12.3 Hydrogen Risk Reduction in Nuclear Power Plant

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Abstract

In case of a severe accident in a nuclear power plant with core melt and hydrogen production, the hydrogen risk is one of the main concerns. It may jeopardize the containment integrity due to violent deflagration that can lead to DDT (**D**eflagration **D**etonation **T**ransient) or even detonation if proper hydrogen mitigation means are not available. The design of the EPR (**E**uropean **P**ressurized water **R**eactor) Hydrogen mitigation and control system is based on the lumped parameter code WAVCO and the 3D code GASFLOW. The concept consists of recombiners and igniters to cope with all scenarios including those without steam. The system has been checked to avoid DDT by the 7λ criteria that's implemented in GASFLOW. Future analysis could deal with determining dynamic pressure loads, if appropriate, and some sensitivity studies to check the hydrogen control measures with respect to different source locations and mass flow rates. Also a conditional criterion for determining the likelihood of fast deflagration should be developed.
Keywords: EPR, hydrogen, severe accident, recombiner, igniter, detonation, transient

Introduction

Hydrogen risks in a nuclear power plant in case of severe accident with core melt is a main concern. It may jeopardize the containment integrity due to violent deflagration that can lead to DDT or even detonation if proper hydrogen mitigation means are not available.
Reliable design of an effective hydrogen mitigation concept requires:

1. Proper tools for the accurate determination of the gas composition in the containment atmosphere before and during hydrogen release for relevant scenarios,
2. Precise knowledge of all relevant accident scenarios which give the necessary information about hydrogen production:
    - Amount and rate as well as temperature of hydrogen and steam mass flow,
    - Hydrogen release time into the containment from start of accident progression,
    - Release condition (low or high release location, jet release), and
    - Direction of the release.
3. Means which can remove hydrogen safely, and
4. A criteria for prevention of DDT and fast deflagration.

This paper deals with the application of lumped parameter codes and 3D-codes and with their limitations.

EPR layout feature with respect to hydrogen mitigation

The design of the layout of the future advanced nuclear power plant EPR is imposed by the fulfillment of the containment integrity against severe accident risk. The main features of EPR in this respect are:

1. A special basement protection where core melt debris can spread on a dedicated large area of about 170 m^2 outside the reactor pit,
2. A large leaktight concrete containment designed for 6.5 bars,
3. A CHRS (containment heat removal system) using sprays with external recirculation,
4. A Hydrogen mitigation and control system, and
5. An in-containment refueling water storage tank, IRWST, which guarantees, with its large amount of water (about 1800 m^3), the cooling of the corium passively and ensures the basement protection as well as the condensation of the steam during initial depressurization of the reactor primary cooling circuit.

The IRWST is located between the reactor cavity and the missile protection cylinder in the lower part of the containment (Fig. 1) and has a four-connection path to the equipment rooms.
Beside the corium cooling, EPR has to cope with the hydrogen risk as a primary safety goal for keeping containment integrity against hydrogen static and dynamic combustion loads because ignition sources in the containment can not be precluded and accidental ignition can not be excluded.
Hydrogen mitigation concept consists of the following two mitigation means:
1. Passive autocatalytic recombiners (PARs), and
2. High frequency spark igniters.
The first component, PAR, has been installed already in several nuclear power plants and their efficiency and qualification has been demonstrated experimentally and numerically for severe accident conditions /1, 2/. Also for the EPR-project, the French and German safety advisory bodies GPR and RSK respectively, recommended the use of PARs.
The second component, high frequency spark igniters, has been developed and tested for commercial use at Siemens KWU. A qualification program has to be carried out for severe accident conditions which has at least to consist of resistance tests to thermal aging and radiation as well as functioning tests in combustible air/hydrogen/steam mixtures.

