1.6 MELCOR 1.8.3 APPLICATION TO NUPEC M-7-1 TEST (ISP-35) AND TWO HYDROGEN SEVERE ACCIDENT SCENARIOS IN A TYPICAL PWR PLANT[1]

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1.- INTRODUCTION.

Combustion of the hydrogen released to the containment during a severe accident is one of the issues to establish the real threats to the third barrier integrity in nuclear power facilities. Computational efforts on management procedures, such as the containment spray operation, are being addressed at the CTN-UPM to cope with the problem. On top of this, studies about in-containment hydrogen distribution and combustion are currently carried out with the codes MELCOR 1.8.3 and ESTER 1.0 - RALOC 2.2.

In this study, MELCOR 1.8.3 has been validated against the NUPEC M-7-1 Test (ISP-35), which already showed in 1993 that a good agreement was reached out when the previous MELCOR 1.8.2 calculations were performed regarding to the He distribution throughout the facility. Nevertheless, some discrepancies were detected when analysing wall and atmosphere temperatures. Generally, well-mixed atmosphere scenarios, in which the role played by the containment water spraying is of the major importance, appear when such a mechanism promotes the onset of convection-driven flow patterns that rapidly homogenize the gas properties. The purpose of the new MELCOR 1.8.3 assessment is to take advantage of the newest implemented models to obtain a more realistic thermalhydraulics simulation (in particular the water film-tracking model in the HS Package). A variation case was also performed to highlight the influence of water spray operation.

In a second part of the study, insights coming from the previous work were used to apply MELCOR 1.8.3 models to a SBO severe accident scenario management in a commercial 2700 MWt 3-loop W-PWR containment. A pseudo 3-D nodalisation is used to obtain a more realistic gas flow pattern simulation. Furthermore, critical parameters such as containment spray starting time in the sequence, effects of geometry and gas burn MELCOR 1.8.3 model user input parameters were studied to illustrate their crucial importance, since they strongly influence the way the combustible gas is released, distributed or burnt in every region of the containment.

Establishment of the kind of accident sequences that can be well simulated (and, on the other hand, those for which MELCOR 1.8.3 results are not reliable at all) by lumped-parameter codes is the background of this work, as is the chance of their improvement to make them able to simulate a wider set of situations, even involving

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large-scale gas unhomogeneities or thermal stratification. Identifying and solving these code shortcomings are the main concern for lumped-parameter code users.

2.- MELCOR 1.8.3 APPLICATION TO ISP-35 NUPEC M-7-1 TEST

A MELCOR nodalisation scheme of the NUPEC facility has been developed for gas distribution and mixing. This facility is a linear ¼ scale model of a typical 4-loop PWR containment, with a total inner volume of 1300 m^3. During the M-7-1 test a steam-He mixture was injected inside the previously steam-preheated containment (He in an amount equivalent to the corresponding H_2 released through the 100% oxidation of the in-core fuel Zry) during a 30 minutes time interval; at the same time the containment sprays were functioning.

This nodalisation consists of 33 control volumes (CVs), 77 flow paths (FLs) and 124 heat structures (HSs) (Fig 1). Containment spray nozzles have been introduced through the SPR package making use of 8 water sources and 20 atmosphere spray junctions. In the HS package it has been taken advantage from the water film-tracking model (one of the novelties of the MELCOR 1.8.3 version), to accurately simulate the heat transfer between the walls and the containment atmosphere through the water film.

Inclusion of the film-tracking model calculations has the aim of simulating the effect that the sprayed water impingement on the containment walls has on the heat transfer. By means of geometrical considerations it was established that an 8.5% of the supplied water was directly sprinkled on the containment walls whilst a 1.6% falled on the inner compartment walls. This made the actual mass flow rate supplied to the containment atmosphere to be decreased in an 8.5%.

Within the framework depicted above the following sequences were calculated:

- The steam preheatup phase.
- The M-7-1 distribution and mixing test (main MELCOR assessment).
- Variation of the M-7-1 test inhibiting the water spraying (computational experiment).

2.1 Main Results

A good agreement was widely found between the experiment data and the numerical results for the M-7-1 test. The main conclusions are the following:

- Atmosphere temperature and pressure falls were slightly overpredicted because of the steam condensation and cooling enhancement made by the code treatment. MELCOR assumes that the water is supposed as being homogeneously distributed in the nozzle vicinity, which is clearly appart from the actual pseudo-conical shape of the spraying pattern that also prevents the inner water drops to strongly interact with the surrounding atmosphere. Relative errors layed about the 3% in both parameters. (Figs 2 and 3).

- The He concentration predictions showed to be well adapted to the experimental measurements (the maximum relative error did not raise above the 11%). In the He-steam injection steam generator compartment, in which the highest released gas concentrations are found, calculations only diverged from the experiment in a 6% (relative error), which means about a 1% in absolute volume concentration (Fig 4). In the containment dome, which represents the 70% of the total free volume of the facility, the differences hardly reach the value of 4% of relative error in the most diverging case.

- Wall temperature predictions were highly accurated, showing the improvement of the wall water film-tracking calculations. Deviations from the experimental (EXPER) data were below the 1.5% and close to 0% in most of the cases, as shown on the FILM-T curve on Fig. 5. In the preceding figure is also reperesented the results obtained without the film-tracking calculations (No.F-T curve) for comparison.

- Calculations of the preheatup phase of the facility (210 minutes previous to the test) were also executed. Although experimental data were not available it could be deduced from the ISP-35 Final Report [1] that relative errors in the pressure peak estimation layed below 16% and those of the temperatures inside the 4%, margin values always overpredicted by the code. This study was focused on the establishment of the facility conditions previous to the test and to assess the code ability to simulate such a situation.

