

Research

**Development of an Input Model to
MELCOR 1.8.5 for Oskarshamn 3 BWR**

Lars Nilsson

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SKI Perspective

Background

Assessments of the source term for Swedish nuclear power reactors are based on calculations made by means of the severe accident analysis code MAAP. This code was developed for the US nuclear industry. MELCOR is another code for severe accident analysis, developed by Sandia National Laboratories for the US Nuclear Regulatory Commission (NRC). Both MAAP and MELCOR are integrated codes that simulate the whole course of events in a severe accident from the initiating event to the source term, i. e. radioactive releases to the environment. In Sweden, MELCOR has mostly been employed in some International Standard Problems (ISPs).

In consequence of plans to increase the power in Oskarshamn 3 there is demand for a MELCOR model that can be used for independent analyses of specific limiting transients and accidents.

Objective

The objective was to obtain an executable and complete input model for the Oskarshamn 3 that meets standard requirements for MELCOR 1.8.5. The input should work in steady-state calculations as well as in tentative accident cases. The intention was also to carry out calculations with the MELCOR model of certain accident sequences for comparison with results from earlier MAAP4 calculations. This work will be reported separately.

Results

An input model has been prepared for the Oskarshamn 3 reactor. Demonstrations calculations, at current nominal operating conditions in Oskarshamn 3 for 3300 MW thermal power, were performed for three cases: (1) initial, steady-state conditions, (2) total loss of AC power and (3) large steam line LOCA. The results are presented in the report.

Project information

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This report concerns a study which has been conducted for the Swedish Nuclear Power Inspectorate (SKI). The conclusions and viewpoints presented in the report are those of the author/authors and do not necessarily coincide with those of the SKI.

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- C. MELCOR 1.8.5 Input files for Oskarshamn 3 BWR. NONBH version, Case specific input for Case 2; Steam Line LOCA.
- D. MELCOR 1.8.5 Input files for Oskarshamn 3 BWR. BH specific version, Case 1; Total Loss of AC Power.

Abstract

An input model has been prepared to the code MELCOR 1.8.5 for the Swedish Oskarshamn 3 Boiling Water Reactor (O3). This report describes the modelling work and the various files which comprise the input deck. Input data are mainly based on original drawings and system descriptions made available by courtesy of OKG AB. Comparison and check of some primary system data were made against an O3 input file to the SCDAP/RELAP5 code that was used in the SARA project. Useful information was also obtained from the FSAR (Final Safety Analysis Report) for O3 and the SKI report "2003 Störningshandboken BWR".

The input models the O3 reactor at its current state with the operating power of 3300 MW_{th}. One aim with this work is that the MELCOR input could also be used for power upgrading studies. All fuel assemblies are thus assumed to consist of the new Westinghouse-Atom's SVEA-96 Optima2 fuel.

MELCOR is a severe accident code developed by Sandia National Laboratory under contract from the U.S. Nuclear Regulatory Commission (NRC). MELCOR is a successor to STCP (Source Term Code Package) and has thus a long evolutionary history. The input described here is adapted to the latest version 1.8.5 available when the work began. It was released the year 2000, but a new version 1.8.6* was distributed recently. Conversion to the new version is recommended.

In version 1.8.5 there is an option to describe the accident progression in the lower plenum and the melt-through of the reactor vessel bottom in more detail by use of the Bottom Head (BH) package developed by Oak Ridge National Laboratory especially for BWRs. This is in addition to the ordinary MELCOR COR package. Since problems arose running with the BH input two versions of the O3 input deck were produced, a NONBH and a BH deck. The BH package is no longer a separate package in the new 1.8.6 code, but its models are incorporated in the COR package.

Two demonstration runs with the NONBH version were carried out, a total loss of power case and a case simulating a large steam line LOCA. The results are briefly presented and discussed in the report.

Complete lists of the input files can be found in the appendices. However, the appendices are not included in the report for disclosure reasons.

The work was done under contract from the Swedish Nuclear Power Inspectorate.

*) During the writing of this report still another code version, MELCOR 2.0, has been announced to be released within short.

Sammanfattning

Rapporten beskriver framtagningen av en indatamodell till koden MELCOR 1.8.5 för kokvattenreaktorn Oskarshamn 3. Indata har delats upp i ett antal delfiler som motsvarar en eller flera av de delrutiner som MELCOR-koden består av.

Indata baseras i första hand på originalritningar och systembeskrivningar som ställts till förfogande av Oskarshamns Kraftgrupp AB (OKG). Data för primärsystemen har kunnat jämföras med en indatafil för O3 till koden SCDAP/RELAP5 som använts i EU-projektet "SARA", där bl a SKI deltog. Vissa uppgifter har kunnat hämtas från FSAR för O3 och även från SKI-rapporten "2003 Störningshandboken BWR".

