Nordisk kernesikkerhedsforskning
Norrænar kjarnöryggisrannsóknir
Pohjoismainen ydinturvallisuustutkimus
Nordisk kjernesikkerhetsforskning
Nordisk kärnsäkerhetsforskning
Nordic nuclear safety research

NKS-46
ISBN 87-7893-099-5

A Study on Hydrogen Deflagration for Selected Severe Accident Sequences in Ringhals 3

Veine Gustavsson
Erik Möller

SwedPower AB, Sweden

January 2002

Abstract

In this report, we have investigated the most important severe accident sequences in Ringhals 3, a Westinghouse 3-loop PWR, concerning hydrogen generation and containment pressure at hydrogen deflagration. In order to analyze the accident sequences and to calculate the hydrogen production, the computer code MAAP (Modular Accident Analysis Program) was used. Six accident sequences were studied, where four were LOCA cases and two transients. MAAP gives the evolution of the accident and particularly the pressure in the containment and the production of hydrogen as a function of time. The pressure peaks at deflagration were calculated by the method AICC-Adiabatic Isochoric Complete Combustion. The results from these calculations are conservative for two reasons. Adiabatic combustion means that the heat losses to structures in the containment are neglected. The combustion is also assumed to occur once and all available hydrogen is burned.
The maximum pressure in five analysed cases was compared with the failure pressure of the containment. In the LOCA case, 373 kg hydrogen was burned and the resulting peak pressure in the containment was 0,53 MPa. In the transient, where 720 kg hydrogen was burned, the peak pressure was 0,69 MPa. This is the same as the failure pressure of the containment. Finally, in the conservative case, 980 kg hydrogen was burned and the resulting peak pressure 0,96 MPa. However, it should be noted that these conclusions are conservative from two points of view. Firstly a more realistic (than AICC) calculation of the peak pressure would give a lower value than 0,69 MPa. Secondly, there is conservatism in the evaluation of the failure pressure.

Keywords

Hydrogen, deflagration, severe accident

NKS-46
ISBN 87-7893-099-5

Pitney Bowes Management Services Danmark A/S, 2002

The report can be obtained from
NKS Secretariat
P.O. Box 30
DK – 4000 Roskilde
Denmark

Phone +45 4677 4045
Fax +45 4677 4046
http://www.nks.org
e-mail nks@catscience.dk

A Study on Hydrogen Deflagration for Selected Severe Accident Sequences in Ringhals 3

Veine Gustavsson & Erik Möller
SwedPower AB

CONTENTS

EXECUTIVE SUMMARY

The objective of this project is to investigate the most important severe accident sequences in Ringhals 3, a Westinghouse 3-loop PWR, concerning hydrogen generation and containment pressure at hydrogen deflagration.

As a background, an overview of previous works is included in the project. Mainly, earlier investigations concerning hydrogen in the Ringhals PWRs are of two kinds: deterministic and probabilistic.

In the deterministic studies a hydrogen burn was initiated in an accident sequence with given assumptions and the pressure peak was calculated. The failure pressure of the containment was exceeded at deflagration of hydrogen in cases with large amounts of hydrogen and high initial pressure before deflagration.

The probabilistic studies are based on results from PSA studies for Ringhals 3. The accident sequences were grouped in six cases. The probability of containment failure at hydrogen deflagration was estimated for each of these groups. The sum of these contributions gives the probability of containment failure. The value obtained in these investigations was $0{,}6 \times 10^{-7}$/year with conservative assumptions.

In order to analyze the accident sequences in the project and to calculate the hydrogen production, the computer code MAAP (Modular Accident Analysis Program) was used. Six accident sequences were studied, where four were LOCA cases and two transients. MAAP gives the evolution of the accident and particularly the pressure in the containment and the production of hydrogen as a function of time.

Our intention was also to derive the pressure peak at deflagration of hydrogen. The pressure peaks were calculated by the method AICC-Adiabatic Isochoric Complete Combustion. The results from these calculations are conservative for two reasons. Adiabatic combustion means that the heat losses to structures in the containment are neglected. The combustion is also assumed to occur once and all available hydrogen is burned.

The peak pressure at deflagration is the sum of the initial pressure, obtained from MAAP, and the peak at deflagration from the AICC calculations. This analysis was performed for one of the LOCA cases, one of the transients and for a third (conservative) case. The maximum pressure in these cases was compared with the failure pressure of the containment.

In the LOCA case, 373 kg hydrogen was burned and the resulting peak pressure in the containment was 0,53 MPa. In the transient, where 720 kg hydrogen was burned, the peak pressure was 0,69 MPa. This is the same as the failure pressure of the containment. Finally, in the conservative case, 980 kg hydrogen was burned and the resulting peak pressure 0,96 MPa.

However, it should be noted that the conclusions above are conservative from two points of view. Firstly a more realistic (than AICC) calculation of the peak pressure would give a lower value than 0,69 MPa. Secondly, there is conservatism in the evaluation of the failure pressure.

1 INTRODUCTION

At the Ringhals site on the west coast of Sweden there are three PWRs operating. All of them are three-loop reactors of Westinghouse design. The first unit, Ringhals 2, was in commercial operation in 1975 and the others, Ringhals 3 and 4 (twin reactors) in 1981 and 1983 respectively.

The containments in the Ringhals PWRs are of the large dry type and filled with air under normal operation. Hence, in case of a severe accident with production of large amounts of hydrogen, the gas mixture in the containment will be burnable if the steam is below a certain limit (55-60 % by volume).

The hydrogen issue is more relevant for Ringhals 3 and 4 than for Ringhals 2 due to the large difference in containment failure pressure. This is the reason why most of the studies on hydrogen for the Ringhals PWRs have been performed for unit 3.

In the next section of this report, work on the hydrogen issue in the past is summarized for the Ringhals PWRs. However, the main purpose of this project was to analyze selected sequences with high hydrogen production, to calculate the peak pressure in the containment at hydrogen deflagration and finally compare the result with the failure pressure of the containment.

2 BACKGROUND

In this section the most important projects on the hydrogen issue for Ringhals 3 are briefly described. Investigations of mainly three different kinds have been performed, namely: deterministic calculations, probabilistic studies and on mitigating measures.

2.1 Deterministic calculations

In 1986 the work on the hydrogen issue for the Ringhals PWRs was summarized and reported in [1]. The earlier investigations on hydrogen deflagration and detonation especially for Ringhals 3 were summed up and the impact on the hydrogen issue from the mitigating systems (filtered venting and redundant containment spray) was discussed.

A distinction between the three units was made because of different failure pressure of the containment. For Ringhals 2 the limit is about 1,2 MPa but for Ringhals 3 and 4 slightly below 0,7 MPa. Therefore, focus is on unit 3 and 4.

A series of deflagration calculations have been performed by KWU by use of the code COCMEL with variation of the initial conditions with respect to the amount of hydrogen burned, the initial steam pressure and the initial temperature.

The main results from this study were the following:

- The containment of Ringhals 3 (and 4) can sustain a deflagration of hydrogen quantities corresponding to oxidation of zirconium in the core in the interval from 85 % to 120 %, dependent on pressure before deflagration.

- The corresponding limit for Ringhals 2 is 170 % zirconium oxidation.

In the COCMEL calculations the following assumptions were made:

- The gas mixture in the containment is homogenous.
- The combustion of hydrogen is complete.
- The containment is represented by one volume.
- The time of burning is very short.

With these assumptions the calculated peak pressure is about the same as the AICC (Adiabatic, Constant-Volume Combustion). Therefore, the results given above include some conservatism.

Potential problems related to hydrogen detonation were also discussed in [1]. An important conclusion is that a global detonation is highly improbable. A reason for this is that such an event requires an initiating energy, which is not available in the containment.

An investigation of local detonations in the containment of Ringhals 3 has been carried out and was reported in [2]. The calculations were performed by use of the code PISCES-2DELK, where both the detonation and the response from the containment building are included. The main results from this study were that the containment could sustain big local detonations, where a hydrogen quantity up to 300 kg is involved, and that the failure pressure of the containment is 0,69 MPa.

A program for severe accident mitigation was completed for all reactors in Sweden by the end of 1988. For the Ringhals PWRs this program included the following two plant modifications: introduction of filtered containment venting and redundant water supply to the containment spray system. These upgrades have some impact on the hydrogen issue.

The importance of the filtered venting system is relatively limited. The possibility to vent out hydrogen from the containment has been investigated and will be described later in this section.

Use of containment spray in a severe accident has different effects concerning hydrogen. An important, and positive, consequence of start of the spray is that the atmosphere in the containment will be more homogenous. Thus, the probability of local detonations will decrease.

Another effect of spray is that steam is condensed. A possible negative consequence is that the steam concentration will be below 55 % by volume some time after start of the spray. The gas mixture in the containment will then be combustible. At high hydrogen concentrations this is a disadvantage, because a deflagration can be initiated and might threaten the integrity of the containment. Therefore, there are restrictions on the use of containment spray if the amount of hydrogen in the containment exceeds a certain level. However, use of the spray has also a positive effect, because the initial pressure (before deflagration) is decreased due to steam condensation.

An investigation of the hydrogen issue from different aspects was performed by Westinghouse in 1987-88 and reported in [3] and [4]. The calculations were carried out by use of the nodal code COMPACT and the containment was divided in 15 volumes.

This work includes also analysis of possibilities of hydrogen burn in the filtered venting system.

In most of the COMPACT calculations it was assumed that 80 % of the zirconium was oxidized during core meltdown and the remaining 20 % was oxidized later in a corium/concrete interaction.

The peak pressure at hydrogen deflagration was evaluated under different assumptions concerning the initial conditions, i.e. temperature and steam concentration in the containment. An important result from the study was that the peak pressure at hydrogen deflagration was well below the containment failure pressure.

After a filtered venting to an initially cold scrubber, a combustible mixture can occur in the free scrubber volume. Assuming that an ignition source is always present, COMPACT predicts hydrogen deflagration in the scrubber. To avoid hydrogen burn in the scrubber after activation of the filtered venting system, the water in the scrubber has an initial temperature of 90 °C.

A series of calculations of the peak pressure at hydrogen deflagration was performed in 1991 for Ringhals 3 by use of the CONTAIN code. This work has been reported in [5]. The purpose of those calculations was to obtain a best estimate value of the pressure after hydrogen deflagration in a total blackout (TMLB) scenario assuming an amount of hydrogen corresponding to 100 % Zr-oxidation.

In the CONTAIN calculations the containment was divided in the following three cells: the reactor cavity, the part between the levels 100-115 and the upper compartment (dome). A large number of sensitivity studies were performed. The most important parameters varied in these calculations were the amount of hydrogen and the speed of the hydrogen flame.

The resulting peak pressure ranged from about 0,47 MPa to 0,8 MPa, where the higher pressures correspond to very conservative assumptions concerning the burning time and the amount of hydrogen burned. In more realistic cases the failure pressure of the containment (0,7 MPa) is not exceeded.

Generally, there is a reasonably good agreement between the results (peak pressures) from the different investigations related above. Only with very conservative assumptions the failure pressure of the containment will be exceeded at hydrogen deflagration.

However, it should be observed that the previous investigations related above were carried out with a lower quantity of zirconium in the core than the inventory today. The difference is about 10-15 %. The calculations presented in later sections in this report have been performed with updated zirconium content in the core.

2.2 Probabilistic studies

The works discussed earlier in this section contained deterministic studies. However, the probabilistic aspect is also of interest. In 1994 a study was performed with the purpose to estimate the probability of containment failure due to hydrogen deflagration in Ringhals PWRs. This work was reported in [6] and [7]. The first of these reports describes the method and the second one the application on Ringhals 3.

The method includes two main parts:

- Condensation to a small number of accident sequences from the PSA level 1 study for Ringhals 3
- Evaluation of the conditional probability of containment failure due to hydrogen deflagration in each of the condensed sequences.

It should be noted that detonation phenomena are excluded in this method. In [6], a separate evaluation was performed concerning DDT (deflagration-detonation-transition), which showed that the contribution to containment failure from detonation is small.