In the latest part of this work the same M-7-1 calculation was repeated, although without the water spraying. This computational test allowed to get some insight on the fact that water spraying promotes an important mechanism to cool and depressurize the containment atmosphere, but with the cost of rising the He volume concentration. Main results from this part were the following:

- The calculated values for pressure were up to a 27% higher than in the M-7-1 test, as shown on Fig 2 (MELCOR 1.8.3 set of curves for the M-7-1 test, No-SPR for the variation case). Furthermore, the containment atmosphere temperature at the end of the gas supply was about 7% above the M-7-1 values. Fig 3 reflects gas temperatures in the most critical control volume.

- He concentrations showed a meaningful increase when spraying, leading to differences of 30% for the maximum concentration values between both cases (Fig 4). In any case, the last calculation performed is affected by the lumped parameter code restrictions to simulate gas atmosphere conditions in which the absence of strong mixing and homogenizing mechanisms is their main feature.

- The steam mass present in containment is a 238% larger than that in the M-7-1 test, which means the efectiveness of water spraying for steam condensing. It is important to keep in mind the fact that the spraying flow rate of the M-7-1 test was overdimensioned in a factor of 4 respect to that of a typical 4-loop plant (water spraying flow rate was scaled by means of area, rather than by volume). Finally, the maximum oxygen concentration did not raise above the 16% in mole fraction, which is a value an 11% lower than in the M-7-1 test.

2.2 Conclusions

MELCOR 1.8.3 calculations performed for the NUPEC M-7-1 experiment have confirmed the code ability to make quite a good simulation of this test. Moreover, inclusion of the film-tracking model leads to a significant improvement of the results, demonstrating the more accurate solution of the heat transfer to the walls when water impinges on them.

As an outcome of this study, the MELCOR 1.8.3 seems to give some confidence when applied to the study of hydrogen behaviour and distribution under severe accident conditions with the water sprays active. Due to the lumped parameter feature of the code, those situations in which enhanced gas mixing mechanisms are expected will be predicted with fairly good degree of accuracy by MELCOR. Such mechanisms have been present during the M-7-1 test and include not only the intense water spray functioning, but also the location of the hot gas injection point in the lowest part of the facility and the gas flow freedom promoted by the open geometry. However applications to those accidental sequences too far away from the M-7-1 test conditions need some caution, as they could lead to poorly reliable solutions.

In the scope on a further and wider assessment of the MELCOR code within the gas mixing and distribution in containment, it would be relevant as a first step the code validation against other experiments similar to the NUPEC M-7-1, in particular those in which containment sprays were inhibited, shorter amounts of hydrogen (He) were released (about 30% of Zry oxidation) or with higher points of gas release. These factors would not enhance the atmosphere mixing and then would lead to large-scale unhomogeneous conditions or stratification inside the containment. In such situations, it would be useful to test the influence of a fine-node highly-detailed nodalisation scheme (mainly in the largest regions of the facility) and the need to the introduction of new models.

3.- MELCOR 1.8.3 APPLICATION TO TWO SEVERE ACCIDENT SEQUENCES WITHIN A TYPICAL W-PWR PLANT

The second part of the works at the CTN-UPM consists of the application of the gained MELCOR 1.8.3 experiences to a real plant in-containment scenario. The nuclear power facility selected is a typical 2700 MWt 3-loop W-PWR Spanish plant. First, a detailed 3-D nodalisation scheme was designed, in particular for those parts in which higher hydrogen buildups are expected. This nodalisation includes 46 CVs, 86 FLs and 137 HSs (Fig 6). Containment spray system has been collapsed to 6 spray sources. Furthermore, making use of the film-tracking model features, they have also been added as a water source those structures in the dome ceiling which condensate the steam and make it drop down as liquid water, as was taken into account the amount of water that was directly sprayed on the containment walls by geometrical considerations.

The hydrogen producing accidental scenario chosen is that of a station blackout (SBO) coincident with the seal failure of the three primary system coolant pumps (RCPSF). The source term released to the containment has been obtained by a previous MELCOR calculation at the CTN-UPM [2]. Main results of the study gave out a total amount of 270 kg of H_2 to be released through the SB-LOCA from t=6600 s to t=8700 s in the sequence due to Zry-steam reaction in the core vessel. This yielded to a 36% of the initial in-fuel Zry inventory oxidation.

Within this initial conditions, several calculations have been carried out at the CTN-UPM. Special effort has been put on the establishment of the influence of several factors on hydrogen distribution and combustion:

- The instant at which the water spray system starts to operate during the sequence as an accident mitigation strategy.
- Effects of geometry to help gas mixing and spreading.
- The MELCOR burn model parameters to establish gas burn speed (depending on the geometry and kind of burn propagation) and propagation conditions to the other regions. This was made with the help of previous experience gained with the ESTER 1.0 - RALOC 2.2 code available at the CTN-UPM and additional bibliography. Used flame speed values were 30 m/s for lower containment and code default values for the open upper free volumes.

The preliminar "in-vessel" phase calculation of the SBO-RCPSF sequence started with the containment atmosphere under steam saturated conditions fixed by the maximum pressure (0.128 MPa) and minimum temperature (25 ^{0}C) given by the Technical Specifications. Furthermore, the above calculations led to the prediction of the vessel failure at t=10000s (being t=0 the beginning of calculation and t=500 s the initial event). Two variation cases were then performed after this previous phase:

- ■ In the first of them, degradation of the core progresses to vessel failure and cavity ablation by the debris, producing an additional amount of combustible gases (H_2 and CO) that is released to the containment up to complete (100%) oxidation of the initially existing Zry. Now it is when the external AC power supply is assumed to be recovered, and water sprays could be available to condensate steam and depressurize the atmosphere. This will be referred as SBO-RCPSF-MCCI sequence in the following.