Basic Methodology

In order to cope with Hydrogen combustion loads, for the design of an appropriate hydrogen mitigation and control system, it is indispensable to have the right knowledge of the mechanisms for:

1. Hydrogen-production;
   - Relevant scenarios,
   - Release time into the containment from start of accident progression,
   - Release location,
   - Direction of the release, and
   - Amount and rate as well as temperature of hydrogen/steam mass flow.
2. Hydrogen-transport, mixing and distribution; and
   - Possible stratification and convection,
   - Hydrogen-concentration gradients between lower area and dome (positive or negative),
   - Local hydrogen enrichment,
   - Homogeneous atmosphere,
   - Local atmosphere inertization, and
   - Potential of the fast deflagration or DDT.
3. Hydrogen-removal.
   - Recombination process
     - * Minimal hydrogen-concentration for the on set of the recombiners,
     - * Minimal initial temperature for the on set of the recombiners,
     - * Hydrogen removal rate,
     - * Effect of pressure, and mixture quality on the hydrogen removal rate,
     - * Efficiency of the recombiners,
     - * Temperature load at the exit, and
     - * Effect on convection.
   - Ignition process
     - * First ignition and continuous ignition,
     - * Condition of the combustion close to and far from the source,
     - * Standing flame condition,
     - * Effect of oxygen dilution,

* Pressure and temperature loads,
* Effect on convection, and
* Fast deflagration and DDT as well as global detonation condition.

In-vessel and ex-vessel hydrogen production for relevant accident scenarios have been estimated with the MAAP /3/ and COSACO /4/ codes, respectively. Uncertainties exist for the prediction of hydrogen/steam production during postulated reflood and in later phases. These uncertainties will be reduced continuously by future development of new models and their validations with suitable experiments. This subject will not be discussed further in this paper.
For the prediction of hydrogen transport and distribution based on relevant scenarios, a lumped parameter code and a 3D-code have been applied.
The most probable scenario with the highest in-vessel hydrogen-production is the SBLOCA (**S**mall **B**reak **L**oss **O**f **C**oolant **A**ccident), which will be considered for the design of the mitigation concept. In the SBLOCA scenario, hydrogen will be released at the break into a steam diluted atmosphere (wet scenario). Depending upon the pre-heating of the structure due to hot steam and buoyancy forces, hydrogen will take the same transport path as steam (both gases are lighter than air) to the dome with an acceleration of the flow. In long term, the hydrogen will be mixed by free convection throughout the whole containment.

In addition, hydrogen-mitigation should include two other scenarios that are EPR specific. In non-LOCA scenarios, hydrogen will be released via the IRWST into a largely dry atmosphere (steam condensation only in the in-containment refueling water storage tank). This scenario brings an additional burden to the hydrogen mitigation concept, because one can not take credit for the inertization or dilution effects of the steam in the containment. The third group is a mixed release scenario. In this case, a portion of the hydrogen will be released through the break (wet atmosphere) and the other part will be released via the IRWST (dry atmosphere).

All the scenarios for the design of the EPR hydrogen-concept can be grouped mainly into these three categories: 1. Wet, 2. Dry, or 3. Mixed releases. These groupings of the scenarios reduce the number of the analysis and simplify the design and justification of the mitigation concept.

For the justification of the mitigation concept, the prevention of DDT for the reference scenarios and resistance of the containment against combustion loads have to be shown. Many experiments in different small and large scaled facilities have dealt with the hydrogen risk for a broad range of initial conditions. The results of these experiments can be concluded as follows:
1. DDT was not observed, if the hydrogen concentration was below 10 volume percent, and
2. DDT developed, only if;
   a. Local hydrogen concentration was higher than 10 volume percent, and
   b. The characteristic dimension of the cloud with average hydrogen concentration greater than 10 volume percent was larger than 7 times the corresponding detonation cell size (7 λ criteria /5/).

These two fundamental criteria help us to design the hydrogen-mitigation concept safely, if both of the above criteria are strictly fulfilled. The use of a proper number of PARs with an optimized arrangement shall ensure that:
1. The global hydrogen concentration is below 10 volume percent, and
2. The AICC combustion pressure is below containment design pressure at all times.
Furthermore the fulfillment of the second criteria for the wet scenarios has to be shown with the 7 λ criteria because of local high hydrogen-concentrations at the break.
Although an ignition source in the containment can not be precluded (high outlet gas

temperature of the recombiners) it is advisable not to credit ignition for the wet scenarios and demonstrate without it the prevention of the DDT with analysis involving a 3D-code.