To obtain the probability of containment failure the results from the two steps given above were used. First, the probability of core damage was derived from the PSA level 1 study for Ringhals 3. Then the probability of containment failure at hydrogen deflagration, given core damage, was estimated.

After condensation of accident sequences from the PSA level 1 study for Ringhals 3, the following six cases were selected: a large LOCA, an average size LOCA, two cases with small LOCA, a transient with loss of feed water and a transient with steam generator tube rupture. These six cases are then evaluated separately in the second step, where the conditional probability of containment failure was estimated.

For each of the six cases the following was evaluated:

- Hydrogen production
- Probability of deflagration
- Pressure in the containment during deflagration.

Hydrogen production was included both from in-vessel and ex-vessel reactions. The first contribution comes from zirconium oxidation and the second one either from FCI (fuel-coolant-interaction) or MCCI (molten-core-concrete-interaction). FCI will occur if the molten material falls down into a cavity partly filled with water and MCCI will be the case if the cavity is dry.

Concerning hydrogen concentrations, two sets of values were used, where one is best estimate and another conservative. The largest conservative hydrogen concentration corresponds to 100 % oxidation of zirconium and a small contribution from oxidation of steel.

The probability of deflagration depends on the composition of the atmosphere in the containment and on the availability of ignition sources.

The gas mixture in the containment is combustible if the following conditions are satisfied:

- The concentration of hydrogen is higher than 4 %, by volume
- The concentration of oxygen is higher than 5 %, by volume
- The steam concentration is lower than 55 %, by volume.

In a severe accident the probability that the atmosphere is steam inerted is high, unless the containment spray is used.

If the spray is started, when the containment atmosphere is steam inerted, the result will be that steam condenses and the gas mixture in the containment can be burnable. As a result of such a transition into a burnable region a deflagration can be initiated if an ignition source is present.

In cases with a hydrogen concentration below a certain limit it is an advantage to burn hydrogen, because it reduces the possibilities for accumulation of high amounts of hydrogen. However, if the hydrogen concentration exceeds a certain limit, restrictions concerning use of the containment spray is recommended, because under such conditions it might be a threat to the integrity of the containment.

Generally, the probability that an ignition source exists in the containment is high. In [7], values in the range 0,80-0,95 were used.

The peak pressure at hydrogen deflagration is the sum of the pressure before deflagration and the increase of the pressure from the deflagration. The pressure in the containment before deflagration depends on the temperature and steam concentration. It was calculated by use of the MAAP code. The increase of the pressure from the deflagration was evaluated from the CONTAIN calculations described in [5].

The evaluation of the conditional probability of containment failure was done by use of two containment event trees. The first one is for the period (from the initiating event) before and the second one after reactor vessel failure. The main reason for this separation is that a hydrogen deflagration before reactor vessel failure reduces the risk for accumulation of large hydrogen concentrations later in the accident sequences.

In summary, the dominating uncertainties in evaluating the probability of containment failure caused by hydrogen deflagration are the following:

- The amount of hydrogen produced during the accident
- The probability of hydrogen deflagration before reactor vessel failure
- The use of containment spray, especially at high hydrogen concentrations.

The two cases (with best-estimate and conservative values for hydrogen production) gave the following results for the probability of the containment failure due to hydrogen deflagration:

- The best estimate case- zero
- The conservative case- $0,6x10^{-7}$ /year.

Consequently, containment failure due to hydrogen deflagration in a severe accident is a residual risk, i. e. in the range of $1x10^{-7}$ /reactor year. However, if such an accident occurred, it would lead to large releases to the environment.

2.3 Mitigating measures

Mitigating measures for hydrogen in severe accidents can be based on the following principles:

- Deliberate burning or recombination of the hydrogen in the containment
- Inertisation of the containment atmosphere
- Removal of hydrogen from the containment by venting.

The last of these options (venting) was investigated in 1997 at Vattenfall and reported in [8] and [9]. A series of MAAP calculations were carried out on two scenarios, where one was a total blackout and the other one a large LOCA as initiating event.

The time behavior of the following three quantities was studied: the pressure in the containment, the amount of hydrogen in the containment and the amount of hydrogen vented out via the scrubber.

During the venting the pressure in the containment must be sufficiently high for two reasons:

- To have an efficient venting the driving pressure must be at least 0,3 MPa.
- To avoid hydrogen deflagration the atmosphere in the containment must contain at least 55 % steam, which corresponds to a pressure of about 0,3 MPa.

In the study it was assumed that the scrubber was manually activated at a containment pressure of about 0,4 MPa.

The main results from the MAAP calculations were:

- If the pressure in the containment is sufficiently high, a large portion of the hydrogen can be vented out.
- Venting of significant amounts of hydrogen is time consuming; it can take several hours and in the meantime the radiation level around the scrubber is high.
- There are sequences where large amounts of hydrogen are produced early and before venting is efficient.

The main advantage related to the use of the filtered venting system to reduce the hydrogen content in the containment is that no installation of new equipment is needed.

The most important disadvantage of using filtered venting is that it gives release of activity to the surrounding of the scrubber and consequently limited access to that area.

The judgement based on our study was that venting is not to be recommended as a mitigating mesure for hydrogen in an early stage of a severe accident. However, it might be useful later on when the activity in the containment atmosphere is lower.

The main conclusions of earlier work on the hydrogen issue for Ringhals PWRs are:

- Calculations of the peak pressure in the containment at hydrogen deflagration have shown results close to the containment failure pressure of Ringhals 3 and 4.
- The probability of containment failure, in Ringhals 3 and 4, under conservative assumptions has been estimated to be slightly below $1x10^{-7}$ / reactor year.

Moreover, the consequences for the environment would be large if such an accident occurred. For these reasons it is motivated to further investigate the hydrogen issue for Ringhals 3 and 4.

In this report a number of sequences with high production of hydrogen are selected and the peak pressure in the containment is evaluated and compared with the failure pressure of the containment.

3 OBJECTIVES

The objective of the project is to investigate the most important severe accident sequences in Ringhals 3 concerning hydrogen generation and containment pressure at hydrogen deflagration.

Focus will be on sequences with reflooding of the damaged core, which are the cases where the production of hydrogen will be highest.

The containment pressure at deflagration will be compared with the failure pressure of the containment.

In this study the first 24 hours after the initiating event are included.

4 ACCIDENT SEQUENCES

The intention in this project is to study accident sequences with high hydrogen production. The selection of sequences is based on the PSA level 1 study for Ringhals 3 reported in [10].

Starting from the large number of accident sequences in [10], a condensation to a small number of cases has been carried out. These are denoted as key accident sequences in the following.

The cases in [10] are condensed to six key accident sequences, where four are LOCA cases and two are transients. The six cases are described separately in the following, where the short notation comes from [10].

4.1 Key accident sequence AX6

This case is a large LOCA with cold leg break. The loss of coolant from the primary system is very rapid and the pressure in the primary system drops to about 0,3 MPa within a minute.

Initially the core is cooled with water from the accumulators and RWST (Refueling water storage tank). After about 30 min. the RWST is empty. If the low pressure cooling system is used with recirculation of water from the sump the core could be cooled and reactor vessel failure prevented. However, in this sequence it is assumed that no decision is taken to initiate recirculation via the sump. Consequently, core damage will occur and later reactor vessel failure.

4.2 Key accident sequence S1H1

The initiating event in this sequence is a medium size LOCA. It is assumed that the PORVs will not open on signal. The system for cooling the core is high-pressure injection in this case. However, due to component failure this system stops and the core melts.

4.3 Key accident sequence S1D1D5

The initiating event in this case is a small LOCA. The pressure in the primary system decreases slowly to a level of about 6 MPa. It is assumed that opening the PORVs reduces the pressure in the primary system. However, the low-pressure system for core cooling is assumed to fail. Consequently, the core will be uncovered and finally the reactor vessel will be melt through.

4.4 Key accident sequence S2H2

Also in this case the initiating event is a small LOCA. The pressure in the primary system is reduced by use of the PORVs. The low-pressure system for cooling the core is assumed to work initially. However, when it comes to recirculation via the sump the system fails. Gradually the cooling of the core will be insufficient and reactor vessel failure occurs.

4.5 Key accident sequence T3LX4

In this sequence the initiating event is loss of feed water and also auxiliary feed water. Furthermore, it is assumed that feed and bleed is not initiated in time. Feed and bleed is a possibility to cool the core by safety injection and release of steam from the pressurizer. The water in the steam generators boils off and the rupture disc in the quench tank bursts. The core will be uncovered and melt down. At reactor vessel failure the melt falls down into a dry cavity.

4.6 Key accident sequence T5D1X1

The initiating event in this sequence is steam generator tube rupture corresponding to an area of 50 cm^2. It is assumed that the pressure in the primary system is not reduced and that the charging pumps do not work. After some time the core melts down and reactor vessel failure occurs. In this sequence a large fraction of the hydrogen will leak out to the environment via the damaged steam generators.

For the following investigations described later in this report, two cases will be selected, where one is a LOCA sequence and the other one a transient.

5 HYDROGEN PRODUCTION

The hydrogen production in a severe accident is the sum of two contributions, namely from in-vessel and ex-vessel reactions. However, from a risk perspective the hydrogen issue should be considered as a whole. Therefore, the total amount of hydrogen in the containment is relevant, independent on source.

5.1 In-vessel hydrogen production

The dominating contribution concerning in-vessel hydrogen production comes from oxidation of zirconium in contact with steam. There are also some small contributions from other metals such as iron.

A theoretical upper limit for hydrogen production by Zr-oxidation in-vessel is of course 100% of the core inventory of zirconium. However, that limit will never be reached, because in the fuel assemblies at the edge of the core, the oxidation of the cladding will not be complete.

5.2 Ex-vessel hydrogen production

In ex-vessel production of hydrogen the sources to be considered are the following:

- Reaction of core debris with water
- Corium-concrete interaction
- Debris-atmosphere interaction
- Corrosion reactions
- Radiolysis of water

Reaction of core debris with water occurs when corium is released from the reactor vessel to a flooded cavity. Experimental results from the FARO program have shown that significant amounts of hydrogen can be produced in this reaction. The interpretations of measurements gave figures of about 0,2 kg hydrogen produced for 100 kg melt. However, a realistic hydrogen production is significantly lower because of limitations in the mixing process of melt and water.

Corium-concrete interaction is of importance in cases where corium is released from the reactor vessel to a dry cavity. A significant part of the hydrogen is produced during the early phase when zirconium is oxidized. Thus, the quantity of Zr oxidized depends on the fraction of Zr oxidized during the in-vessel phase of the accident. Conservatively, it can be assumed that the remaining mass of Zr is oxidized by corium-concrete interaction.

Later in the in corium-concrete interaction other elements will react, such as Si, Cr and Fe. The release rate from these reactions will be relatively small, typically rates of 4 g/s, and last for several days.

Debris-atmosphere interaction will give a contribution to the hydrogen production in accident sequences with reactor vessel failure at high pressure in the primary system. The primary process is oxidation of metal in the debris droplets spread in the containment. The main contribution comes from zirconium, which has not reacted earlier in the accident.

Corrosion reactions are of some importance in containments with significant amounts of zinc and aluminum. Some types of paint and galvanized steel contain zinc. Corrosion reactions are generally relatively slow and depend strongly on the acidity in the containment.

Radiolysis of water occurs in sump, where water molecules are split due to irradiation from the fuel debris. The process is slow and the hydrogen production is of the order of 100 kg/month. Therefore, radiolysis is not important in this study but is more of interest in a long-term perspective.

6 ACCIDENT SEQUENCES ANALYZED AND CALCULATED WITH MAAP

In order to analyze the threat to the containment due to hydrogen deflagration, selected severe accident sequences have been simulated with the MAAP 4.0.4. code. The six sequences briefly described in previous section have all been recalculated with the newest version of the code to analyze which of them to be selected in the case where deflagration will take place. The results, the sequence selection criteria and a general description of the calculation program are presented below.