- ■ In the second one, the external AC power is recovered, which allows the plant operator to reflood with water the vessel just before its failure. Depending on the degradation status of the core, the remaining metallic Zry oxidation will be enhanced, producing additional H_2 amounts in-vessel (nevertheless, oxidation of more than 75% of the initial Zry looks quite unreliable under such scenario). At the same time, containment sprays will also be available. Information coming from previous studies at the INEL (USA) made with SCDAP/RELAP/MOD3 [3] has been used to make an estimation of the additional H_2 and steam sources from the primary circuit during the reflood phase. This will be named as a SBO-RCPSF-Reflood sequence.

3.1 SBO-RCPSF-MCCI Sequence. Main Results

3.1.1 Base Case. Case 1a

This scenario consists of the accident progression beyond the reactor vessel failure due to the unrecoverability of the lost inventory in the primary circuit by any coolant injection system. The containment spray system is also unavailable under SBO conditions. Once the vessel failed, the external AC power is supposed to be recovered and the sprays may be on. The instant in which the water spraying is started is highly important for the released gas distribution and the likelihood of burns within the containment.

A first calculation was performed assuming the sprays inhibited during the whole hydrogen release (which takes place until the metallic phase layer in the cavity is extinguished. This occurs at t=16800 s in the calculation, but it is not important later than t=15000 s). When the MCCI phase of the sequence starts (t=10000 s) hydrogen and steam are released to the cavity, and the initially sealed connection to the lower containment is assumed to be opened. Local minor burns appear in the cavity, pushing the very hot gases away until the cavity atmosphere is oxygen-starved.

Gas is distributed to the regions above until a new burn starts at 14280 s in the lowest containment (CV-73. Fig 7 shows the H_2 fraction in the volume) which propagates to the whole building, producing a pressure peak of 0.55 MPa (Fig 9). About 450 kg of the released H_2 and 350 kg of CO burn in this sudden burst. No detonation model is available for the MELCOR BUR package, but the burn could be so violent to produce a higher pressure increase. Atmosphere gas temperature rises up to 1100 K (Fig 8). Gas cools slowly through the containment walls until water spraying starts at t=22700 s by user's choice. The cooling and depressurizing effect is clearly shown on the previous figures, but not too much in the lowest containment (CV-73) since very hot gas (mainly steam) is still coming from the cavity and is a bad vented region. One more issue is the fact that water spraying promotes gas mixing by introducing a larger heat sump at the top of the dome, trying to set a stable gas flow pattern with characteristic gas speeds about 0.5-0.8 m/s. No gas drawing or induced turbulences effects are simulated with MELCOR. No more important events take place regarding to hydrogen in the containment.

3.1.2 Effects of MELCOR BUR Package Parameters. Effects of the Computational Hardware. Cases 1b

Results presented above show to be highly sensitive to the user input in the MELCOR 1.8.3 BUR Package [4], in particular regarding to the TFRAC parameter (which accounts for how long must a burn progress in a region to be propagated to the next one) which ranges from 0.0 (immediate propagation) to 1.0 (propagation after burn is complete). Preceding results were obtained with TFRAC=0.7 for the lowest containment and propagation to the regions above, and fixed to TFRAC=0.3 for the free region. Larger values of TFRAC (0.75 or higher) inhibited the burn propagation to the higher regions, and lower values allowed faster propagations which yielded to gradual gas burns as it is released. In both of the cases, lower values of the pressure peak were observed (around 0.2-0.3 MPa).

So sensitive may be the code to this parameter that making calculations with the same user input on different machines may lead to different results. The base case was run on a DEC-Alpha 2000 OSF machine. But when done on a DEC-Alpha 2000 Open VMS version, a previous burn propagation pattern was restricted to the lower part of the containment (t=13100 s) and later on a second one affected to the whole facility (t=14720 s). The pressure peak value was, however, of 0.52 MPa in this case (similar to the one explained).

3.1.3 Effects of Water Spray Starting Time. Case 1c

As deduced from the sequence description, in the base case the water spraying does not influence (for hydrogen mitigation issues) once such a great burn has taken place. That is why an alternative calculation was done introducing the water sprays at t=13000 s, before the great burn is to be expected. It showed also irrelevant to perform the calculation for times longer than 30000 s, since no important events are expected anymore.

A new alternative case was then run in such conditions on a DEC-Alpha Open VMS version machine. The results are quite different to the base case. A series of local burns takes place in the lower containment from t=13020s to t=16890 s. The pressure increase is shown on Fig 9 case 1c. When water sprays are on, two effects take place at the same time: gas mixing promotion and steam condensing. This makes pressure to decrease instantaneously, but also hydrogen concentration raises up to the burn limits (Fig 7), producing the onset of succesive local burns that now extend to the lower containment. In this case the pressure only reaches a moderated value of hardly 0.24 Mpa (Fig 9), since combustible gas is gradually elliminated by flashing burns at the bottom and gas heat is rapidly removed by the sprayed water. About 390 kg of H_2 (410 of CO) disappear by burning. Fig 8 shows the gas temperature evolution in the lower region.

3.1.4 Effects of the Containment Geometry. Cases 1d

It has been arisen essential for the results above the fact that the combustible gas may reach the highest regions of the containment to allow the burns to be propagated to the whole containment, since they always started in the lowest part. So it makes neccesary for the gas to find a way to spread through the uppermost containment. Variations in the flow area from the lowermost to the immediately above region (CVs 73 to 63), may also restrict the burn propagation patterns to the lower containment if this flow area is small (about $90m^2$ for each one of the three sectors the containment is divided into) or allow the propagation to other regions if large (150 m^2). Both cases led to low pressure peaks predictions (0.2 - 0.3 MPa). It is remarkable that the as-built area is 120 m^2 originated 0.55 MPa, as already explained in case 1a.