To fulfill the second criteria for all totally or partly dry scenarios (e.g. LOOP **L**oss **O**f **O**ff set **P**ower or mixed release), a sufficient number of the high frequency spark igniters with an optimized arrangement close to the exit of the IRWST should remove the hydrogen immediately within a very short distance of the release location. The diameter of the cloud comprising ignition point and the release location should be shorter than 7 times the detonation cell size based of its average mixture quality (7 λ criteria). In addition, the first criteria for these scenarios will obviously be fulfilled.

Proper composition knowledge of the atmosphere in every location during the course of an accident is indispensable for the design and assessment, as well as the justification of the mitigation concept. This will be achieved with two computer programs WAVCO (lumped parameter code) /6/ and GASFLOW (3D-code) /7/.

Application of the WAVCO code provides an optimized arrangement of the recombiners to ensure that
1. The global hydrogen concentration is below 10 volume percent, and
2. The AICC combustion pressure is below containment design pressure at all times. The appropriate scenarios are LOCAs with high hydrogen production (e. g. SBLOCA 20 cm ^{2}).

Application of the GASFLOW code will show:
1. Prevention of DDT for the wet scenarios with the 7 λ criteria without taking credit for ignition (e. g. igniter near break location or hot outlet gas temperature of the recombiner),
2. Successful burning of hydrogen and prevention of hydrogen accumulation in the dry scenario (e. g. LOOP with reflood), and
3. Determination of the hydrogen distribution just before ignition of hydrogen mixtures near the IRWST openings in equipment rooms for further determination of potential dynamic loads due to local deflagration on the containment structures (e. g. mixed released scenario).

The results of both computer codes must be compared and assessed.

Lumped parameter code WAVCO

WAVCO is a multi-compartment code developed at Siemens for severe accident containment analysis involving gas distribution, pressurization of the containment and determination of the thermo hydraulic conditions for a given source term. With suitable compartmentalization of the containment volume (80000 m ^{3}) in 50 to 100 lumped volumes, it can be demonstrated if local high average hydrogen concentration conditions can exist during accident progression. The main advantage of lumped parameter calculations is the reasonable computer time for accidents lasting longer than one day like SBLOCA 20 cm ^{2}. The other advantage is the rough information about the pre-conditioning of the structure and steam/air composition, which can be used for the start of a detailed 3D hydrogen-distribution calculation at any time during the accident progression to save computer time. The result of the calculation with a 50 lumped volume model and with 40 Siemens auto catalytic recombiners type FR90/1-1500 can be seen in Fig. 2, which shows the actual hydrogen-accumulation in the containment for two wet scenarios, SBLOCA 46 cm ^{2} and LBLOCA (surge line break), and one dry scenario, LOOP with reflood. Without going into the detail, the main result can be summarized in the following way:

1. Optimized arrangement of the recombiners inside the equipment rooms and a few in the dome promote convective flow, which homogenizes the atmosphere in the containment,

2. Recombiners alone can remove in a short time significant amount of hydrogen, which can keep the adiabatic iso-choric combustion pressure p_{AICC} below design pressure, and
3. Due to high local hydrogen-concentrations, a 3D-calculation has to provide justification for the prevention of DDT and determination of dynamic pressure loads.

3-D code GASFLOW

GASFLOW is a finite volume computer code, which has been developed at Los Alamos National Laboratory in USA and FZK in Germany. The code is designed to be a best-estimate tool for predicting the transport and mixing as well as recombination and combustion of hydrogen for simulating design basis and beyond design basis or severe accidents in the containment of nuclear power plants. The prediction of local mixture quality and hydrogen removal can be achieved by solving the transient, three dimensional, compressible, Navier-Stokes equations for multi-component gas mixtures. GASFLOW can predict clouds with critical mixture quality and sizes (7λ criterion) which could lead to DDT. A GASFLOW 120,000-cell EPR model has been provided to:
1. Demonstration the exclusion of DDT, and
2. Guaranty sufficient oxygen transport to igniter positions.