Modelleringen har gjorts för O3 reaktorns nuvarande drift med 3300 MW_{th}. Avsikten är dock att grundmodellen ska kunna användas även för studier av aktuella effekthöjningar. Härdmodellen har sålunda gjorts med antagande av att alla patroner är av typen Westinghouse-Atoms SVEA-96 Optima2.

MELCOR är ett datorprogram för beräkning av svåra haveriers förlopp i lättvattenreaktorer och som utvecklats av Sandia National Laboratory på uppdrag av amerikanska kärnkraftinspektionen NRC. Indatamodellen för O3 togs fram för den senaste MELCOR-version 1.8.5 som fanns tillgänglig vid uppdragets början. En ny version, 1.8.6* har nyligen börjat distribueras.

Version 1.8.5 av MELCOR har en extra modell, BH (Bottom Head) som är avsedd för noggrannare beräkning av förlopp i nedre plenum och av tankgenomsältning än som görs med den ordinarie COR-modellen. BH-modellen har utvecklats av Oak Ridge National Laboratory (ORNL) speciellt för BWR och är ett tillägg till COR-modellen. Emellertid uppstod problem att genomföra beräkningarna med BH-modellen vilka inte kunde lösas inom projektet. Eftersom den separata BH-rutinen har slopats i den nya kodversionen 1.8.6, och ORNLs modeller inarbetats i COR-rutinen, rekommenderas att de här framtagna indatafilerna för O3 konverteras till den nya kodversionen.

Beräkningar med MELCOR 1.8.5 genomfördes av två haverisekvenser, totalt elbortfall samt stort brott på en ångledning (LOCA) som demonstrationsfall. Resultaten presenteras och diskuteras i rapporten.

Komplett utskrift av alla indatafiler finns i Appendix A-D. Dessa bilagor har utelämnats i rapporten med hänsyn till sekretess.

Arbetet har genomförts på uppdrag av Statens Kärnkraftinspektion, SKI.

*) Under rapportskrivningen har det kommit till kännedom att en nyare kodversion, MELCOR 2.0 snart kommer att vara tillgänglig.

1 Introduction

Severe accident analyses and assessments of the source term for Swedish nuclear power reactors are based mainly on calculations made by means of the severe accident analysis code MAAP. This code was developed for the US nuclear industry. MELCOR [Ref. 1] is another code for the same applications, developed by Sandia National Laboratories for the US Nuclear Regulatory Commission (NRC). Both MAAP and MELCOR are integrated codes that simulate the whole course of events in a severe accident from the initiating event to the source term, i. e. radioactive releases to the environment. In Sweden, MELCOR has mostly been employed in some International Standard Problems (ISPs).

In consequence of plans to increase the power in Oskarshamn 3 there is demand for a MELCOR model that can be used for independent analyses of specific limiting transients and accidents. An input model to MELCOR 1.8.5 has earlier been produced for Ringhals 3 by Lentek [Ref. 2].

The objective was to obtain an executable and complete input model for the Oskarshamn 3 that meets standard requirements for MELCOR 1.8.5. Although MELCOR is originally made for parametric studies the code has been successively developed towards a so called “best estimate” code. Therefore, default and recommended input parameters were used as far as possible.

The report describes the input preparation and the modelling of the different systems in Oskarshamn 3. The input is divided in a number of subfiles for one or more of the model packages which constitute the MELCOR code. Two demonstration calculations were performed and the results are presented and discussed.

2 Oskarshamn 3 BWR

The Oskarshamn 3 (O3) Boiling Water Reactor (BWR) is located on the Baltic coast about 25 km north of the town of Oskarshamn in Sweden. It is the largest of the three BWRs at the site, all operated by the OKG AB utility. The O3 reactor was supplied by ASEA-Atom (now Westinghouse-Atom AB) and was taken into operation in 1985.

O3 is an advanced 3300 MW_{th} BWR with eight internal recirculation pumps. Operating pressure is 7.0 MPa. The core has 700 fuel elements and 169 control rods with B₄C as absorber material. The reactor vessel is about 21 m high and has an inside diameter of 6.4 m. The 150 mm thick wall consists of carbon steel clad by stainless steel on the inside.