6.1 General description of the MAAP-code

The Modular Accident Analysis Program (MAAP) version 4 is a computer code that can simulate the response of light water reactor plants during severe accident sequences, including actions taken as part of accident management. The code predicts the evolution of a severe accident starting from full power conditions given a set of system malfunctions and an initiation event. Furthermore, models are included to present the actions that could stop the accident by in-vessel cooling, external cooling of the RPV or cooling the debris in containment (ex-vessel cooling).

The MAAP version used in this report is the most recent one released, MAAP 4.0.4. The Manual used for this analysis is the MAAP4 Users Guidance Volume 1-4 [11], including all officially released updates. The latest update is dated June 25, 1999 and the updates are also included in the parameter-file distributed with the version 4.0.4 in December 2000.

MAAP is using a parameter-file to describe the specific plant analyzed. This file is extensive and includes both physical data for the plant as well as control functions and specific parameters for the plant. The Ringhals PWR parameter-files were updated and quality assured when the new 4.0.4 version was taken in use. Some minor modifications to the parameter-file were done after correspondence with Ringhals in May 2001. The parameter-file used in this analysis is dated 2001-05-23.

6.2 Hydrogen production modeling in MAAP 4.0.4

The modular program package MAAP4 includes more than one hundred different subroutines that interact in different phases and actions within the severe accident simulation. Phenomena and development are described and many of these subroutines are used at different stages in the calculation. It is not a goal to give a neither a complete or a detailed description of how MAAP handles the hydrogen production throughout the sequence. The following discussion is merely an indication of the structure and where the most fundamental information is outlined. More detailed information can be found in the MAAP4 manual [11].

One major subroutine that handles the thermal-hydraulics is the *HEATUP*. It is the subroutine that controls the different calculations and transfers data from one module to the next. The physical basis of the model can be briefly described in 10 different partly chronological subsections, namely:

1. General core model
2. Heat-up of the water pool and covered core nodes
3. Core – upper plenum natural circulation
4. Heat-up of uncovered nodes
5. Radial radiation heat transfer
6. Molten debris pool and crust calculation
7. Collapse of degraded core nodes
8. Core spray and Quenching
9. Fuel – cladding interaction
10. Collapse of remaining core

In many of the different chronological steps above there is production of hydrogen from different phenomena. A difference is made to whether the core node is covered or uncovered. The hydrogen production is mainly calculated within two different subroutines divided up in this way, *COVER* for the covered nodes and *ROW* for the hydrogen generation in the uncovered nodes. Each node represents six different components; all do to some degree contribute to the hydrogen production. They are:

1. Fuel (U_2O)
2. Cladding (Ziracloy – Zr, ZrO_2, U-Zr-O)
3. Stainless steel (SS, stainless steel oxide)
4. Control rod (Zr, ZrO_2, Ag-In-Cd, SS, B_4C)
5. Fuel canister (absent in PWR)
6. Water flow

Two different interactions are analyzed in the scope of hydrogen production, the metal - water interaction (or steam in the uncovered nodes) and stainless steel – water reaction. Details about the models for the interactions can be found in the MAAP manual. More complicated phenomena regarding generation of hydrogen occur during debris particle oxidation during the transfer from RPV to the adjoining compartments like the cavity. There are several subroutines handling this calculations, one is *DBJET*. The last phenomenon mention in this brief description is the corium-concrete interaction, often called CCI or MCCI (MCCI = Molten corium concrete interaction). Concrete erosion and its chemical decomposition will result in gas releases, of which one is hydrogen.

This phenomenon is covered in the subroutine *DECOMP* and has been added and modified in the recent updates of the MAAP code.

6.3 Hydrogen deflagration in MAAP 4.0.4

The combustion of hydrogen and carbon-oxide is handled by the subroutine *FLAMM*. It is supposed to be a carefully tested and validated model to analyze different kinds of burns within the containment. *FLAMM* calculates the flammability for complete burn, uncompleted burn, autoignition and the adiabatic, isochoric complete combustion (AICC) pressure and temperature given the composition of the gas mixture and the temperature in a compartment. The burn is studied in great detail with different models and criteria for flame propagation. Different ignition criteria can be set and in this way it can be manipulated to the users wish.

However, in this report the MAAP option to calculate the deflagration and pressure peak was not used. The early simulations when this was used indicated several small burns, which strongly effected the total hydrogen content in the containment, took place. The aim to study the worst case - conservative case - in this analysis resulted in the crude decision to inactivate the *FLAMM* subroutine and instead manually take out the data needed for a hand calculation according to the above mentioned AICC calculation. This is further discussed in the section 0.

6.4 Accident sequences calculated with MAAP 4.0.4

Six of the sequences listed in ref. [10] were recalculated with the new version of MAAP and the results showed good agreement with the previous calculations. The difference regarding timing of the events such as reactor vessel failure was expected and is a result of the changed modeling of the molten corium and steel vessel interaction. The results from the screening calculation of the sequences are shown in Table 1. Note that the results are limited to what is of interest to this analysis and shall not be seen as a complete sequence analysis.

The amount of hydrogen produced in each case was significantly higher than expected due to several reasons, mostly caused by the greater total mass of Zirconium in the fuel elements in the present core. Some important parameters for this analysis are listed in Table 2 and are directly gathered from the Ringhals 3 MAAP parameter-file.

In the detailed analysis of the hydrogen production and containment pressure, two of the above-mentioned sequences were chosen namely, S1H1 and T3LX4. Each of these sequences is discussed below. Both of these sequences were modified slightly to create an extremely severe case where a high amount of hydrogen was produced and allowed to exist in a high-pressure environment.

With the normal settings for MAAP it is indicated that hydrogen burn would occur numerous times throughout the sequences, which is not according to the worst case scenario. Therefore the hydrogen burn option in MAAP has been manually turned off to allow a hydrogen concentration buildup. The result is that a high hydrogen mass and concentration will contribute to the major deflagration that will endanger the containment.

Table 1. Summary of the recalculation of the sequences

Time of event and results:	Sequence					
	AX6	**S1H1**	**S1D1D5**	**S2H2**	**T3LX4**	**T5D1X1**
Core Uncovered [s]	13	29621	22292	31780	3386	38843
Reactor Vessel failure [s]	13173	43252	50432	45035	9473	58550
Total mass of hydrogen in containment [kg]	176	370	436	409	681	98[1]
Fraction of clad reacted in vessel [%]	14	39	46	42	50	59
Max mole-fraction of Hydrogen in containment [%]	2.57	3.32	9.91	3.55	14.5	1.68
Max pressure in containment – No hydrogen deflagration [kPa]	396 (@ 25s)	471 (@ 45900s)	311 (@ 51893s)	500 (@ 63595s)	367 (@ end of calc.)	500 (@ 155522s)

Table 2. Selected MAAP parameters used in the calculations

MAAP Parameter:	**Value:**
Plant initial core full thermal power, QCR0.	2.775×10^9 W
Total mass of UO2 in the active core region, MU20.	82015 kg
Total initial mass of zircalloy (Zr) in the cladding including the fuel and water/control rods in both the active and non-active core regions, MZR0C.	20080 kg
Number of fuel pins in core, NPIN.	41448
Nominal full power primary system average water temperature, TWPSNM.	576 K
Nominal full power primary system pressure, PPSNOM.	15.51×10^6 Pa
Initial mass of water on the secondary side of one steam generator, MWSG0.	44500 kg
Initial pressure on the secondary side of each of the S/Gs, PSG0.	6.05×10^6 Pa
Secondary side total fluid volume, VSG.	170.0 m^3
Refueling water storage tank (RWST) initial water mass, MRWST0.	2.1×10^6 kg
Total free volume of the compartments, VOLRB(1)..(7)	5.2×10^4 m^3
Free volume of the Upper compartment, VOLRB (7)	3.458×10^4 m^3

[1] In this case most of the hydrogen leaks out through the broken SG-tubes.

6.4.1 Hydrogen analysis of the sequences

The main aim with this detailed analysis of the simulated accident sequences has been to determine the worst case in line of a hydrogen deflagration which may endanger the last protection barrier – the containment. In the sequences discussed, a high level of hydrogen mass and mole fraction is achieved in the containment and the high initial pressure in containment, before deflagration, is also a strong factor to the endangered containment.

The pressure in the containment is limited by the containment pressure relief system ("Scrubber" or System 365), which is passively activated by the burst of the scrubber relief disc. This occurs at containment pressure of 5 bar (0,5 MPa). However, activation of the scrubber is of no importance because of the rapid pressure spike from the hydrogen deflagration. Therefore, the aim has been to find points in the sequences where the deflagration criteria, see Table 3, are fulfilled in a high containment pressure situation. At this point a manual calculation of pressure peak from a complete hydrogen deflagration is done, see next section for model used and assumptions made in the pressure peak calculation. In the following sections (section 0 and 0) the results from the MAAP calculations are presented for each case analyzed, the focus is on containment pressure, total hydrogen mass and mole fraction of the gases in the upper compartment (the dome). For each case a summary is given of what process has contributed to hydrogen production. This is done for the sake of completeness and to identify important features of the sequence for further analysis.

Table 3. Deflagration criteria

Gas mixture component:	**Critical concentration: [mole fraction]**
Hydrogen	> 4%
Oxygen	> 5%
Steam	< 55%

6.4.2 Pressure peak analysis

The overall goal of this report is to investigate the containment integrity during a hydrogen deflagration. Earlier in this report several other detailed reports have been summarized. In this section the consequence of hydrogen deflagration on the Ringhals 3 power plant is presented.

The pressure peak calculation is a theoretical Adiabatic Isochoric Complete Combustion (AICC) calculation based on common accepted methodology. The fundamental equation for the calculation is the energy balance equation:

$$(m_{H2}c_{vH2} + m_{O2}c_{vO2} + m_{N2}c_{vN2} + m_{H2O}c_{vH2O})\, T_0 + m_{H2}Q_{H2} =$$
$$(m_{H2f}c_{vH2} + m_{O2f}c_{vO2} + m_{N2f}c_{vN2} + m_{H2Of}c_{vH2O})\, T_f$$

Where: m_X – mass of gas component
c_{vX} – specific heat of component, constant volume
$_f$ – indicate post deflagration state
T_0 – temperature before deflagration.
Q_{H2} – released energy per mass unit burnt hydrogen [12]

In this equation all the variables before the hydrogen burn is given from the MAAP calculation. The specific heat variables have been identified for the corresponding temperature before the hydrogen burn. The complete burn makes it possible to calculate the mass of the components in the gas-mixture after the burn. The temperature of the gas-mixture does correspond to the peak pressure that is theoretically achieved in the containment through the ideal gas model. This is only an estimate due to the assumptions made in the model:

- Adiabatic burn is assumed, i.e. the heat losses to structures is neglected
- A complete combustion is presumed, which is conservative
- The compressibility of steam is simplified, only the specific heat is analyzed and steam is not a ideal gas

But as the AICC-methodology gives the most conservative case it is a good indication of the maximum peak pressure. The level of conservatism in the AICC-methodology for this analyzes is not within the scope of this report.

In line with previously mentioned argument the composition of the gas-mixture is gathered from the MAAP node "upper compartment" but is applied to the entire free volume of the containment. No consideration to the up/down-ward flame theory has been done. The assumption is that all hydrogen is instantaneously burnt throughout the containment.

In the following sections the two sequences have been analyzed and the maximum peak pressure is presented.

6.5 Medium size LOCA without PORV and no High pressure recirculation, S1H1

The initiating event is a medium size LOCA on the cold leg, 6 cm diameter corresponding to a break area of 28,27 cm^2. It is assumed that the PORV's will not open on signal nor will the high-pressure injection work.

The initial LOCA makes the primary system to rapidly lose pressure and consequently the containment pressure increases, see Figure 1. The HPI (charging pumps) and LPI add coolant to the core for the next 3,7 hours and keep a sufficient amount of water in the reactor vessel. However when the accumulators and the RWST are dry after 5,3 hours there is no more water available. As no recirculation is assumed the water level in the vessel rapidly decreases and the core will be uncovered at 8,2 hours after the initiating event. At this point hydrogen is starting to be released from the cladding oxidation. The hydrogen will be transported with the stream out from the reactor vessel to the containment through the cold leg rupture, see Figure 2.