3.1.5 Conclusions

After external AC power recovery, it has been studied the effect of water spraying beyond reactor vessel failure and combustible gas production by concrete attack. Gas mixing promotion effects have been addressed, though they are not predicted very effective in the lower containment. If local combustible gas buildups appear in such regions, it seems preferrable starting water spraying as soon as possible. When concrete ablation has progressed far enough, gas explosions may be expected in any case. That is when local burns may be convenient to elliminate gradually the threat of a global explosion in the low bad-vented regions. Furthermore, water sprayed in the atmosphere helps to gas cooling under such a burn as an additional energy sink.

Another features of code and plant modelling have also been highlighted. In particular, the need of burn model improvement in the case of MELCOR would be desirable to more detailed analysis of gas combustion phenomena in severe accidents. Experimental tasks may be helpful in the establishment of improved correlations for burn under different propagation regimes.

Influence of scaling and geometry in nuclear plant containments may be other of the issues to be in mind for future designs or improvements of the existing. Anyway, keeping apart detonation risk and some code limitations in H_2 distribution and combustion the large-dry concept of the most PWR containments show their ability as partial passive mitigation for hydrogen threats; combustible gas concentrations hardly reach values above 10%-12% in volume. This is close to the lower limits for spontaneous ignition, as generally assummed.

Table 1 shows a summary of the preceding main results.

3.2 The SBO-RCPSF-Reflooding Sequence

From the initial primary phase of the SBO-RCPSF accident, in this case it is assumed that external AC power to the plant is recovered before the core degradation may progress up to vessel failure. The plant operator may then try to recover the loss of primary circuit water by starting the HPCI system to the reactor vessel, simultaneously to the water spraying within the containment.

As published in a previous NUREG [3] documentation, reflooding of a partially degraded core implies an additional hydrogen generation in-vessel. The most unfavourable conditions arise when water addition is done to a very high temperature, in the time previous to its final collapse. Such a core may be subjected to temperatures about 1800 K. This is the core status that will be assumed in the present section at t=9000 s (some 17 minutes before the predicted vessel failure) when reflooding is initiated by the operator as well as the containment spray system.

From the same study it is derived that core reflooding must be made at a too strong injection rate for the HPCI system to remove the heat stored in the fuel and structures. This fact will produce intense Zry oxidation reactions in the presence of large amounts of steam. That is why the primary system is supposed to be depressurized to allow the accumulators to discharge cold borated water into the reactor core. This will produce the immediate evaporation of most of the water which will enhance the Zry oxidation. The power released by oxidation may be higher than that coming from decay heat in the fuel.

Based on the previous and other studies, it may be estimated that the initial phase of such a heated reactor core reflooding would enhance the remaining Zry oxidation in a lapse of time of a few minutes. Assumption of oxidation increase up to 70% in about 15 minutes seems quite reasonable. From this moment on, oxidation reactions are extinguished and the reactor cools down slowly by water boiling and steam release to the containment.

Under conditions exposed above, previous calculations were carried out at CTN-UPM to evaluate the threats to the containment. Sharp hydrogen concentration buildups were addressed in the whole atmosphere by establishment of stable circulation loops in the open free region, but not beyond the ignition limits. This is helped by water condensing and gas cooling provided by water spraying.

That was why a new calculation was performed under the new hypothesis of oxidation increase up to 85%, with the same assumed limits for hydrogen ignition. This value of oxidation seemed to be the lower limit in the plant to produce severe hydrogen burn scenarios within the containment. This will be named the base case for the SBO-RCPSF-Reflooding sequence.

3.2.1 Base Case. Case 2a

As said previously, several minutes before the vessel failure the operator is able to depressurize the system to allow the core reflood and to start the containment sprays. Additional hydrogen (340 kg) and steam are released to the containment in the following 900 s through the three main coolant pump seals. Water spraying helps and promotes gas mixing that set homogeneous conditions in the containment, except for the lowest part, lying out of the reach of the gas recirculation loops.

On the other hand, sprinkled water condensates the steam present, increasing the volume fraction of hydrogen and the other no condensible gases (Fig 10). This is done through the whole containment almost simultaneously, thus ignition limits may be reached out and burns start near any of the release locations. This occurs inside the pressurizer chamber just when hydrogen release is ending (t=9900 s). Moreover, as hydrogen composition in the containment is also close to the limits (above 7.5% in any case), flame is propagated through all directions (upwards from the bottom), with a total consumption of 535 kg of H_2 in 18 s. Gas temperature and pressure increase, reaching values of above 900 K and 0.56 MPa, respectively, shown on Figs 11 and 12.

Later on, the gas cools down helped by the sprays during their injection mode, and finally through the containment walls. No more remarkable events are predicted.

3.2.2 Effects of Spray Starting Time. Case 2b

This calculation tries to show the influence of the spray system initiation delay, making it to start 1000 s later than the AC recovery (t=10000 s). Hydrogen release coming from the reinitiated Zry oxidation by the fast core reflooding has just ended, and only steam is supplied out in the lowest containment. Hydrogen is pushed to the upper regions, and homogenization is achieved about 7.5% when containment sprays are on. Strong steam condensation in the uppermost regions and in the open free containment is arisen, while the lowest remains poorly influenced by the mixing circulation loop phenomena occurring above. This makes hydrogen presence in the atmosphere to be increased on and on (Fig 10), until ignition limits (10%) are reached out and burn is initiated at t=15940 s in the uppermost dome. Flame is then propagated downwards to the whole containment, since hydrogen composition is above the downward propagation limit (>9%) by means of the previous homogenizing mechanisms. Now gas temperature arises up to 1200 K (Fig 11), probably because of the more rapid hydrogen consumption when flame is originated in the upper free region. Such a deflagration stands for 2-3 s, and elliminates 558 kg of H_2, and seems to be more violent than that of the base case. However, the pressure peak in this case shows the same value (0.56 MPa), since it departs from a lower value of pressure (0.15 MPa) against the base case (0.23 MPa) as water sprays have been able to condensate steam during a longer time interval (about 6000 s). See Fig 12.