Without going into the details, the main results can be summarized in the following way:
1. Potential risk of DDT exists only in the case of dry scenarios, which says sole mitigation means as recombiners can not prevent DDT in the containment,
2. With at least one igniter at each exit of IRWST opening to equipment rooms, hydrogen can burn and the oxygen inflow to the flame is sufficient to sustain combustion,
3. After the first burn of hydrogen, a standing flame was established,
4. Standing flames strongly promote convective flow in the containment,
5. Determination of dynamic pressure loads must be determined in case of LOCA and mixed releases (therefore, a conditional criterion for occurrence of fast deflagration should be developed), and
6. Sensitivity studies are necessary for source release locations, orientations, and strengths.

Fig. 3 shows the 2D-velocity field through a cut across the flame at the maximum hydrogen release rate (1.5 kg/s) time for the LOOP case with reflood. The combustion product gas velocity increases to 26 m/s in the upper area of equipment rooms and in the dome. Figs. 4 and 5 show hydrogen and steam volume concentrations in the do me at the crane elevation for the same time. The maximum hydrogen concentration is 13.4 volume percent (20.2 volume percent steam), and the minimum hydrogen concentration is 6.9 volume percent (22.5 % steam) for the SBLOCA 20 cm^2 case.

Conclusions

Hydrogen risk reduction, based on relevant scenario for the EPR as a future advanced nuclear power plant with the features like a special protected basement for spreading and an IRWST for passively cooling of the core melt outside the reactor pit, has been demonstrated.

All the scenarios with hydrogen production can be grouped into three categories: wet, dry, and mixed releases. This grouping simplifies the justification of the mitigation concept which consists of PARs (foreseen for the wet scenarios), high frequency spark igniters (foreseen for the dry scenarios) and both PARs and high frequency spark igniters (foreseen for the mixed scenarios).

The application of the lumped parameter code WAVCO and the finite volume computer code GASFLOW have demonstrated the justification of the hydrogen mitigation and control system.

The results of the current analyses can be summarized:

1. Accelerated homogenization of the atmosphere occurs due to convective flow promoted by recombiner and igniter action,
2. Recombiners alone remove, in short time, significant amounts of hydrogen,
3. Adiabatic iso-choric combustion pressure P_{AICC} is below the design pressure,
4. 3D-calculations are necessary for justification to prevent DDT and determination the dynamic pressure loads;
   a. To demonstrate the exclusion of DDT development for the EPR hydrogen mitigation concept,
   b. To demonstration that sufficient oxygen transport to the igniter positions occurs to sustain hydrogen combustion as a standing flame, and
   c. To show the development of four standing flames after igniting the hydrogen mixture.

Future analysis should deal with the determination of the dynamic pressure loads and some sensitivity studies to check the hydrogen control measures with respect to source location, orientation, and strength effects. Furthermore, a conditional criterion for the occurrence of fast deflagration should be developed.

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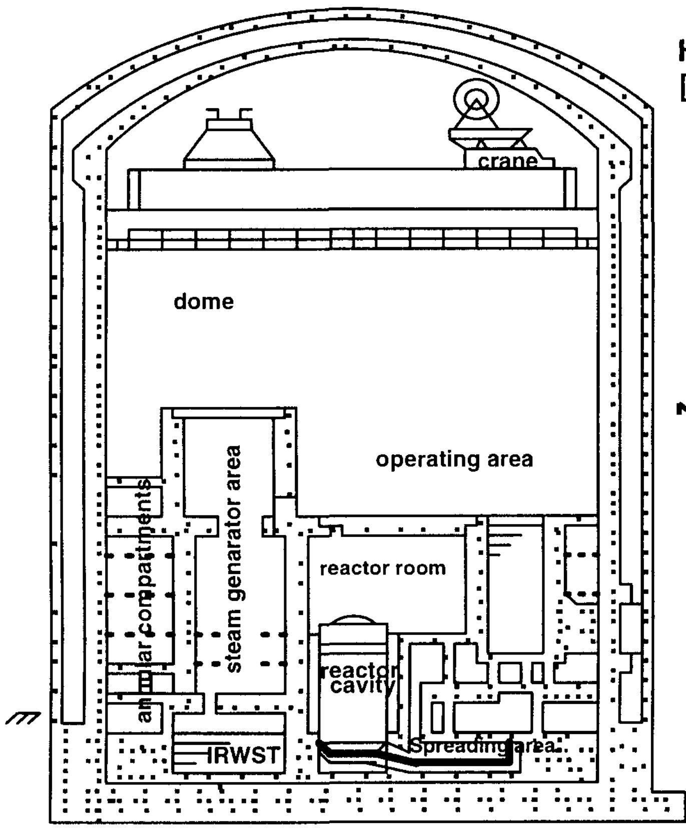