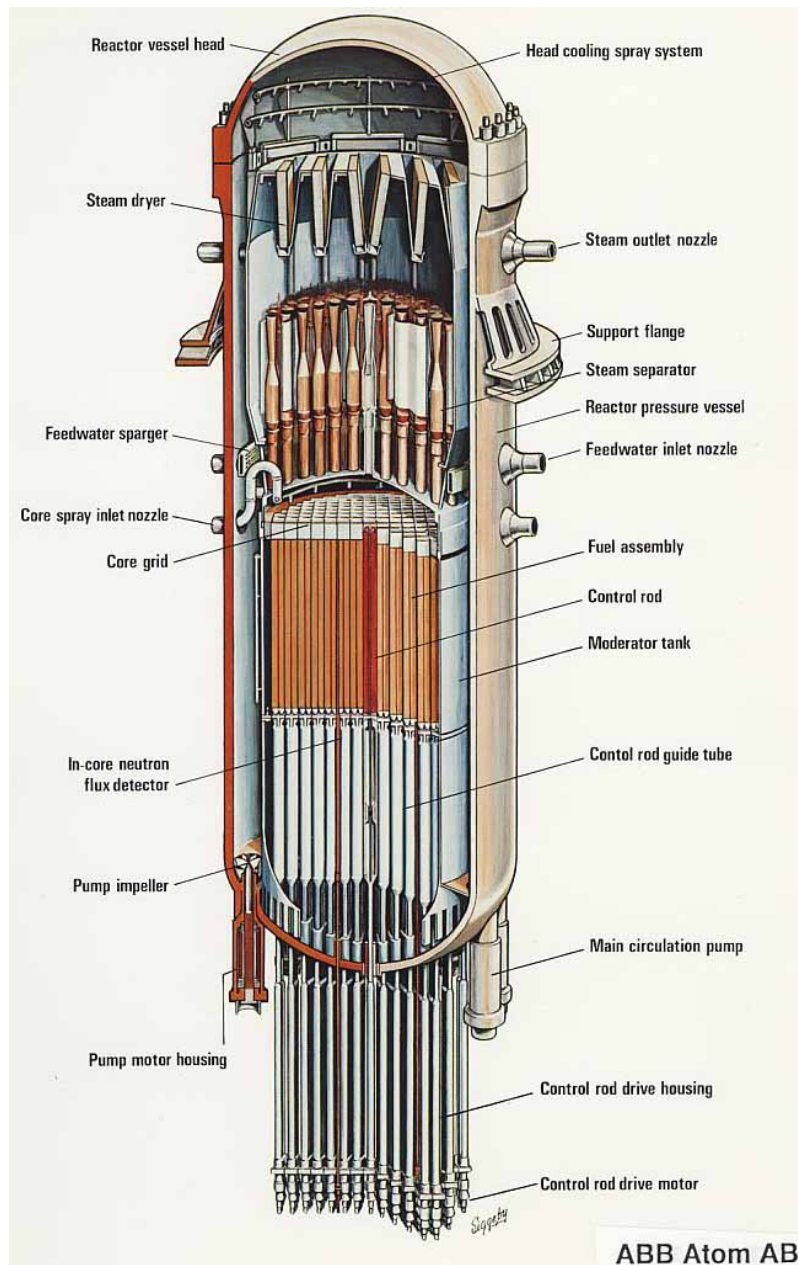


Figure 1. Reactor Vessel and Internals

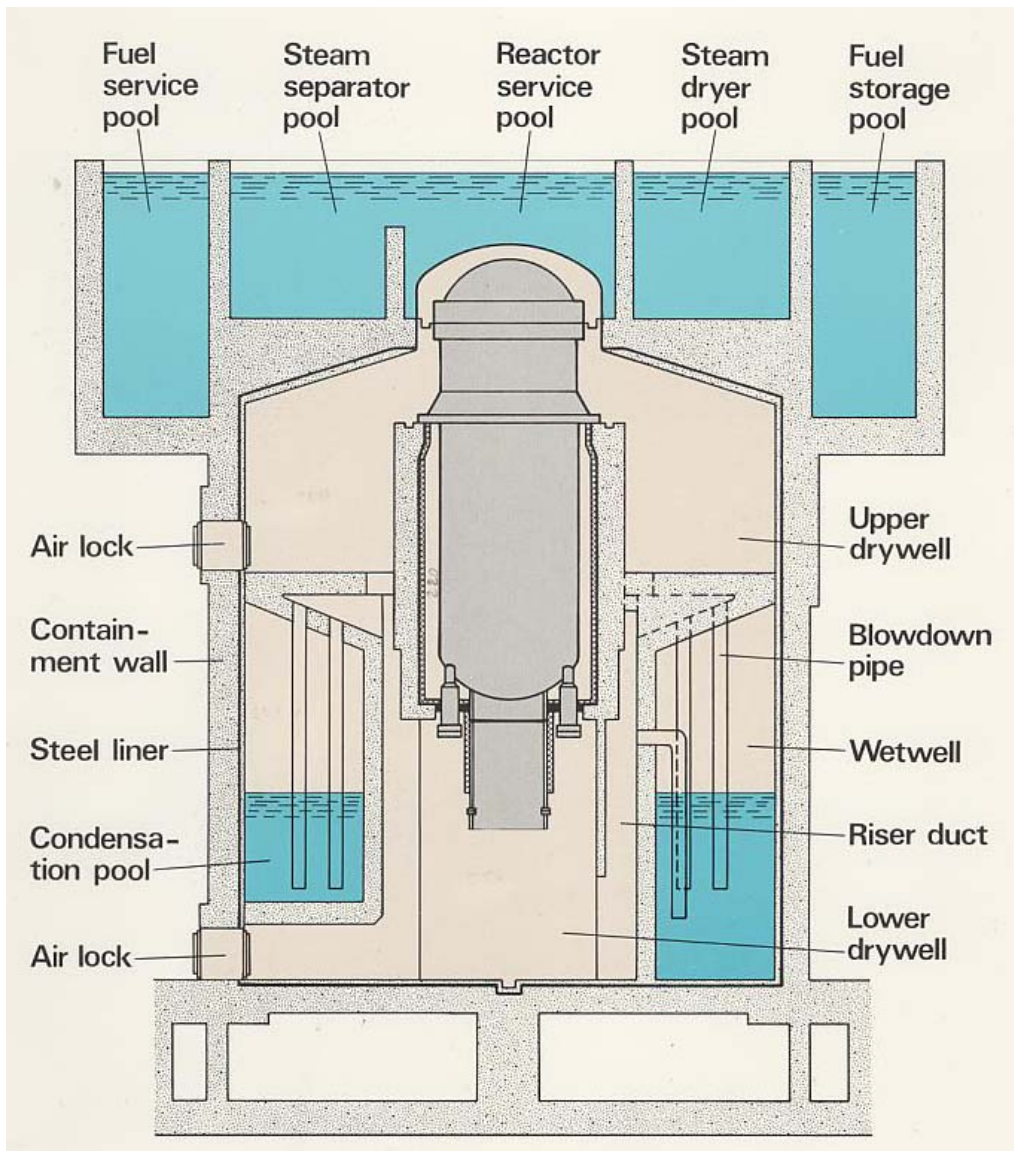


Figure 2. Principal sketch of the reactor containment

The reactor containment is of the Pressure Suppression (PS) type with vertical blowdown pipes. The outer cylindrical shell of pre-stressed concrete has a height of about 30 m and a diameter of 25.5 m on the inside. It is sealed at the top by a large steel cupola to the reactor service pools above the containment. The containment also functions as a radiological shield to the environment. The gas volume is filled with nitrogen to prevent ignition of hydrogen if such would be generated in case of a severe accident.

The design pressure of the containment is 0.6 MPa. Two different venting systems are installed to prevent overpressurization. A pipe system with rupture disk that bursts at a pressure of 0.5 MPa facilitates filtered venting of the containment through the Multi-Venturi Scrubber (MVSS). If the containment pressure exceeds 0.65 MPa another rupture disk opens for venting directly to the atmosphere.

2.1 Safety Systems – brief description

This brief description of the safety systems is focusing on safety functions which are relevant for severe accident studies and which are taken into account in the MELCOR model.

At normal operation any disturbance is surveyed and correction made by automatic functions controlling reactor power, ensuring sufficient cooling and preventing radioactive releases through safeguard measures. If an abnormal failure or accident occurs there are a number of diverse safety systems which will be activated. A basic design principle is to have a high degree of redundancy and many safety functions are thus distributed on four independent subsystems.

To make a severe accident possible some of the safety systems must fail. The condition assumed here is loss of power to all cooling systems, possibly in combination with other failures as a pipe break, Loss of Coolant (LOCA) as initiating event. Some assumptions may not always be realistic, or might have very low probability, but can be of interest for parametric studies.

As a consequence, the Emergency Core Cooling Systems (ECCS), systems 323 and 327 are assumed to fail, and are not considered in the MELCOR model. System 323 is the low pressure core cooling system that begins to inject water when the back pressure goes below about 0.12 MPa and has a full capacity of around 360 kg/s per each of the four loops. Two loops inject water as top spray above the core and two loops feed into the downcomer facilitating reflooding of the core from the bottom. The high pressure system 327, the auxiliary feed water, has also four loops, all going to top spray nozzles above the core. The capacity is there totally 90 kg/s almost independent of back pressure.