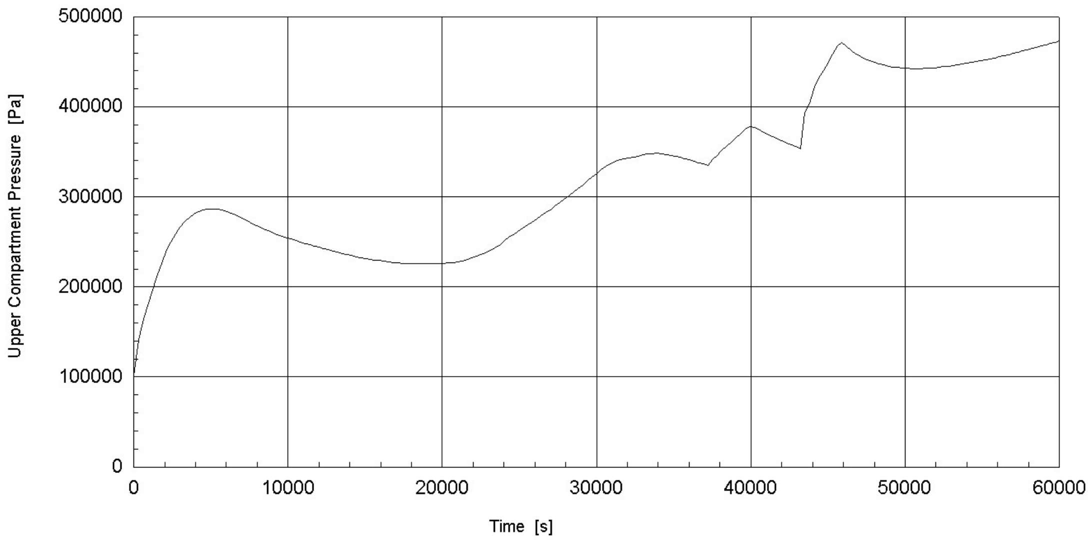

Figure 1. Containment pressure (node: Upper compartment) as a function of time (sequence: S1H1)

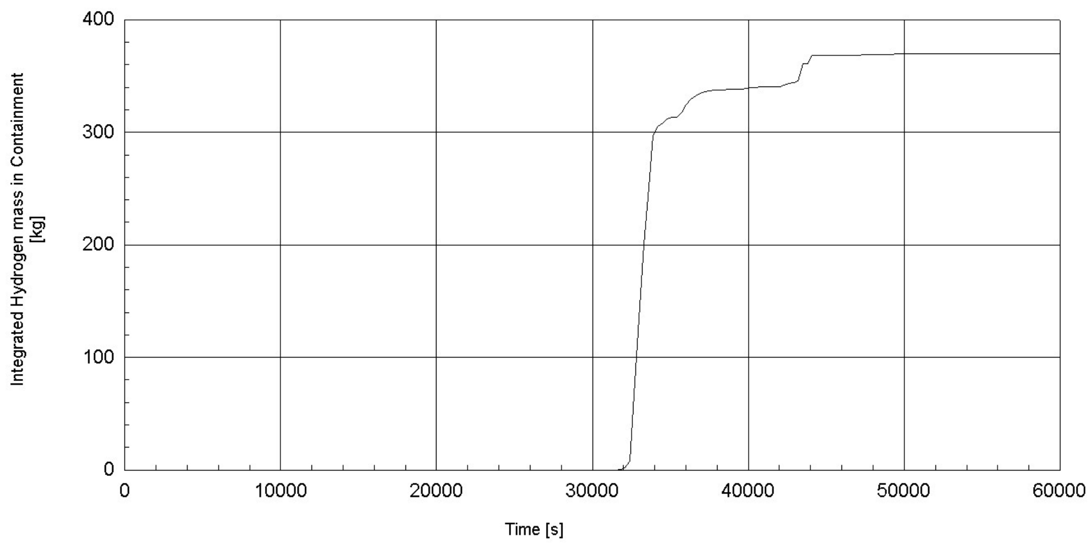

Figure 2. Integrated mass in the Containment. Sum of all hydrogen production phenomena (sequence: S1H1).

The time after the core has uncovered is when we have the highest hydrogen production rate due to the overheated cladding. The maximum hydrogen production rate is 4,04 kg/s logged at 10,3 hours.

The degraded core is relocated to the bottom of the vessel and a reactor vessel creep rupture appears after almost exactly 12 hours. Some amount of the molten corium relocates into the wet cavity and soon the water is saturated and the corium exceeds the melting temperature of the concrete. This results in MCCI and more production of hydrogen. After 15 more minutes an extensive reactor failure is logged and a large amount of the degraded core is relocated to the cavity. Throughout the relocation of corium to the wet cavity FCI is taking place and contributes to the integrated production of hydrogen. A summary of the most important events is listed in Table 4.

Table 4. Time of important events in the S1H1 sequence

Time [s]	Time [h]	Event according to MAAP
34	0,0	Reactor scram due to low primary system pressure
50	0,0	Low pressure injection pumps (LPI) on
50	0,0	Charging pumps on
13240	3,7	Charging pumps disabled
13634	3,8	Accumulator water depleted
19244	5,3	RWST water depleted
19244	5,3	LPI insufficient NPSH
23839	6,6	Main coolant pumps off
29621	8,2	Core has uncovered
43252	12,0	Reactor pressure vessel (RPV) fail due to creep rupture
43252	12,0	1^{st} compartment (cavity) corium pool temp. > concrete melt
44087	12,2	RPV extensive failure

6.5.1 S1H1 – results regarding hydrogen content in containment

In the sequence a medium LOCA transfers energy and water from the primary system to the containment, which directly affects the containment pressure, see Figure 1. In the graph the different events affecting the upper compartment is seen. The reactor vessel failure is clearly seen at 43250 sec.

The total hydrogen mass produced in the sequence is shown as a graph over the total mass in the seven compartments, see Figure 2. It is noted that the total mass in containment is 370 kg. The results also show the integrated masses produced in the three different processes earlier mentioned. They are hydrogen generated from oxidation of Zirconium in the core (Figure 3), from the metal (Stainless Steel) surfaces (Figure 4) and MCCI (Figure 5). Please note that the magnitude of the latter two is one order of magnitude, or more, less than the contribution from the Zirconium oxidation.

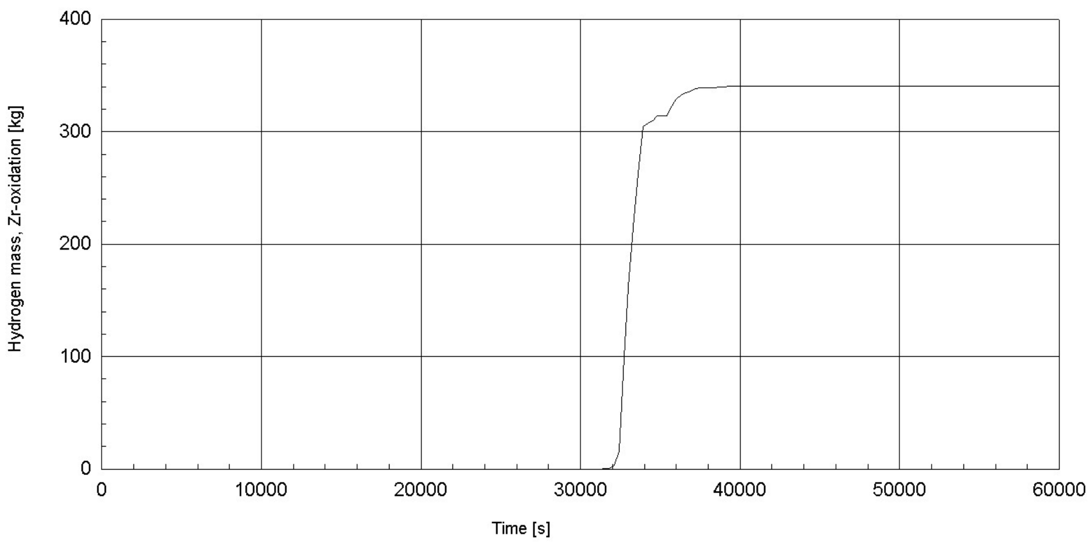

Figure 3. Integrated mass of hydrogen from the Zirconium oxidation (sequence: S1H1)

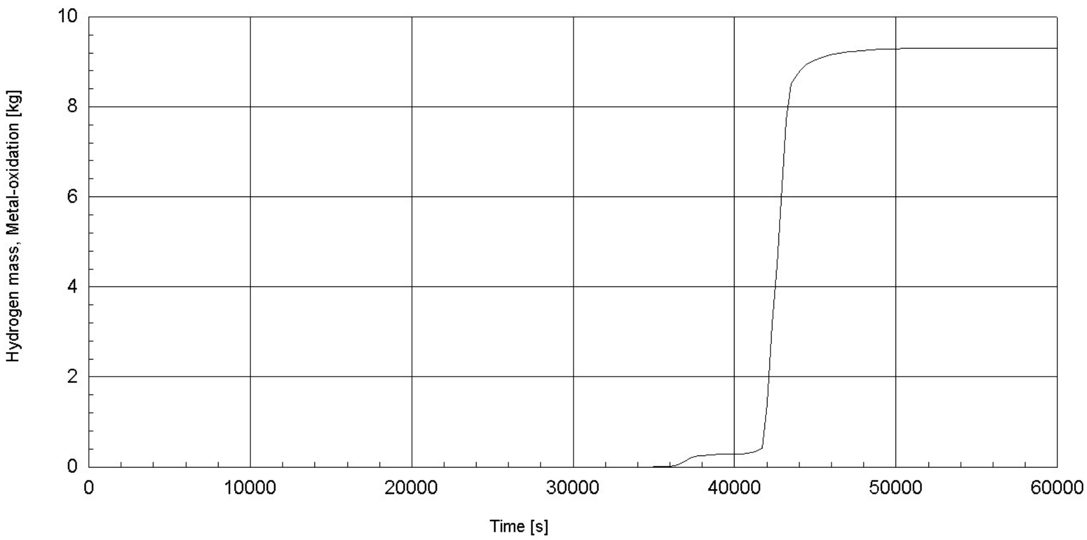

Figure 4. Integrated mass of hydrogen from the metal (surfaces) oxidation (sequence: S1H1)

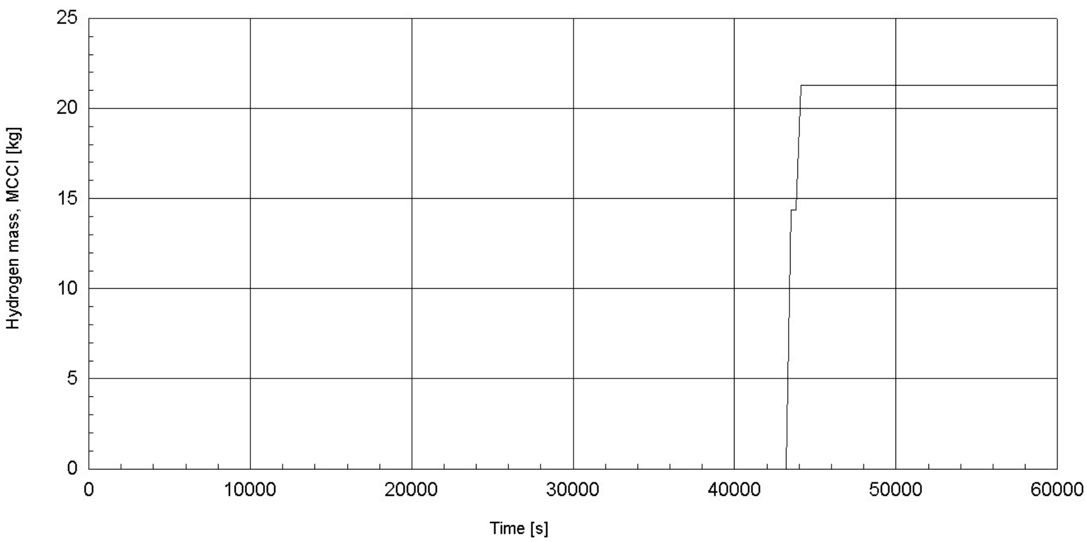

Figure 5. Integrated mass of hydrogen from the MCCI (sequence: S1H1)

As the mass of hydrogen is determined it is now of importance to study the content of the gases in the containment. The following three figures, (see Figure 6 - 8) show the mole fractions of the upper compartment in the containment. The results show that the deflagration criteria are not fulfilled due to the high steam fraction, >55 % and the low fraction of hydrogen. The conclusion is that in this sequence no deflagration is expected to occur. However if the containment spray will be started the individual fractions will drastically change. This is simulated in the following section.