3.2.3 Effects of Spraying Without Combustion. Range of Uncertainties. Case 2c

In this variation case, it is supposed core reflooding but in-vessel Zry oxidation does no progress further than 70% . On top of that, lower limit for hydrogen ignition is decreased to 9% since a shorter additonal release of this gas (260 kg) is expected. Containment sprays are started at t=13000 s in the sequence to establish the concentration increase by steam condensation.

The only remarkable feature is that pressure rise reaches 0.3 MPa (Fig 12) during the 900 s of the non condensible release and then descends as the still released steam is condensed on the containment structures, mainly in the upper dome. Falling droplets may help to further steam condensation as an additional spray source able to relax pressure down to 0.26 MPa in the time the containment sprays are activated. A sharper steam removal is addressed. This makes hydrogen composition (steady around the value 5.7%) to arise to 8.4% in the upper region, still below the lowered ignition limit (Fig 10). As gas mixing forces stand, the containment atmosphere homogenizes slowly in its lower parts. Temperature is shown on Fig 11.

3.2.4 Effects of Flame Speed Parameters. Case 2d

This execution corresponds to that of the base case, but with water spraying initiated at t=14000 s and MELCOR BUR Package flame speed parameters set to default values via code correlations. It must be underlined that previous cases used fixed user choice values (user experience). This case is thus similar to 2a (large hydrogen release) and 2b (delayed spray start, but even later). The aim was to address the influence of burn progression in the volumes in the flame propagation and maximum gas pressure and temperature (similar to case 2b). No meaningful additional results were given by this calculation, however. See Figs 10, 11 and 12.

3.2.5 Effects of Combustion at Low Concentrations. Case 2e

The last example corresponds to case 2c (70% Zr oxidation) modified to allow hydrogen burns at more lowered limits for ingnition (now set to the maximum concentration predicted, 8.4%). Sprays are started at t=9000 s as in the base case. That is why hybrid results between cases 2a and 2c would be expected. In particular, burn limit is set to a critical value, so that burns will be only allowed when a significant amout of steam has been condensed (to say, later than a good degree of homogenization has been achieved). Hydrogen combustion starts then at t=15400 s in the uppermost regions. This is a delayed in time burn similar to that of case 2b (although spray action is quite early). The reason is that local hydrogen buildups that originated burns in the lowest containment in the case 2a now are not present. However, since now the mixture is poorer in combustible gas, atmosphere temperature and pressure reach 1100 K and 0.5 MPa. Burn is also quite fast (it lasts for 3 s) although now 460 kg of hydrogen are burnt. Figs 10, 11 and 12 show the main parameter evolutions.

3.2.6 Conclusions

Containment atmosphere behaviour under reflooding scenarios may be observed from a different point of view as additional hydrogen release may be limited under the maximum degree of in-vessel Zry oxidation expected. In particular, MELCOR does not predicts harmful effects if oxidation does not exceed 70% and homogenization is enhanced by mixing mechanisms. However, it has been proven that spray operation may have the effect of modifying non-combustible mixtures to combustible ones.

Good venting of the gas released in local rooms to the open containment is desirable and may be helped by water spraying. Nevertheless, if such homogenization is obtained and gas burns become a real threat in any place, the high mass of gas released would promote a global deflagration. Containment sprays seem to be able to make a good mixing in about 1000 s or less. Steam condensing by water spraying is expected to increase hydrogen concentrations in an additional 3%. One more time, design of large free volumes for PWR containment behaves as a passive mitigation countermeasure for hydrogen buildups when local accumulations are avoided. More effective venting of lowest compartments should be desirable to elliminate their effect as burn initiators when expected.

Again, Table 1 summarizes the main results for the calculations done.

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5.- REFERENCES

[1] H.Tezuka, T.Hirose, **Final Comparison Report on ISP-35: NUPEC Hydrogen Mixing and Distribution Test M-7-1**. OECD Report OECD/GD (95) 29, NEA/CSNI/R (94) 29, Paris, France, December 1994

[2] F. Martín-Fuertes, J.A. Fernández, E. Meléndez, **MELCOR 1.8.2 Calculations of Two Blackout-Type Accidents (TMLB' and S3TB'). A Partial Comparison with SCDAP/RELAP5** , Cátedra de Tecnología Nuclear, ETSII, UPM, CTN-06/95, July 1995

[3] P.Kuan, L.J.Hanson, D.J.Pafford, K.S.Quick, R.J.Witt, **Implications for Accident Management of Adding Water to a Degrading Reactor Core**, NUREG/CR-6158, EGG-2644, February 1994

[4] Sandia National Laboratories, **MELCOR 1.8.3 Computer Code Manuals**, NUREG/CR-6119, SAND93-2185, Vols. 1 and 2, March 1995

