally the multicompartment code DDIFF (up to 50 comp.) has been used, which is applicable especially for short time pressure-difference analysis.

4. Course of Meltdown Accident

In the following an overview is given on the course of the accident sequences analysed.

Large LOCA and complete failure of all low pressure recirculation systems (low pressure case)

The analysis for a core meltdown accident under low system pressure has been performed based on the assumption that after a large LOCA the low pressure recirculation systems fail completely. This accident sequence was analysed also in the German Risk Study /1/.

The accident starts about 20 min. after blowdown when the recirculation systems are assumed to fail. At that time the reactor pressure vessel (RPV) is completely reflooded.

After about 0.6 h, the waterlevel has decreased to the top of the active core as a consequence of the evaporation of the remaining coolant by decay heat. Core meltdown will start about 1.1 h after blowdown. At about 1.4 h, the lower grid plate of the core is assumed to fail. The molten core is expected to slump into the lower plenum of the RPV. Residual water inside the plenum will be evaporated, before about 2.5 h after blowdown also the RPV is supposed to fail due to the attack of molten material.

The failure of the RPV marks the end of the in-vessel-melt phase of the accident, during which up to about 1350 kg of H_2 may be generated due to the Zr - H_2O reaction.

In the subsequent ex-vessel-melt phase, melt-concrete interaction will decompose thermally the concrete of the basement of the reactor building. Besides the erosion of the concrete, the release of steam and gases like CO_2, CO has to be expected from the melt and again of H_2 as a result of different metal-water reactions.

Emergency power case and complete failure of the auxiliary power supply (high pressure case).

Core meltdown under high system pressure can occur if in an emergency power case the redundant auxiliary power supply is also assumed to fail completely. Such an event would cause loss of feed-water supply. Therefore the secondary side of the steam generators would become dry after certain time. The loss of the heat sink will increase the pressure in the primary circuit until relief valves open. Energy produced in the core will be transfered out of the primary circuit by coolant via the relief valves and the pressurizer-drain tank into the containment. In this way the primary circuit becomes more and more empty, while the relief valves keep the pressure high all the time. About 2 h after the beginning of the accident, core uncovery starts followed by the meltdown of the core. After failure of the lower core support structure and slumping of the core into the lower plenum, the RPV is expected to fail after about 3 h.

Thus the characteristic feature of this accident sequence is that in comparison to the low pressure case, the in-vessel-melt phase of the accident takes place under full system pressure.

The high-pressure failure of the RPV can initiate a rapid release of a large amount of superheated steam and of H_2 (due to Zr - H_2O reaction) into the containment. Additionally, a discharge of coolant from accumulators on the hot core fragments may occur, triggered by the depressurization of the primary circuit, and/or a contact between core material and sumpwater may take place. Both events will result in steamgeneration. Thus as a consequence of the HP-failure of the RPV a steam spike in the containment atmosphere is expected.

As in the low pressure case the ex-vessel-melt phase of the accident will continue in a melt-concrete interaction with the events mentioned in the discussion of the "low pressure case".

5. Results

Low Pressure Case

Figure 1 shows the pressure-time history for the low pressure case without violent H_2- burning (solid line). Our calculations indicate failure of the containment shell after about 4 days assuming a failure pressure of 8.5 bars of the containment. The long term pressure increase is mainly due to a sump-water ingression to the surface of the melt during melt-concrete interaction. This happens when the innermost shield inside the reactor cavity,initially seperating sump-water from the melt is penetrated.

Figure 2 gives the course of the H_2- enrichment in the containment atmosphere, presuming homogeneous mixing of the H_2- steam-air mixture. Because in the low pressure case H_2 and steam are generally released in a continuous way, the assumption of homogeneity may be satisfied. /2/.

In the low pressure case the flammability limit for a self sustaining combustion of the H_2 is exceeded at about the end of core heatup, i.e. within about 2 hours after the accident has started. The course of H_2-enrichment is strongly effected by the event of sump-water ingression during melt-concrete interaction. As a consequence of increasing steam generation, the atmosphere of the containment will become inerted.

Thus,violent H_2- burning will be restricted to deflagration, no detonation has to be expected. Furthermore a deflagration will be possible only within a limited time interval (~ 1 day). The results given are practically independend of the fraction of oxidized Zircaloy at the end of the in-vessel melt phase.