Fig. 1 : EPR Containment Section : 0° – 255°

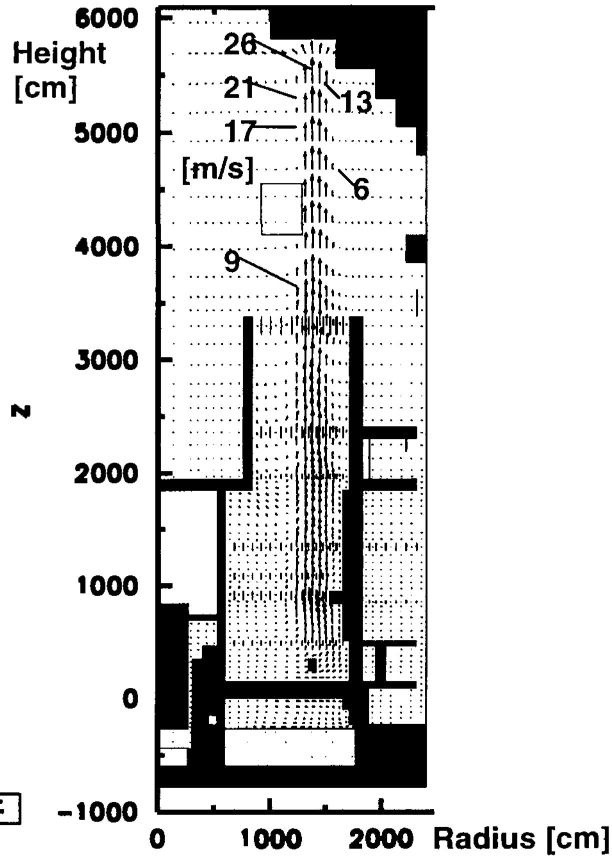

Fig. 3 : EPR; LOOP scenario with igniters
2D–velocity field at the time of maximal hydrogen release