Case	Main Features	P_{max} MPa	T_{max} (local) K	Burn Start Time (local) s	Burn Duration s	H_2 (CO) Burnt kg	Spray Effects
SBO - RCPSF - MCCI Sequence Vessel Failure t=10000 s Concrete Ablation: H_2 (CO) mass: 740 (>450) kg							
1a	t_{spr} = 22700 s	0.55	1100	14284	9	450 (350)	Gas Cooling and Depressurization
1b	t_{spr} = 22700 s (OpenVMS) - - -	0.52 ---	1000	(13057) 14724	(1) 13		Similar to case 1a
1b'	TFRAC=0.6/0.75	0.2-0.3					
1c	t_{spr} = 13000 s	0.24	380 (1300)	(13022-16890)	(1-2)	390 (410)	Local Burn Promotion: Global Burn Avoiding
1d	t_{spr} = 22700 s (Sensitivity to flow areas)	0.2-0.3					
SBO - RCPSF - Reflooding Sequence t=9000 s : Core reflooding & Water spraying In-vessel Zry oxid = 85% (610 kg of H_2, No CO)							
2a	As explained	0.56	920	9898	18	535	Cooling. Burn start in the bottom
2b .	t_{spr} = 10000 s	0.56	1200	15940	2-3	558	Violent burn by homogenisation
2c	70% oxid, 9% lim, t_{spr}= 13000 s	0.3	420	No burns	None	None	Cooling, Depressurizing, Mixing
2d	Flm speed (def), t_{spr} = 14000 s	0.56	>1200	18608	4	566	Similar to case 2b
2e	70% oxidation, 8.4% lim, t_{spr}= 9000 s	0.5	1100	15401	3	460	Similar to case 2b

Table 1. Main Results for SBO - RCPSF Sequences

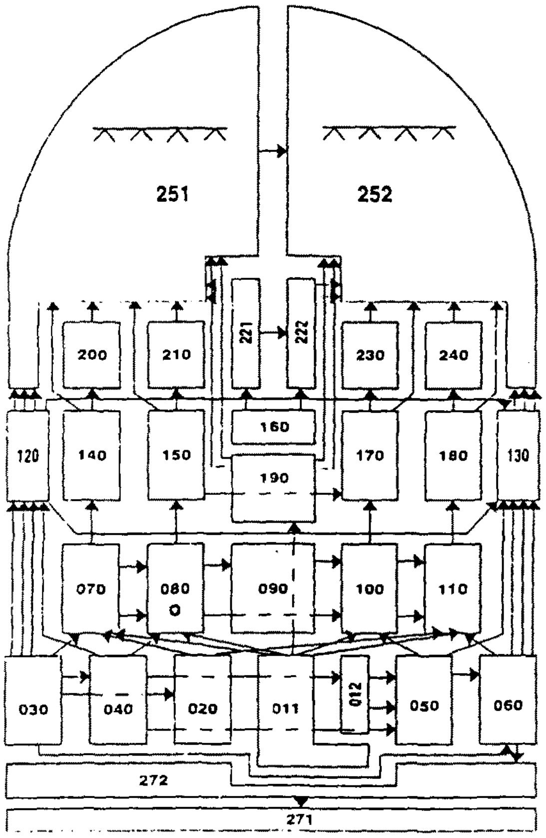


Fig. 1. NUPEC nodalization.