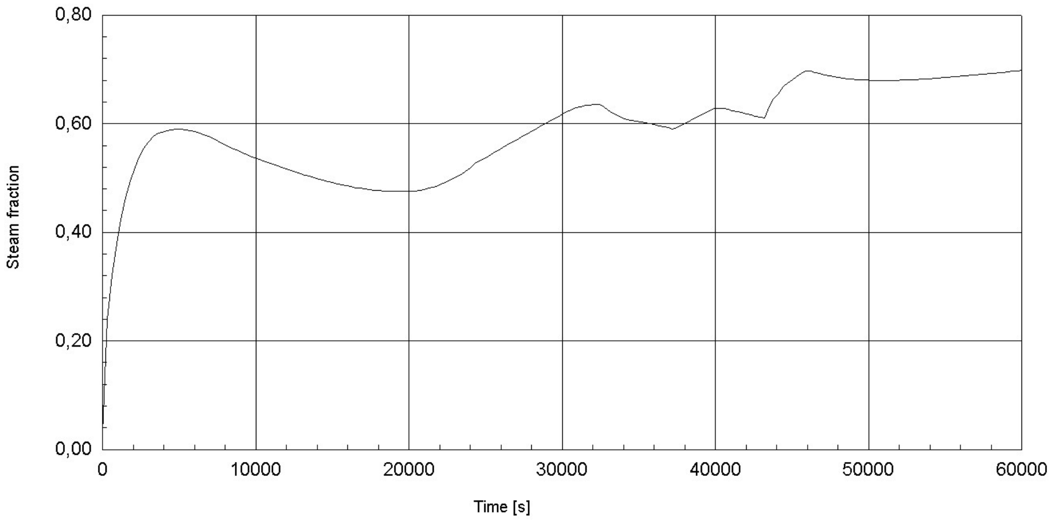

Figure 6. Mole fraction of steam in containment (sequence: S1H1)

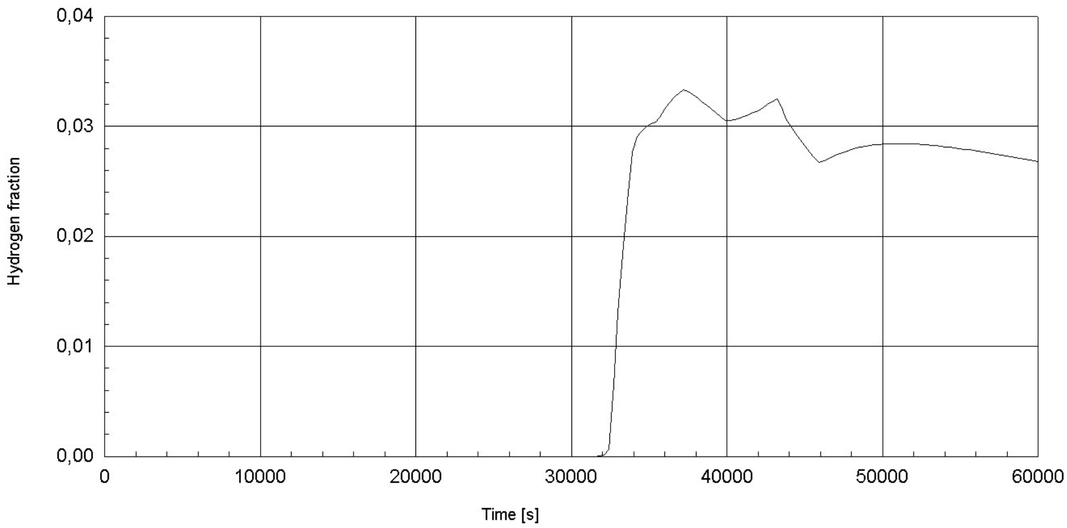

Figure 7. Mole fraction of hydrogen in containment (sequence: S1H1)

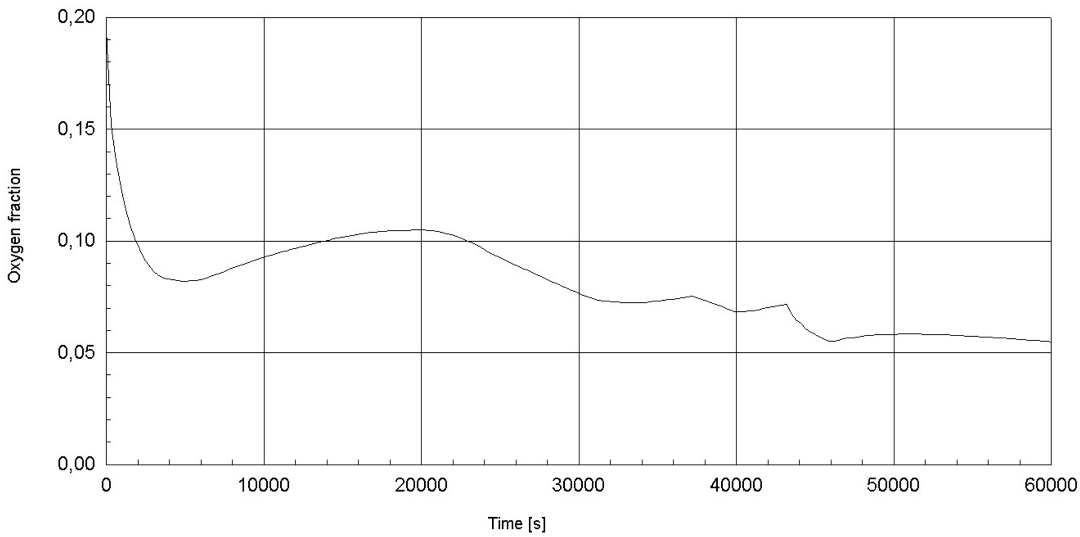

Figure 8. Mole fraction of oxygen in containment (sequence: S1H1)

6.5.2 Modified S1H1 – containment spray enabled.

The S1H1 has been shown not to meet the criteria for hydrogen deflagration. However there is a risk that containment spray is started and if that occurs the deflagration criteria are met and a burnable gas mixture is achieved. In the following recalculation of S1H1 the containment spray is assumed to start at t= 50000 sec. The following figures, Figure 9 - 11 show an environment where deflagration is probable.

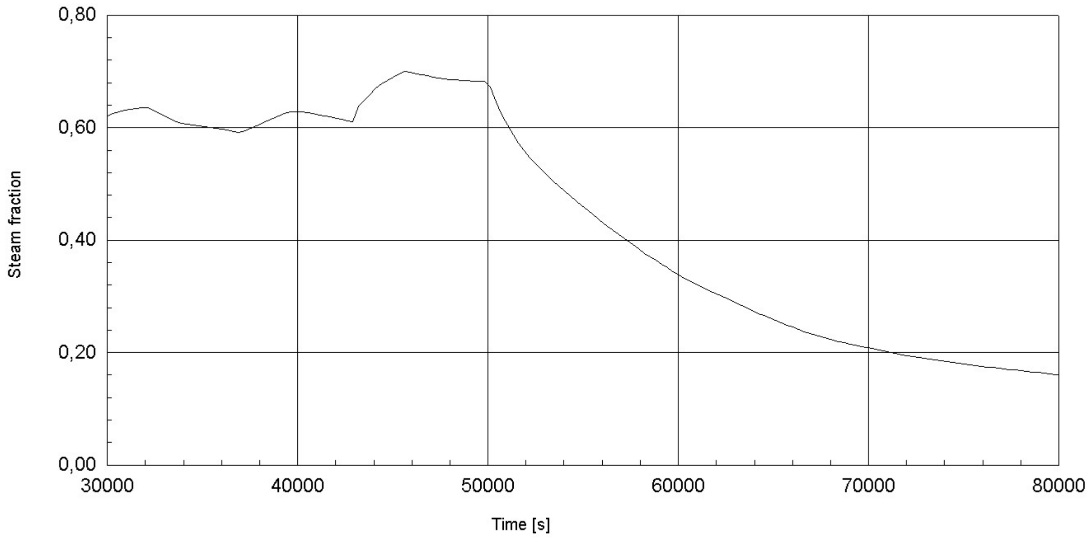

Figure 9. Mole fraction of steam when containment spray is started at t=50000 s (sequence: S1H1-mod)

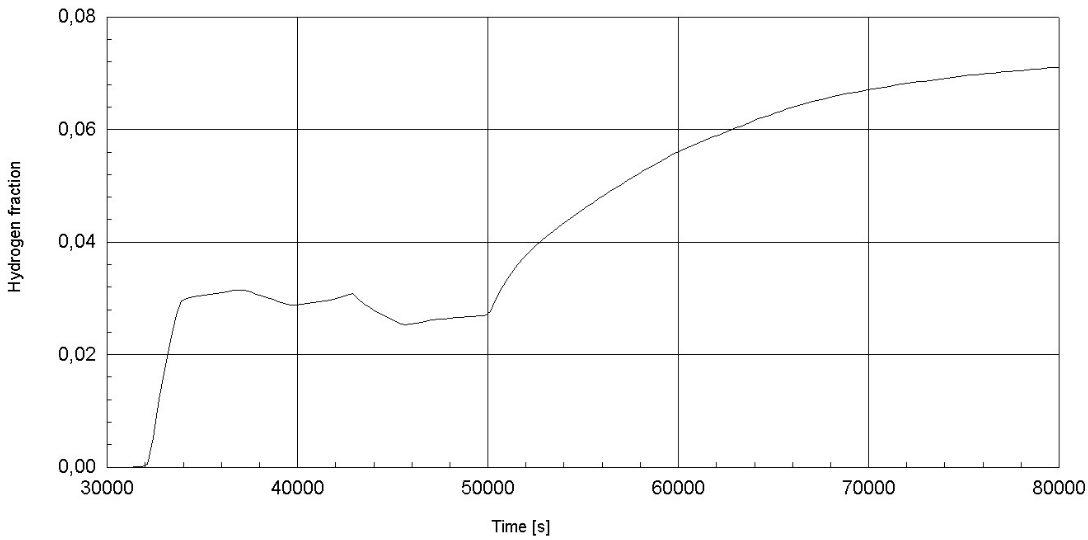

Figure 10. Mole fraction of hydrogen when containment spray is started at t=50000 s (sequence: S1H1-mod)

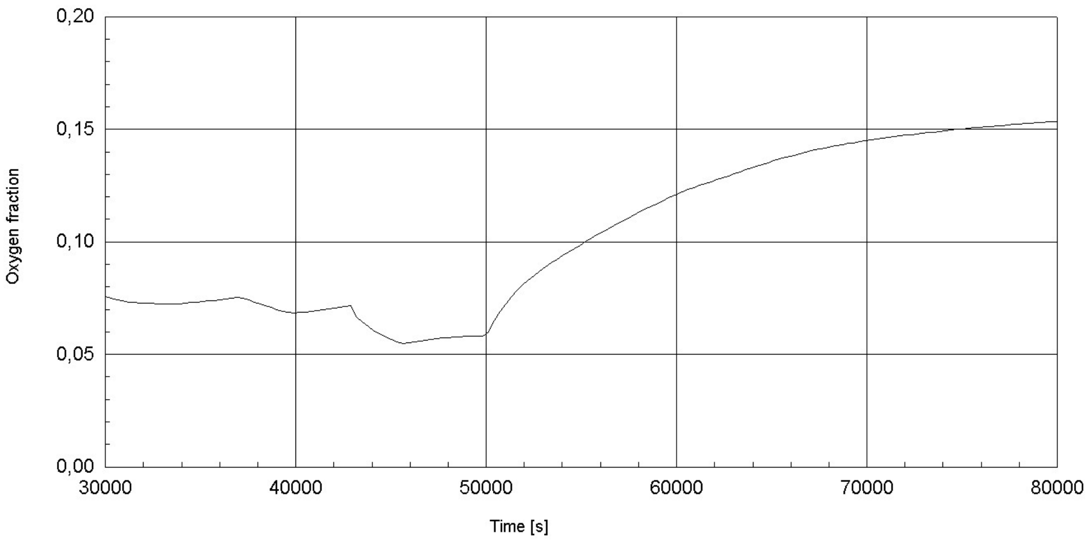

Figure 11. Mole fraction of oxygen when containment spray is started at t=50000 s (sequence: S1H1-mod)

To calculate the total pressure peak in containment the above results are used and are superposed on the initial pressure in containment when the deflagration took place, see Figure 12. These results are used as input parameters in the next section where the pressure peak is calculated.