In figure 1, also the increase of the containment pressure in case of a H_2-deflagration is shown occuring when the H_2-enrichment exceeds the flammability limit. In the calculation the extent of the Zr - H_2O reaction at the end of core heatup is assumed to be 60 %. The pressure spike is in the order of the design pressure of the containment but well below its expected failure pressure (8.5 bars).

Figure 3 gives the corresponding temperature response of the atmosphere. Additionally, the surface temperatures of the containment steel shell and of steel and concrete structures inside the containment are shown, which can be interpreted as the temperatures of those parts of the structures not "seeing" the flame front. The temperature of the containment atmosphere exceeds 800° C, declining with a time constant of a few minutes.

Practically the same results as discussed are obtained for the pessimistic assumption of 100 % oxidation of Zircaloy up to the end of core heatup, if ignition of the H_2 -air-steam mixture is presumed at the flammability limit. The difference is that the deflagration will occur a short time earlier.

High Pressure Case

Figure 4 reproduces the pressure-time history within the containment for the high pressure case. The depressurization of the primary circuit after RPV-failure will result in a pressure spike not exceeding the failure pressure of the containment.

In figure 5, the time dependend course of H_2 -enrichment is shown, presuming again homogeneity of the containment atmosphere. The calculations are done with the assumption of 100 % oxidation of the Zircaloy before RPV-failure, and by varying the degree of destorage of energy of core fragments due to contact with water (from sump-water and/or accumulators). Immediately after depressurization of the primary circuit, the flammability limit is exceeded in no case. A deflagration may eventually become possible during a later phase of the accident as a consequence of steam condensation, but only if the fraction of oxidized Zircaloy at the end of the in-vessel-melt phase is already near 100 %. A second condition, necessary for the possibility of a deflagration is that steam generation due to destorage of energy of core fragments will be low.

Within a certain time interval after failure of the RPV the assumption of an existing homogeneous atmosphere has to be expected inadequate. For that phase of the accident, the course of the concentration of the H_2 -steam-air mixture for a containment divided into 22 subcompartments, has been calculated by the DDIFF-code. Figure 6 shows the course of concentration in three subcompartments (reactor cavity, lower steam generator compartment, containment dome). In the reactor cavity the H_2 -enrichment becomes high. Still the flammability limit is not reached, due to the fact that air is driven out and steam comes additionally in. In compartments located far away from the RPV the amount of entering H_2 decreases rapidly, and hence the flammability limit is not exceeded again.

6. Conclusion

Calculations for a large dry containment of a PWR performed so far indicate, that in meltdown accidents with low as well as high primary circuit pressure during the in-vessel-melt phase, only H_2 -deflagration may become possible but no detonation. No violent H_2 -burning is even expected in the situation of a failure of the RPV at full system pressure, when a large amount of H_2 may be released from the primary circuit into the reactor cavity. In general the possibility for occuring a deflagration with respect to sufficient H_2 -enrichment seems to be more restricted in high pressure accident szenario than in a szenario with low system pressure. The pressure increase due to a deflagration will not reach the failure pressure of the containment in a low pressure case, if the combustion takes place when the flammability limit will be exceeded.

Results obtained so far have to be confirmed and supplemented, before final conclusions concerning occurence and consequences of violent H_2-burning for the containment integrity can be drawn. Additional analyses are necessary especially with regard to the questions of local H_2-enrichment in the containment and the local pressure history inside subcompartments during H_2-burning.

References

/1/ The Federal Minister of Research and Technology: "The German Risk Study". A Study of the Gesellschaft für Reaktorsicherheit (GRS), Cologne, 1979

/2/ H. Reineke et. al.: "Numerical Investigation of the Stratification in the Containment during a Core Melt Accident". Final Report BMFT 150 - 383, IVA, Seelze, 1981