The safety systems considered for the MELCOR model are:

- The hydraulic fast actuating power shut-off system 354 (scram system) which gives full insertion of all control rods in less than 6 s after initiation. (There is also a manually activated boron shut-off system, not considered here). Scram is automatically initiated if certain conditions are fulfilled. The rather complicated control system is not modelled, instead scram conditions are set by simple control functions and the conditions are either isolation signal caused by high containment pressure, or a preset time delay.
- Pressure control and relief system 314. Sixteen valves connect to the four steam lines and the outlet pipes are forked into 64 blowdown pipes ending in the wetwell (WW) pool. Should the turbine valves close, if steam dump is not possible and after isolation of the steam lines, the 314 valves will automatically control the pressure at 7.0, maximum 7.05, MPa by steam relief to the WW. When low downcomer water level is reached system 314 will act as ADS, Automatic Depressurization System. Eight valves then open with full capacity and decrease the reactor pressure to facilitate operation of the low pressure ECCS. The ADS is initiated upon low DC level, L4, 0.5 m above core exit

combined with an environmental condition, i. e. high containment pressure. A delay of 10 minutes has been introduced before ADS opening.

- Pressure Suppression (PS) Condensation system 316 in the containment described above. This is an inherently passive system designed to limit the containment pressure. Steam leaking or blown out from the primary system to the drywell is discharged through the 24 blowdown pipes into the wetwell pool where it is condensed. Vacuum valves in eight large pipes between wetwell and lower drywell ensure that the wetwell pressure will not be higher than that in drywell.
- Containment spray, system 322. It consists of four loops with coolers, all taking water from the wetwell pool. The maximum capacity of each loop is 100 kg/s. Two loops feed spray nozzles in the upper drywell and the two others go to nozzles in the gas volume above the wetwell pool. The latter are working under normal operation to control the pool temperature at 20 C and for adjustments of the pool level. The safety functions of system 322 are to reduce the containment pressure and condense steam in the atmosphere in case of a LOCA, and to wash out aerosols that might leak out from the vessel.
- There are several other safety systems and functions to maintain the integrity of the containment, such as system 358 for flooding of lower drywell from the wetwell pool and system 362, the MVSS. These and their modelling in MELCOR are described further in section 5.3.

3 The MELCOR 1.8.5 Code

The MELCOR code [Ref. 1] is developed by Sandia National Laboratory (SNL) under contract from the U.S. Nuclear Regulatory Commission (NRC). MELCOR is a successor to STCP (Source Term Code Package) and has thus a long evolutionary history.

MELCOR is a fully integrated code that models all phases of severe accident progression in a LWR plant. It is a so-called lumped parameter code, i.e. zero-dimensional with respect to the modelling of hydrodynamic volumes. Thermodynamic state properties are then given in one point in each cell of the volume and considered as constant within the volume. The spatial geometry is given in input as a volume/altitude table. Each volume can have a pool and an atmosphere fraction; the latter can consist of steam and a number of non-condensable gases. Two-phase models allow for steam bubbles in the pool and water droplets, “fog”, in the atmosphere. If the non-equilibrium thermodynamics option is chosen, different temperatures and phase conditions can exist in pool and atmosphere. Space can also be occupied by other material, e.g. core structures which can melt and relocate. This is named the *virtual volume* that can change the original free volume available to hydrodynamic materials.

Through connections with flow paths having lengths and inclinations sort of a three dimensional model of the reactor system can be built. The code comprises a driver module and a large number of various model packages, such as the control volume hydrodynamics package, flow path, core description, heat structure, radionuclide package, etc. The number of packages, which are engaged in the execution, is dependent on the problem to be solved.

Various severe accident phenomena in both PWRs and BWRs can be treated by MELCOR. Version 1.8.5 includes models for, among others, the following:

- Thermal-hydraulic response in the reactor coolant system, reactor cavity, containment and confinement buildings.
- Core heat-up, degradation and relocation.
- Core-concrete attack.
- Hydrogen production, transport and combustion.
- Fission product release, transport, and deposition.
- Impact of engineered safety features on thermal-hydraulic and radionuclide behaviour and on hydrogen combustion.
- Passive Autocatalytic Hydrogen Recombiner by the PAR package
- A Bottom Head package developed by Oak Ridge National Laboratory especially for detailed modelling of melt progression in a BWR lower head.

MELCOR calculations are executed in two steps, MELGEN and MELCOR. MELGEN is the input processor to which the majority of the input is written. It carries out the input check, and if the input is accepted it writes preliminary initial conditions to a

restart file. MELCOR then needs only a short input, mainly time-step and execution parameters for the transient calculations. Only few input data can be changed in the MELCOR input.

MELCOR runs produce a number of output files; a diagnostic (.DIA) file displaying input errors and non-fatal warnings to assist the user in debugging the input, an output text file (.OUT), a binary restart (.RST), a plot file (.PTF), and a message file (.MES). The latter announces major events in the accident progression and by means of control functions the user can flag for events of special interest such as valve actuations, containment failure, etc.

The code package also includes a graphics processor HISPLT, retained from earlier versions and which needs a special input. However, plotting is more conveniently made directly from the plot file by means of the general graphics code XMGR5, or its successor ACGRACE. Figure 3 below illustrates the relation between the various codes and files in the MELCOR package.