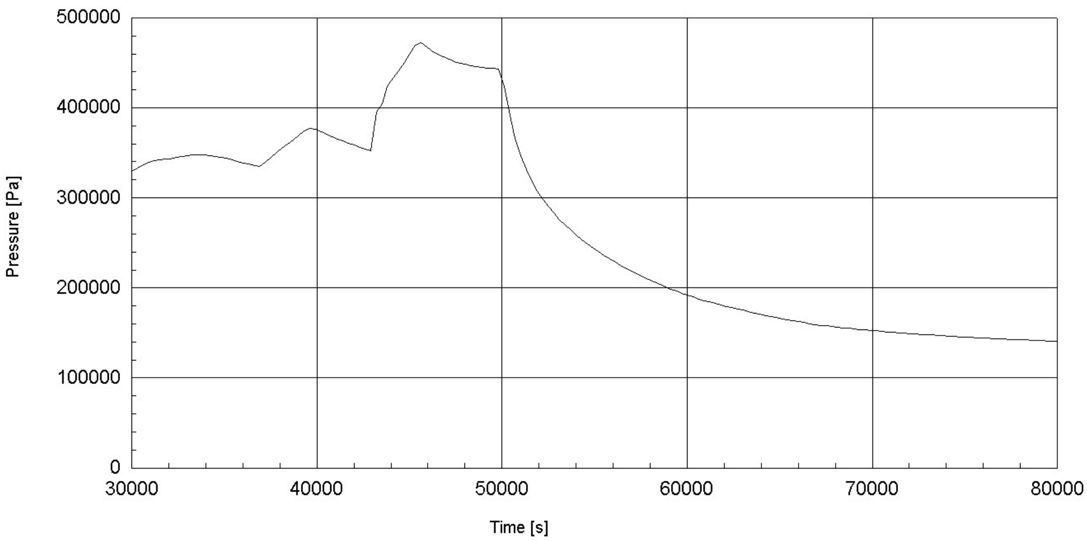

Figure 12. Pressure in containment when spray is enabled at t=50000 s (sequence: S1H1-mod)

6.5.3 Pressure peak in the S1H1 sequence

As discussed earlier the original S1H1 sequence did not bring the gas-mixture into a hydrogen burn mixture. Therefore the sequence was modified to start the containment spray after 13,9 hours. This pressure peak calculation is carried out for that case.

Based on the results from the MAAP calculation it is assumed that a hydrogen deflagration will take place 14.7 hours into the sequence. The following important data are collected from the MAAP results, see Table 5. The results are also shown and discussed in previous section.

Table 5. Data transferred from MAAP to AICC calculation

Variable used in the AICC calculation:	**Data from MAAP:**
Time in sequence	52800 sec
Mole fraction H_2	4,0 %
→ correspond to:	373 kg
Mole fraction N_2	34,7 %
Mole fraction O_2	8,7 %
Mole fraction H_2O	52,7 %
Temperature	384 K
Containment pressure	284 kPa

The AICC calculation gives a post deflagration temperature of 724,8 K, which correspond to a pressure peak of 526 kPa. The analysis shows that the containment is not threatened in this sequence. The estimated containment failure pressure of Ringhals 3 is 0,7 MPa.

6.6 Transient with total loss of feed water and no Feed and Bleed, T3LX4

A transient initiates this event where the main and auxiliary feed water is lost. It is also assumed that the initiation of feed and bleed procedure is not enabled as instructed for this sequence.

As the feed water is lost to the steam generators at time zero the temperature of the primary system rapidly increases. After only 36 seconds the low-level indication in the steam generator will trig a reactor SCRAM. During the following 50 minutes the pressure relief valves will release the excess energy to the containment. The pressure in the containment will increase, see Figure 13. The main coolant pumps will stop as a result of the low water level in the reactor vessel. After 56 minutes the core begins to uncover and oxidation of the zirconium starts and produces hydrogen. The pressure increases due to gases, now blended with small amount of hydrogen, released into the containment. After 1,7 hours the MAAP code calculates a creep rupture on the hot leg. This is however suppressed in this calculation, as we like to have a transient that leads to reactor pressure vessel failure and a large production of hydrogen[2]. When the

[2] A MAAP calculation where creep rupture in the hot leg is actually happening shows a significantly less production of hydrogen.

containment pressure reaches 0.3 MPa the containment spray is started. This will reduce the containment pressure from 2,4 hours into the sequence. Soon after this the reactor vessel fails due to ejection of instrument penetration tubes, time 2,6 hours. Corium is relocated into the dry cavity and more hydrogen is produced through MCCI. A detailed discussion about hydrogen will follow in next section. The integrated mass of hydrogen in the containment is shown in Figure 14. The RWST is empty after 3 hours and the containment pressure will start to increase again. An extensive RPV (reactor pressure vessel) failure occurs after 4,7 hours. This failure does not strongly affect the hydrogen issues or the containment pressure due to the earlier RPV-failure. The main events of the sequence are listed in Table 6.

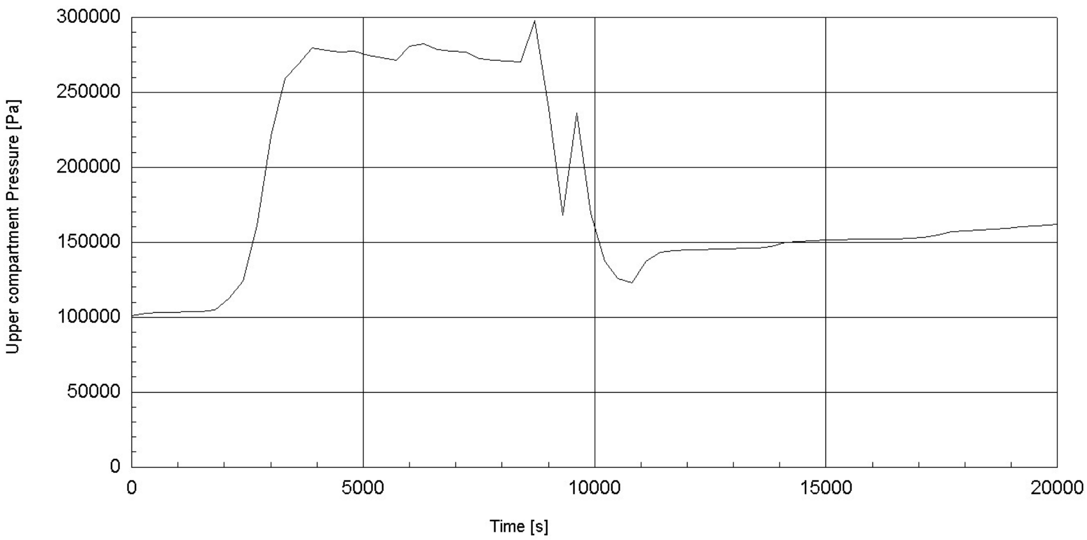

Figure 13. Containment pressure (node: upper compartment) as function of time (sequence: T3LX4)

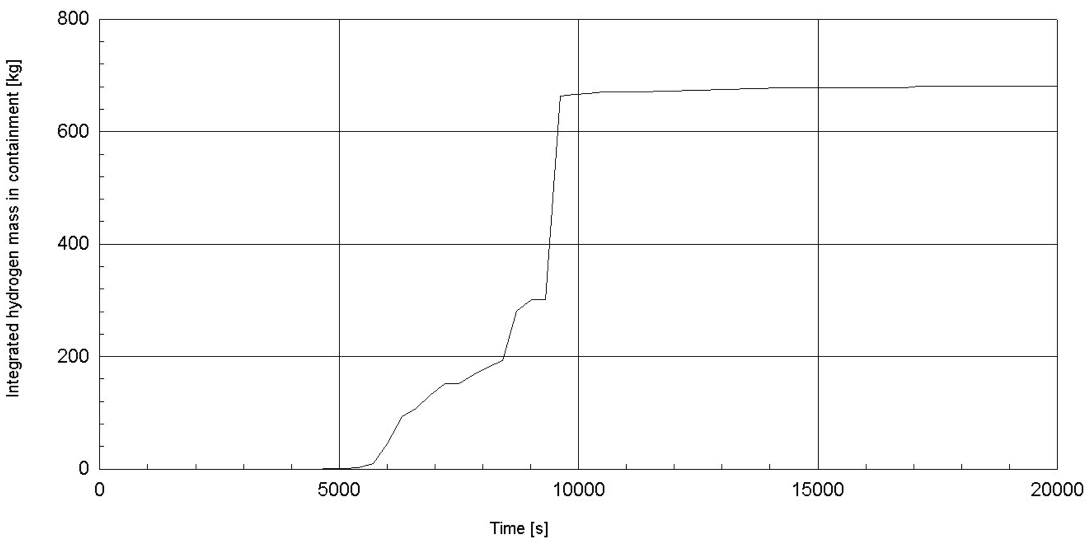

Figure 14. Integrated mass in containment, sum of all hydrogen production phenomenon (sequence: T3LX4)

Table 6. Time of important evens in the T3LX4 sequence

Time [s]	Time [h]	Event according to MAAP
36	0,0	Reactor scram due to low SG water level
1997	0,6	Quench tank rupture disk failed
3386	0,9	Core has uncovered
8594	2,4	Relocation of core material to lower head has started
9473	2,6	RPV failed due to ejection of instrument penetration tubes
9474	2,6	Corium present in cavity
9474	2,6	1^{st} compartment (cavity) corium pool temp. > concrete melt
9475	2,6	Charging pumps on
9475	2,6	LPI on
9498	2,6	Accumulator water depleted
10545	2,9	Charging pumps disabled due to insufficient NPSH
10912	3,0	RWST water depleted
10912	3,0	LPI pumps disabled due to insufficient NPSH
16970	4,7	RPV extensive failure

6.6.1 T3LX4 – results regarding hydrogen content in containment

The transient analyzed is chosen due to the relatively high contribution of hydrogen that comes from the MCCI process. Early in the sequence the pressure in containment increases due to opening of the pressure relief valves. This is seen in Figure 13. The different events can be seen in the graph, the enabled containment spray at 8795 sec and the vessel failure at 9473 sec.

The total hydrogen mass produced in the sequence is shown in Figure 14 and the final total mass, produced in all processes, is 678 kg. It is of interest to note that a large contribution is from the MCCI process. In the following two graphs the origin of the hydrogen is shown, oxidation of Zirconium, see Figure 15, and MCCI in the dry cavity, see Figure 16. Finally there is also a small contribution from oxidation of the metal (mostly Stainless Steel) surfaces, approximately 2 kg – not shown in graph.