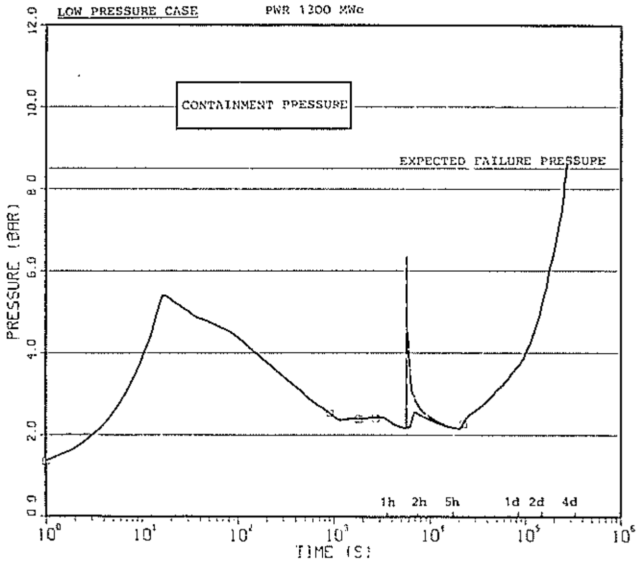

Fig. 1: Pressure-Time History without and with (--) Deflagration at Flammability Limit (Low Pressure Case)

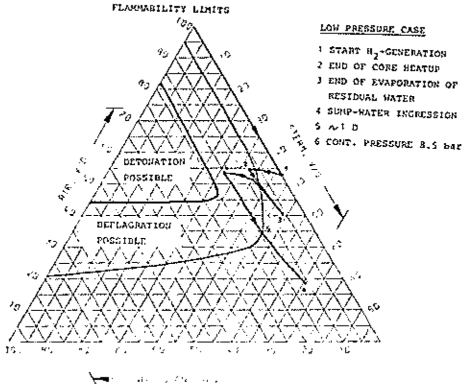

Fig. 2: H_2 - Enrichment within the Containment Atmosphere

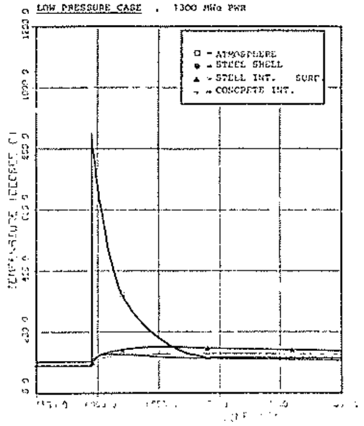

Fig. 3: Temperature-Time History; Deflagration at Flammability Limit

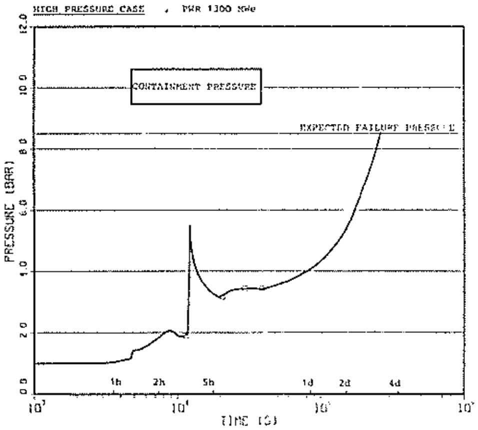

Fig. 4: Pressure Time History (High Pressure Case)

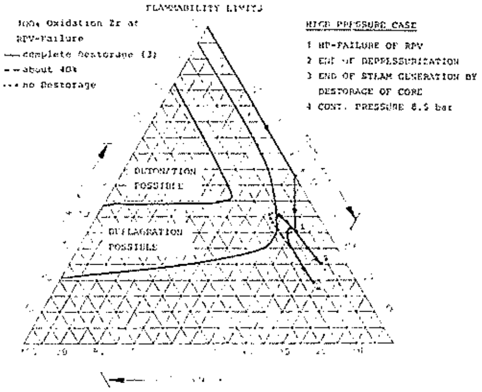

Fig. 5: H_2 - Enrichment within the Containment Atmosphere; Effect of Energy Destorage of Core Fragments

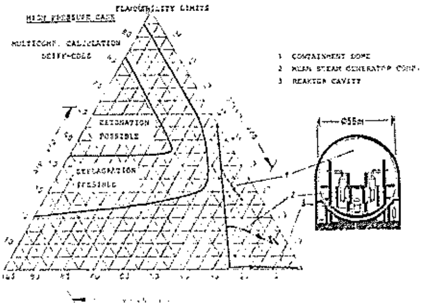

Fig. 6: H_2 - Enrichment within different Subcompartments