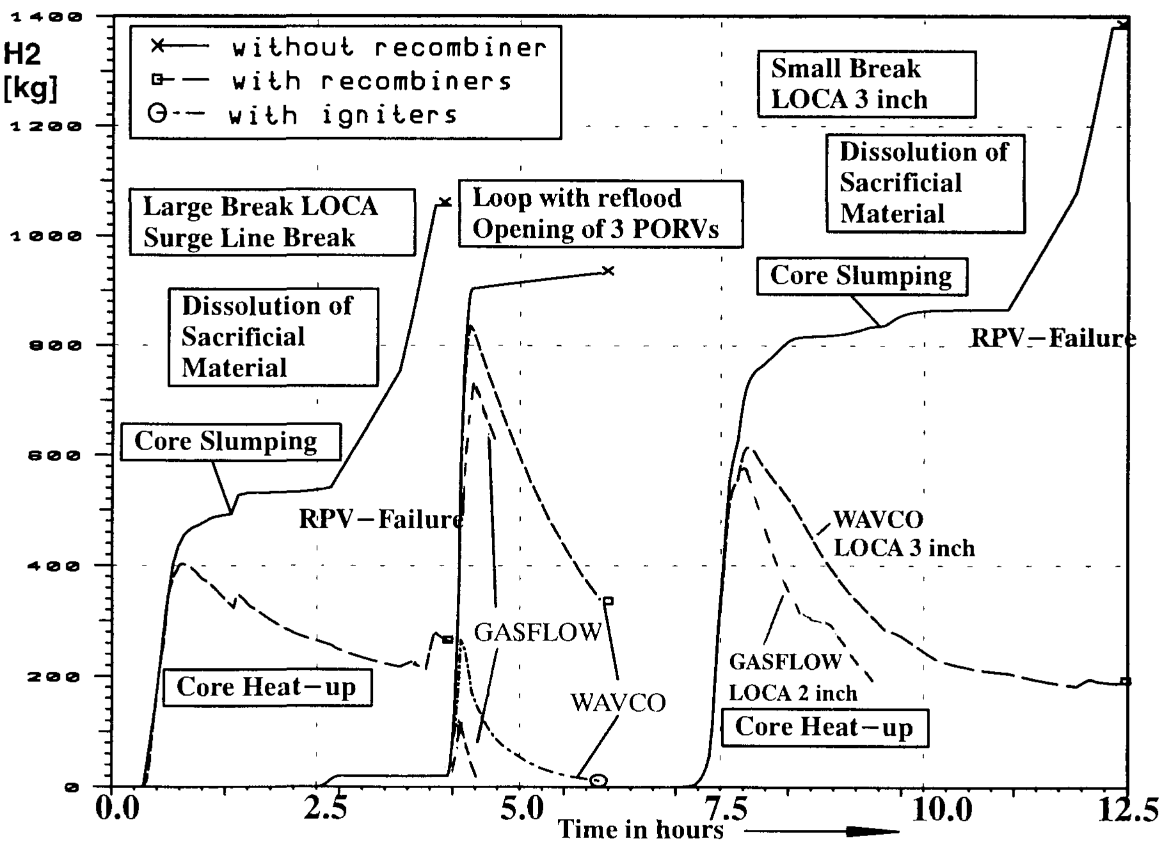

Fig. 2 : H2 release of different scenarios (cumulative release and actual amount)

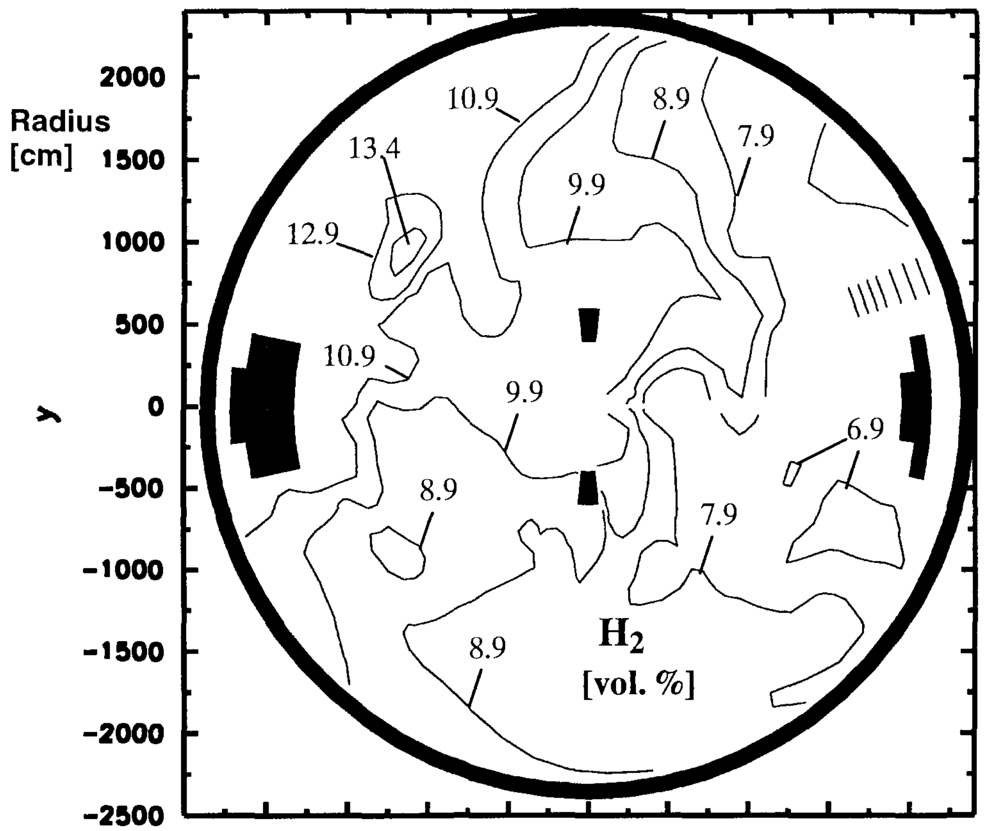

Fig. 4 : EPR; SBLOCA 20 cm² scenario with only recombiners
H_2 volume concentration in the dome at the crane elevation and maximal hydrogen release rate