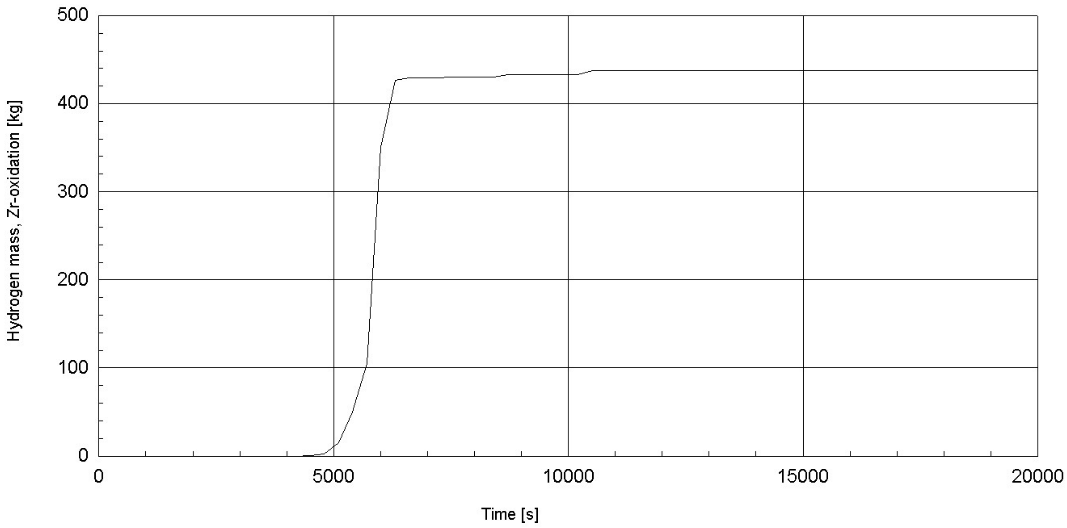

Figure 15. Integrated mass of hydrogen from the Zirconium oxidation (sequence: T3LX4)

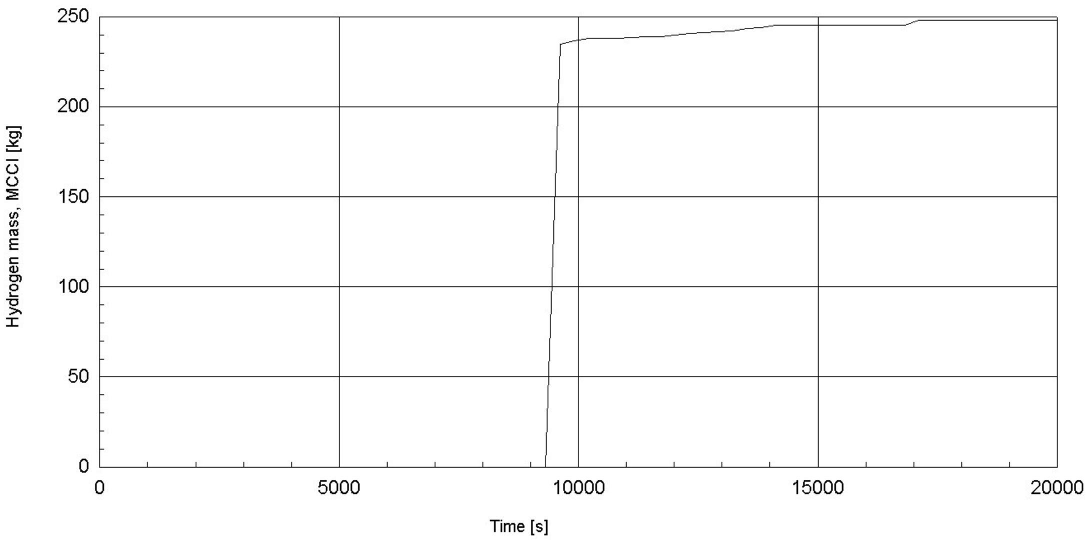

Figure 16. Integrated mass of hydrogen from the MCCI (sequence: T3LX4)

The total mass of hydrogen is an important factor to determine the extension of the possible deflagration if the criteria for hydrogen burn are fulfilled. In the following three graphs the mole fraction of the limiting components in the gas mixture is shown, Figure 17-19. As the graphs show there is a gas mixture that is burnable from about 9000 sec into the sequence. The next information is to study the pressure in the containment to simulate the worst case and let the deflagration occur at a high initial pressure, the containment pressure graph is shown in Figure 13.

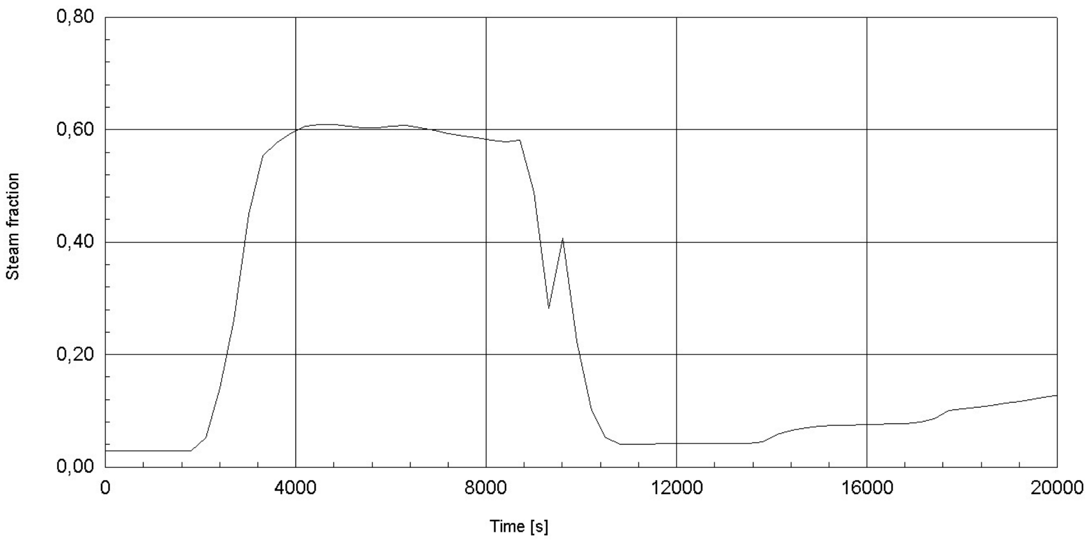

Figure 17. Mole fraction of steam in containment (sequence: T3LX4)

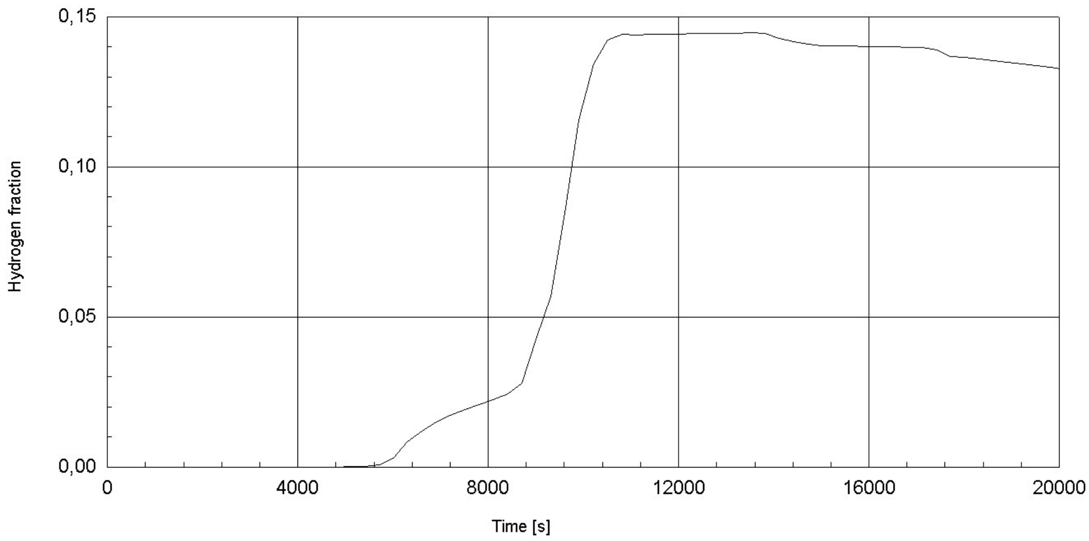

Figure 18. Mole fraction of hydrogen in containment (sequence: T3LX4)

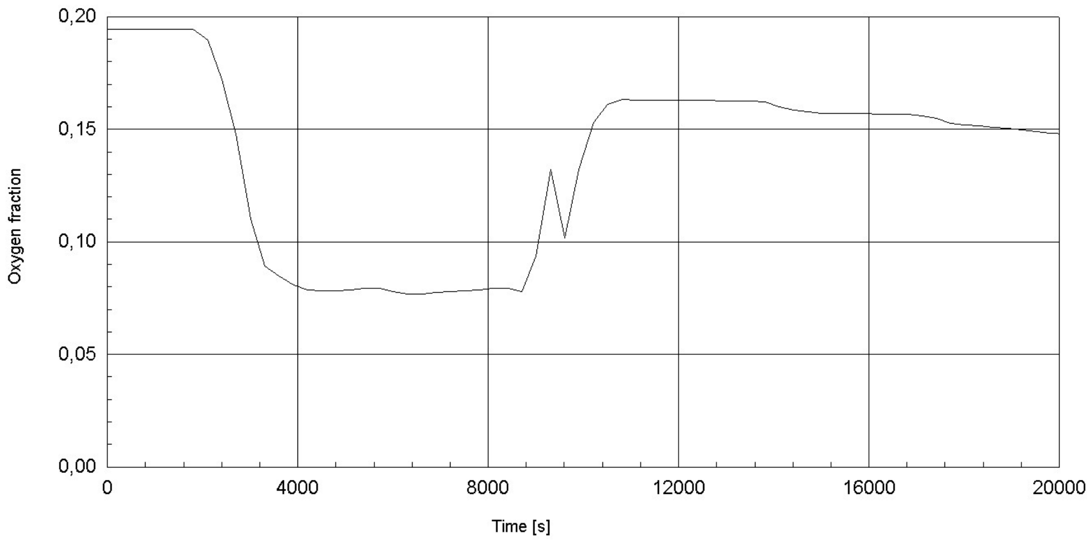

Figure 19. Mole fraction of oxygen in containment (sequence: T3LX4)

6.6.2 Pressure peak in the T3LX4 sequence

The second sequence, the transient, shows a higher integrated mass of hydrogen in the containment – 720 kg. The hydrogen mass production and sequence events have been discussed in previous sections. The MAAP results used in the AICC calculation are presented in Table 7. Two cases are presented, as it will be shown that the peak pressure is dangerously close to the estimated containment failure pressure. The data is collected from the results presented in the previous sections. The reason for the two cases is that there is a large difference in the initial pressure when the pressure peak is calculated. The first case is calculated at the pressure peak, resulting from the RPV failure, but this case has a slightly lower amount of hydrogen in the containment. The second case is calculated at more stable conditions and where the amount of hydrogen is maximized.

Table 7. Data transferred from MAAP to AICC calculation

Variable used in the AICC calculation:	Data from MAAP: (case 1)	Data from MAAP: (case 2)
Time in sequence	9610 sec	17100 sec
Mole fraction H_2	10,4 %	14,0 %
→ correspond to:	663 kg	720 kg
Mole fraction N_2	47,7 %	62,6 %
Mole fraction O_2	11,9 %	15,6 %
Mole fraction H_2O	29,9 %	7,8 %
Temperature	357 K	375 K
Containment pressure	236 kPa	153 kPa

The time of AICC calculation was selected shortly after the reactor pressure vessel failure when a high containment pressure existed, 2,7 hours into the sequence. At this time the spray is reducing the pressure rapidly and the mixture of the gas-mixture in containment is under a rapid transient. Therefore, the result is somewhat uncertain but is still considered to be a good estimate of the maximum pressure peak in the containment. The calculation gives a post deflagration temperature of 1171 K, which corresponds to a pressure peak of 693 kPa.