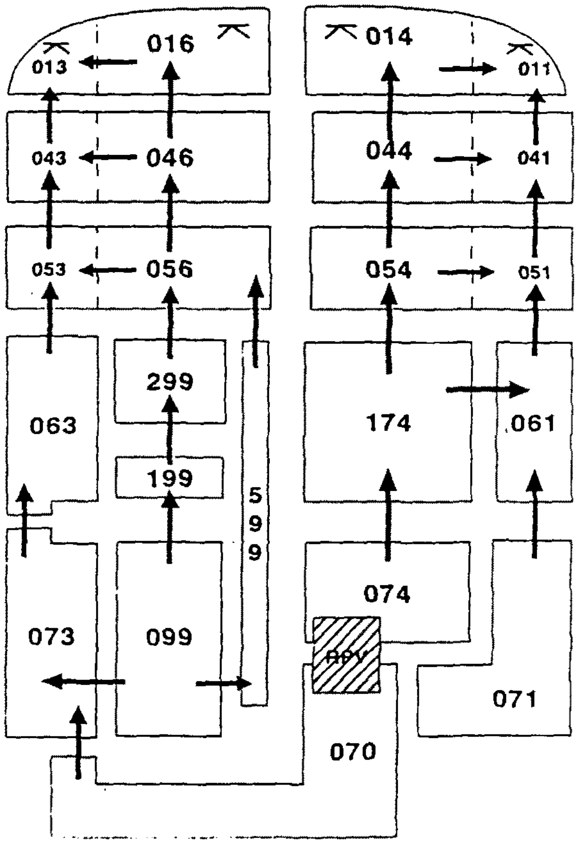


Fig. 6. W-PWR containment

Fig.2 ISP35: CONTAINMENT PRESSURE

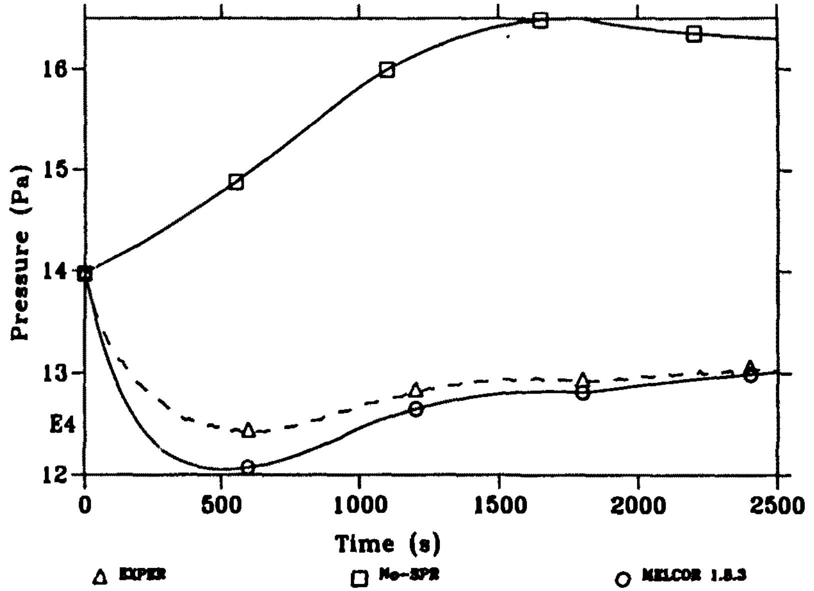


Fig.3 ISP35: GAS TEMPERATURE IN INJECTION SG

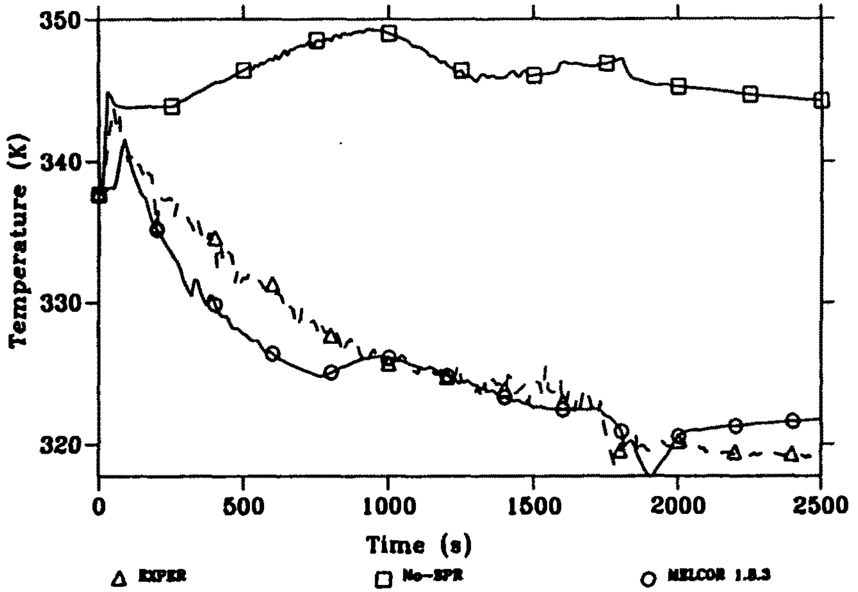


Fig.4 ISP35: He CONCENTRATION IN INJECTION SG

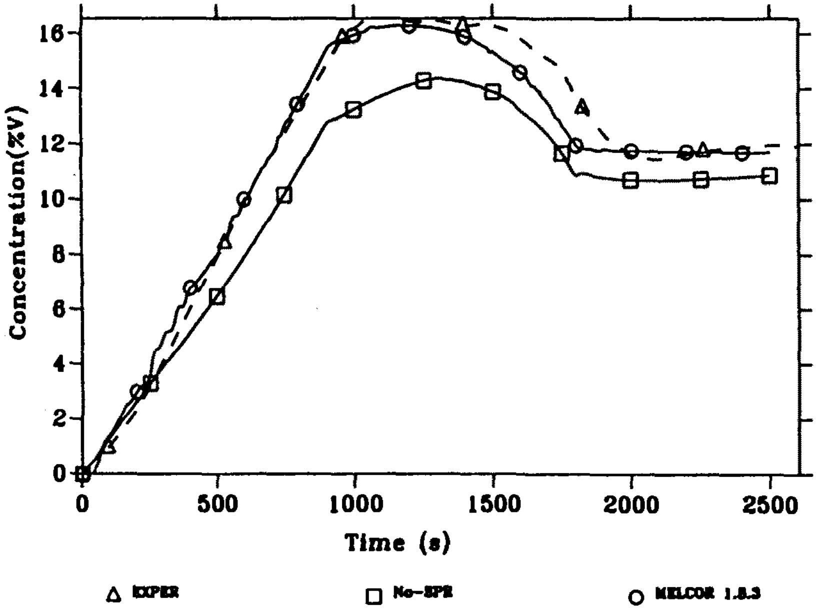
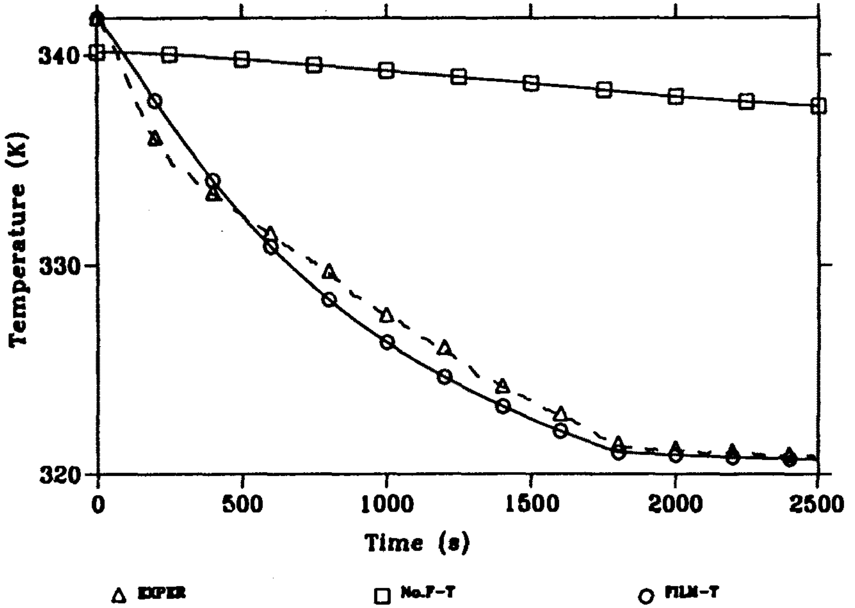