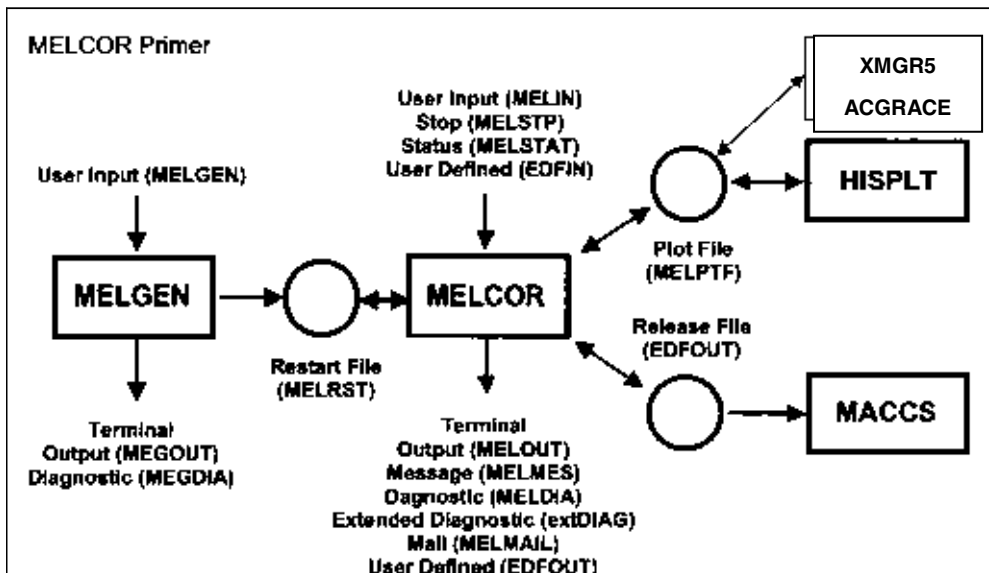


Figure 3. Relationship between the various codes and files in MELCOR

MACCS calculates off-site consequences of radioactive releases, i.e. from the source term, to the environment. The file names shown in the figure are default names which can be optionally changed by the user.

The latest released version, available to present project, was MELCOR 1.8.5, denoted “BASE CODE VERSION 1.8.5(A), SEP –25-2000, BASE CODE QZ”. This version was distributed at the 5th MELCOR User’s Workshop, May 10-15, 2001 in Bethesda, MD, USA.

A new code version, MELCOR 1.8.6 presented at the year 2005 MELCOR users workshop was released recently. This version has incorporated the Bottom Head model into the COR package. A 1.8.5 input deck needs a certain degree of upgrading before it can be run with the new code version.

4. Basic information and data used for the Oskarshamn model

The MELCOR input model of the O3 hardware is mainly based on original drawings and system descriptions made available by courtesy of the utility OKG AB [Ref. 3]. Other major sources of information are:

- FSAR (Final Safety Analysis Report). The latest, revised edition [Ref. 4] was studied at SKI and information relevant to the input preparation was recorded. This comprises various system descriptions and important flow diagrams. Complementary and some updated system descriptions were later obtained from OKG.
- Fuel data for the new core loading containing SVEA-96 Optima2 assemblies were made available by favour of the department of Core and Fuel Management of OKG (Classified information).
- An input file for O3 to the Severe Accident Code SCDAP/RELAP5 that was used in the EU project SARA sponsored by SKI [Ref. 5]. The SARA input models only the primary system. Since it has been quality assured it could be employed for checking of some corresponding data in the MELCOR input deck.
- The so called “2003 Störningshandboken för BWR” (BWR disturbance response handbook) [Ref. 6].

An input file for the Finnish Olkiluoto-1 BWR made available by SKI was also of some help. The Finnish deck is an updating from input to older versions of MELCOR and lacks input to the Bottom Head package.

Appendix A contains a compilation of hardware data derived from the different sources fitted to MELCOR input format.

5. Input Modelling

5.1 Organisation of the modelling work

Since the MELCOR code consists of a number of model packages, and a full plant input is rather comprehensive, it was found suitable to spread the input set over a number of files corresponding to one or more of the MELCOR packages. These plant input files are called by the “R*I*F” command in the MELGEN execution file here named “O3init”. The MELCOR input is written to a separate file “O3melcor”. The files were edited in simple text format, (.txt).