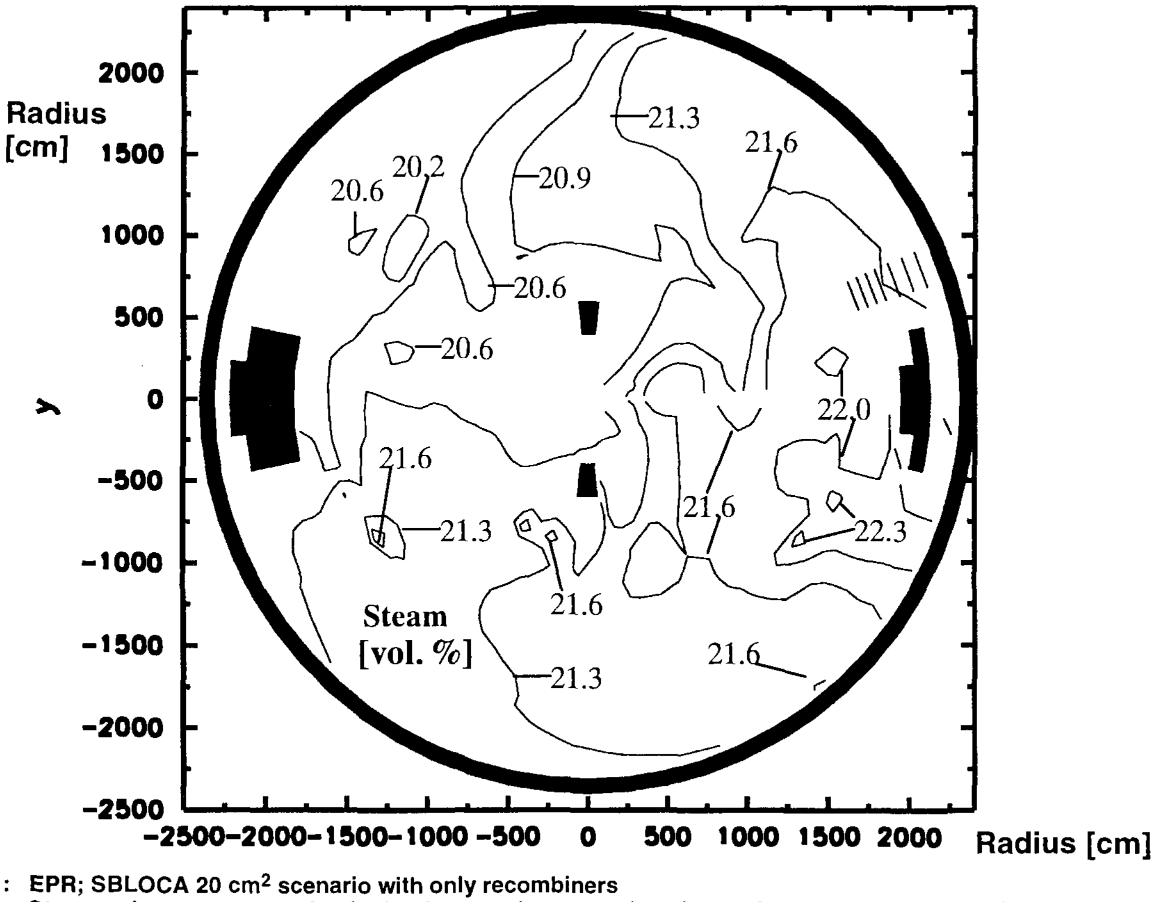

Fig. 5 : EPR; SBLOCA 20 cm² scenario with only recombiners
Steam volume concentration in the dome at the crane elevation and maximal hydrogen release rate