Due to the high-pressure peak at this time a second time was selected to verify the danger of this sequence. The second case studied was later into the sequence, 4,8 hours into the sequence. At this time the containment pressure was significantly lower but a slightly higher mass of hydrogen was identified in the containment (see maximum integrated mass at sequence in previous sections). Main source to the additional hydrogen is transferred hydrogen to the containment from the reactor vessel. The AICC calculation gives a post deflagration temperature of 1817K, which corresponds to 690kPa.

Both cases studied for this sequence show a maximum pressure peak equal to the containment failure pressure, 0.69 MPa. The latter of the two studied cases is especially important to observe as the temperature is very high and the compressible steam fraction in the gas-mixture is low. Therefore, this case can be a serious threat to the containment.

6.7 Result discussion and summary

In this chapter of the report, analyses of two sequences resulting in hydrogen build-up in containment have been presented. The initial conditions before the hydrogen deflagration have been carried out with the most recent version of the MAAP code. With this initial conditions an AICC direct calculation of the pressure peak has been calculated.

The computational phase of the analysis is considered to be a realistic and correct simulation of two possible severe accident sequences. The assumption that no early hydrogen burn is taking place is a conservative one and should be taken in consideration in the overall conclusion.

The second phase of the analysis, that is a hand-calculation based on rather simple methods with AICC, does include a number of simplifications. With no internal importance the following issues shall be taken in consideration when studying the results:

- ✓ 100% hydrogen content is burnt
- ✓ the burn is instantaneous
- ✓ all energy released is absorbed in the atmosphere as increased internal energy

In addition to this fundamental assumptions a few calculation simplifications have been made, such as calculation of the specific heat capacity for the gas data. The data for the heat capacity is gathered for a predicted temperature and then corrected in one iteration calculation. However it was noted that this correction was of small influence on the final result – especially if set in relation to the three assumptions mentioned above. All the assumptions have been made from a conservative point of view.

The results and initial conditions pre-deflagration for the three cases in the two analyzed sequences are presented in Table 8.

Table 8. Results and initial conditions for AICC

	S1H1 – modified.	T3LX4 –case 1	T3LX4 –case 2
Pre-AICC calculation:			
Mass of Hydrogen	373 kg	663 kg	720 kg
Temperature	384 K	357 K	375 K
Containment pressure	284 kPa	236 kPa	153 kPa
Pressure peak calculated with AICC:			
AICC-temperature	724,8 K	1171,4 K	1817,6 K
Pressure increase	242 kPa	457 kPa	537 kPa
Pressure peak	526 kPa	693 kPa	690 kPa

7 HYDROGEN PRODUCTION IN A CONSERVATIVE CASE

The results from the MAAP code given above are obviously not a worst case. Therefore, a conservative sequence will be set up and investigated concerning production of hydrogen and peak pressure in case of deflagration.

7.1 Hypothetical conservative accident sequence

This scenario will be very briefly described here and has not been simulated by MAAP or any other code. It is assumed that the initiating event is a medium LOCA and that the core is reflooded during a long period. Because of loss of recirculation from the sump, reactor vessel failure occurs late in the sequence. The reactor cavity will be partially filled with water when the reactor vessel fails.

7.2 Hydrogen analysis of the conservative sequence

In the scenario described above the fraction of zirconium oxidation will be high. The reasons for this are that steam will be available for oxidation and a long time elapses from the initiating event to reactor vessel failure. Still there should be some metallic zirconium left in the assemblies at the edge of the core. However this amount of remaining metal is impossible to quantify. Therefore, it is assumed that the zirconium in the core is completely oxidized in this case.

The mass of zirconium in the core of Ringhals 3 is approximately 20 tonnes. A complete oxidation of this amount gives 880 kg hydrogen.

For ex-vessel contributions to the hydrogen production directly after the reactor vessel failure there are, as described earlier in this section, the following three possibilities:

- Reaction of core debris with water
- Core-concrete interaction
- Debris-atmosphere interaction

In the scenario selected here, only the first of these three mechanisms is possible. The main contribution in this case normally comes from oxidation of zirconium in the melt when it falls down into the reactor cavity. However, in our case all zirconium was oxidized before reactor vessel failure. Therefore the only contribution comes from oxidation of other metals, mainly iron.

The amount of hydrogen produced by this mechanism is hard to estimate. Some indication can be obtained from experiments in the FARO programme mentioned above. Another work of interest in this context is [13], which is a review of hydrogen production during melt/water interaction in LWRs. In this report it is suggested that additional oxidation of core material in the lower head will add a few percent to the total hydrogen production. However, no firm upper limit can be supported on the basis on available data and models.

In the conservative case a contribution from oxidation of iron of 100 kg hydrogen will be assumed. No other ex-vessel contributions will be considered. The slow oxidation of zinc and aluminum as well as radiolysis is neglected as hydrogen sources. Therefore, the total amount of hydrogen in the conservative scenario is 980 kg.

7.3 Pressure peak in conservative sequence

An AICC calculation on a hypothetical conservative case like this is connected with several uncertainties. Important data about the gas-mixture is unavailable and this is vital to an AICC calculation. However a calculation has been made on the base of the modified S1H1 sequence, see section 0. The fundamental data have been selected to be the same except of the mass of hydrogen. It is assumed that more than double amount of hydrogen is not changing the gas-mixture – this is a major but deliberate step from the reality. It is done to only have one source of error and to maintain some connection to a real sequence. The change in the AICC calculation is only connected to the additional combustion energy due to the higher amount of hydrogen in the gas-mixture. It can be pointed out that the combustion energy in this case will be a factor of 2,6 more than the internal energy in the gas-mixture, this indicates that the assumption above does not influenced to a great deal on the outcome of the AICC calculation.
The calculation gives a post deflagration temperature of 1317 K, which corresponds to 955 kPa. The latter calculation is however somewhat more uncertain due to the fact that the additional water vapor produced in the gas-mixture is not taken in consideration. However, it is clearly indicating that a containment failure will occur.

8 CONCLUSIONS

The hydrogen issue in case of a severe accident has been studied for Ringhals 3. Several accident sequences with high hydrogen production have been selected and the peak pressure at deflagration has been compared with the containment failure pressure of the Ringhals 3 containment.

The MAAP code has been used to calculate the evolution and specifically the hydrogen production in the different accident sequences studied in the project.

To estimate the peak pressure at hydrogen deflagration after accumulation of large amounts of hydrogen, the AICC (Adiabatic Constant Volume Combustion) method was used. The results obtained by AICC are conservative because the heat losses to structures are neglected and the burning time is assumed to be zero.

Three cases have been analyzed in detail, one LOCA, one transient and a conservative case.

- ✓ In the LOCA case, 373 kg hydrogen was burned and the resulting peak pressure in the containment was 0,53 MPa.
- ✓ In the transient, where 720 kg hydrogen was burned, the peak pressure was 0,69 MPa. This is the same as the failure pressure of the containment.
- ✓ Finally, in the conservative case, 980 kg hydrogen was burned and the resulting peak pressure 0,96 MPa.

However, the results are conservative from two aspects. Firstly, a more realistic (than AICC) calculation of the peak pressure would give a lower value than 0,69 MPa. Secondly, there is conservatism in the evaluation of the failure pressure of the containment.

It should also be noted that a higher failure pressure of the containment has an impact on the probability of containment failure from hydrogen deflagration. In section 2.2 the value $0{,}6 \times 10^{-7}$ /year of that probability was given, estimated from conservative assumptions. A relatively small increase in the failure pressure of the containment would decrease that probability strongly.

9 ACKNOWLEDGEMENTS

The financial contributions from The Nordic Nuclear Safety Research Program, The Swedish Nuclear Power Inspectorate and Ringhals AB are gratefully acknowledged.

The authors are also grateful to Gunnar Jung, SwedPower AB for performing an independent review of the work and for suggestion to improve the report.

10 REFERENCES

1. W. Frid, ”Vätgasförbränning i Ringhals 2,3 och 4 inneslutningar i samband med svåra haverier”, Rapport, BEK-PM 62/86

2. B. Olsson, E. Bergsten ”Ringhals kraftstation B3, Studie av lokala vätgasdetonationer och dess dynamiska inverkan på reaktorinneslutningen”, PM, EV-28/81

3. R. Prior, V. Srinivas ”Ringhals 3, Analysis of the Behavior of Hydrogen in the Containment and Containment Vent System Following a Severe Accident, Sensitivity Studies Report”, Westinghouse Electric Corporation, SEP/87/1037, December 1987

4. R. Prior, V. Srinivas ”Ringhals 3, Analysis of the Behavior of Hydrogen in the Containment and Containment Vent System Following a Severe Accident, Analysis Extension Report”, Westinghouse Electric Corporation, SEP/88/263,May 1988

5. V. Gustavsson, G. Lajtha ”Ringhals 3 – Calculated Peak Pressure in R3 Containment due to Hydrogen Deflagration after a Severe Accident”, Rapport, PK-60/91

6. V. Gustavsson, ”Metod för bestämning av sannolikheten för brott på inneslutningen på grund av vätgasförbränning i PWR” Rapport, PT-131/92

7. V. Gustavsson, ”Ringhals 3- Sannolikheten för brott på inneslutningen på grund av vätgasbrand vid ett svårt haveri” Rapport, PT-75/94

8. V. Gustavsson, K.Hedberg ”Ringhals PWR- Preliminär undersökning av utvädring av vätgas genom skrubbern” Rapport, GES 169/96

9. V. Gustavsson, K. Hedberg, S. Al-Falahi ”Ringhals PWR- Undersökning av utvädring av vätgas genom skrubbern” Rapport, GES 5/98

10. J. Nirmark, ”Ringhals ¾ säkerhetsstudie”, Rapport, PT-11/92

11. MAAP4- Modular Accident Analysis Program for LWR Power Plants, Volumes 1,2,3 and 4, Research Project 3131-02, Computer Code Manual, EPRI, May 1994

12. Handbook of Chemistry and Physics, CRC-Press, 66th Edition, 1985

13. In-Vessel and Ex-Vessel Hydrogen Sources - Report by NEA Groups of Experts, NEA/CSNI/R(2001)15, Oct-2001 (http://www.nea.fr/html/nsd/docs/2001/csni-r2001-15.pdf)

Title	A Study on Hydrogen Deflagration for Selected Severe Accident Sequences in Ringhals 3
Author(s)	Veine Gustavsson & Erik Möller
Affiliation(s)	SwedPower AB, Sweden
ISBN	87-7893-099-5
Date	January 2002
Project	NKS/SOS-2.3
No. of pages	34
No. of tables	8
No. of illustrations	19
No. of references	13

Abstract

In this report, we have investigated the most important severe accident sequences in Ringhals 3, a Westinghouse 3-loop PWR, concerning hydrogen generation and containment pressure at hydrogen deflagration. In order to analyze the accident sequences and to calculate the hydrogen production, the computer code MAAP (Modular Accident Analysis Program) was used. Six accident sequences were studied, where four were LOCA cases and two transients. MAAP gives the evolution of the accident and particularly the pressure in the containment and the production of hydrogen as a function of time. The pressure peaks at deflagration were calculated by the method AICC-Adiabatic Isochoric Complete Combustion. The results from these calculations are conservative for two reasons. Adiabatic combustion means that the heat losses to structures in the containment are neglected. The combustion is also assumed to occur once and all available hydrogen is burned.

The maximum pressure in five analysed cases was compared with the failure pressure of the containment. In the LOCA case, 373 kg hydrogen was burned and the resulting peak pressure in the containment was 0,53 MPa. In the transient, where 720 kg hydrogen was burned, the peak pressure was 0,69 MPa. This is the same as the failure pressure of the containment. Finally, in the conservative case, 980 kg hydrogen was burned and the resulting peak pressure 0,96 MPa. However, it should be noted that these conclusions are conservative from two points of view. Firstly a more realistic (than AICC) calculation of the peak pressure would give a lower value than 0,69 MPa. Secondly, there is conservatism in the evaluation of the failure pressure.

Key words Hydrogen, deflagration, severe accident

Available on request from the NKS Secretariat, P.O.Box 30, DK-4000 Roskilde, Denmark.
Phone (+45) 4677 4045, fax (+45) 4677 4046, e-mail nks@catscience.dk, www.nks.org.