The description of the input preparation is here divided into sections, one for each of the following files:

- O3primsyst** Input to the Control Volume Hydrodynamics (CVH), the Flow Path (FL) and the Heat Structure (HS) packages for the reactor vessel with steam lines.
- O3core** Input to the COR package for the reactor core and lower plenum. This file has also input to the Transfer Process (TP) package which is needed as an interface for transfer of core debris between other packages, viz. the COR, the Fuel Dispersal Interactions (FDI) and the Cavity (CAV) packages.
- O3dch-rn** Decay Heat (DCH) and RadioNuclide (RN) packages input. These together specify the composition of radionuclides and their spatial distribution, among others, the power distribution in the core.
- O3cont** Input for the containment to the packages CVH, FL, HS, the Containment Spray (SPR) and to the CAV packages.
- O3cf** Control Function (CF) input, especially for valves and pipes and safety systems in the containment. This file also contains CFs which have to be built in order to produce certain plot variables not provided otherwise by the code. Additional plot variables can be defined here.
- O3material** Physical property data of a large number of materials are stored in the MELCOR data base. Any other material can be introduced by denoting it a name and specifying the properties needed. Ascending numbers from 1 and up are used for water and fluids in free spaces, i. e. in pools and in the atmosphere, to represent material in the CVH package. The numbers 1 through 3 are reserved for water, 1 for liquid (pool), 2 for mist and 3 for steam. Numbers from 4 and higher are used for non-condensable gases for which the number and material mnemonic have to be specified in the Non-Condensable Gas (NCG) input.

- O3init** File for initiation and case specific input. Here are the Execution (EXEC) parameters, the NCG and calls by the R*I*F command to the other input files given. This file contains also case specific input in form of Control Functions and Table Function(TF) which defines the transient to be calculated.
- O3bh** Input to the Bottom Head (BH) package that is based on the model developed by Oak Ridge National Laboratory especially for BWRs. This package models the vessel parts below the core support plate, i. e. the lower plenum and the lower head vessel wall and is intended to give a more detailed simulation of the damage progression there than the COR package does.

The input set can be executed with or without the BH package input. Without BH input the melt progression in lower plenum and the melt-through of the lower head is calculated by the COR package. If the BH input is included this calculation is done by the BH package provided that certain parameter values in the COR input are changed. It was therefore considered convenient to make two complete input sets, one “NONBH” and another “BH” input deck.

The preparation of the Oskarshamn 3 input is as far as possible made according to the recommendations in the user’s manual, i. e. default values were normally used for parameters whose value can be chosen by the user. The basic input parameters are given by the Control Volume (CV), the Flow Path (FL) and the Heat Structure (HS) data, which together describe the major reactor system, except for the core for which dimensions and structure data are specified by the COR input.

The nodalization for the reactor vessel is shown in Figure 4. Figure 5 illustrates the cross sectional division of the core. Figure 6 shows the nodalization of the containment. The MELCOR model for Ringhals 3 comprises totally 25 control volumes, 47 flow paths and 61 heat structures. The different input records are characterized by a MELCOR package identifier (e.g. CV for the Control Volume package), followed by a component number and a record type identifier. Component numbers are assigned three digits for CV and FL and 5 digits for HS. The leading, first digit was chosen to be 1 for the primary system, 2 for containment, 3 for safety and auxiliary systems, 8 for the MVSS and 9 for the environment. In addition, control volumes can be assigned a system number by the “CVTYPE_{enn}” record. Here number 1 was used for the primary system, 2 = containment, 3 = MVSS, 4 = environment and 5 = feed water source.

All elevations must refer to a common reference point, which in the MELCOR model was chosen to be at the bottom, inside of the reactor vessel. The elevations of the O3 buildings in OKG drawings refer to another level, probably the sea level. Thus the following relation is valid:

$$z(MELCOR) = z(OKG) - 116.338 \text{ m}$$

Main input data for control volumes, flow paths and heat structures are listed in Tables in Appendix A.

Only those safety systems which might be active in a severe accident are modelled. Therefore the core cooling system 323, the auxiliary feed water system 327, or the boron injection system 351 are not taken into consideration.

5.2 Reactor Vessel and Primary System (File O3prim syst)

Data of thermodynamic volumes, flow paths and heat structures are input in this file, except for the structures in the core and in lower plenum which are specified in the O3cor file. Volumes within the reactor vessel and in the steam lines to the inner isolation valves are included. The nodalization diagram for the vessel is shown below.