Fig.5 ISP35: WALL TEMPERATURE IN 251-CYLINDER



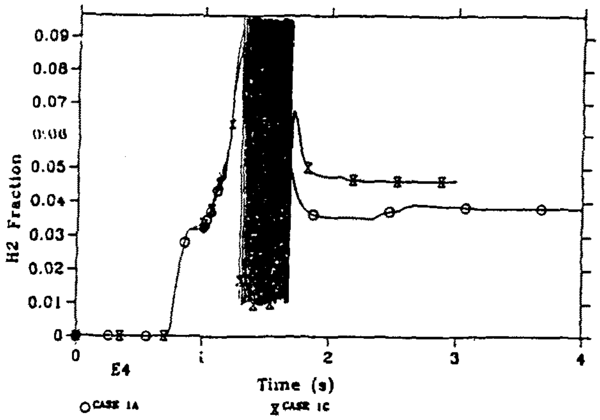


Fig.7 SBO-RCPSF-MCCI HYDROGEN MOLE FRACTION

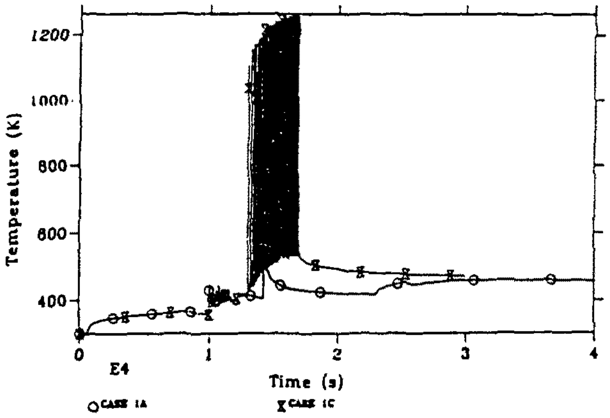


Fig.8 SBO-RCPSF-MCCI GAS TEMPERATURE

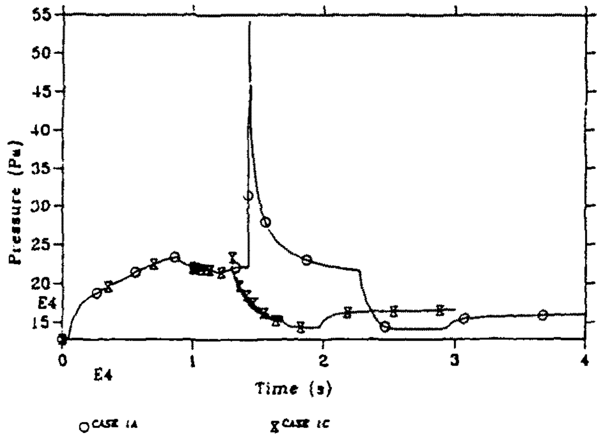


Fig.9 SBO-RCPSF-MCCI CONTAINMENT PRESSURE

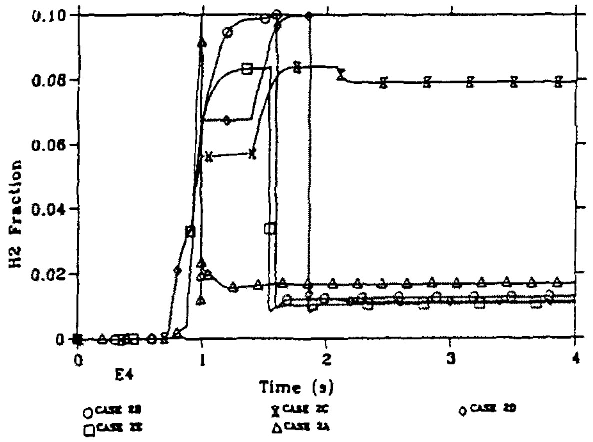


Fig.10 SBO-RCPSF-Reflood HYDROGEN MOLE FRACTI

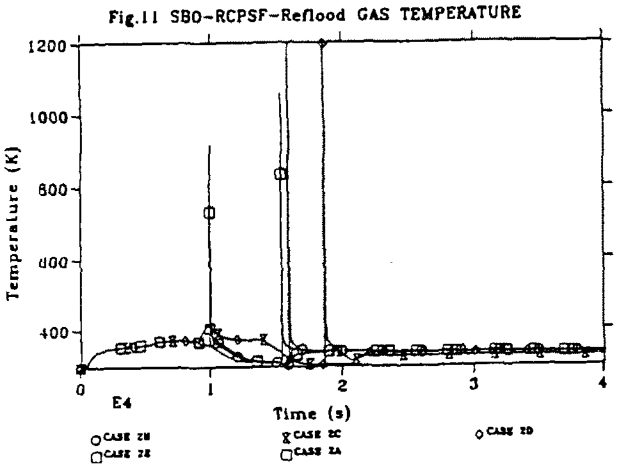


Fig.11 SBO-RCPSF-Reflood GAS TEMPERATURE

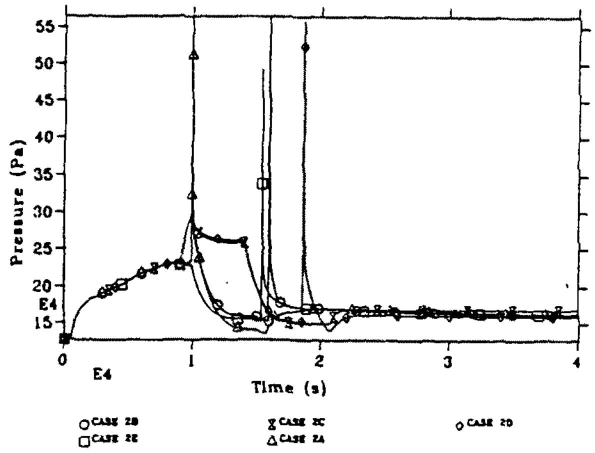


Fig.12 SBO-RCPSF-Reflood CONTAINMENT PRESSURE