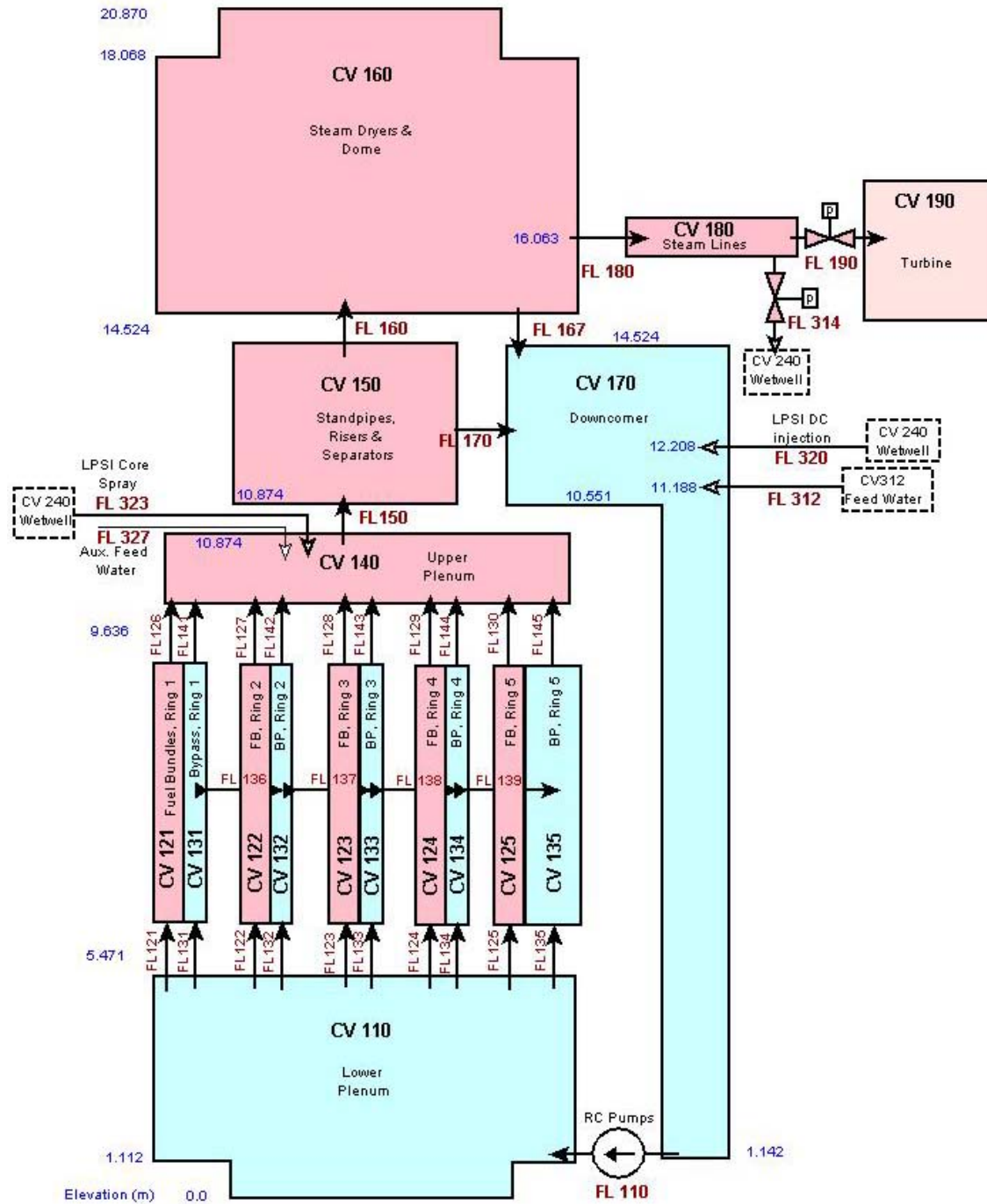


Figure 4. MELCOR Nodalization of the O3 Reactor Vessel

The main components are the reactor pressure vessel with its eight internal recirculation pumps, the moderator tank with its support vessel, reactor core, control rod guide tubes, steam separators, steam dryers and the annular downcomer region. Outer systems, modelled here, are only the steam lines up to the isolation valves inside the containment. Other connecting pipes as for feed water and safety injection are modelled in the file “O3init”. Some crucial dimensions of the vessel are given below:

Table 1. Main dimensions of the reactor vessel and primary system (Nominal at 20 °C)

Inside height of pressure vessel	20.870 m
Inside diameter of pressure vessel	6.428 m
Wall thickness of pressure vessel incl. SS plating, cylindrical part	0.161 m
Wall thickness of pressure vessel incl. SS plating, bottom head	0.168 m
Inner/outer diameter of moderator tank support	4.815/4.895
Inner/outer diameter of moderator tank	5.094/5.174
Number of control rods (Control rod guide tubes)	169
Number of steam separators	165
Number of steam lines	4
Total free volume in vessel, excluding steam lines	547.5 m ³
Volume in steam lines up to isolation valves	Appr. 23.0 m ³

The pressure vessel wall material is carbon steel (ASME SA 508 and SA 533) with a 5 mm stainless steel welded plating on the inside. The bottom head has furthermore a 7 mm plating of manganese steel in between. The thermal insulation of the reactor vessel below the tank support skirt is not applied directly on the outer wall but on the inside of the biological shield with a 580 mm gap between to allow cooling and inspection.

The MELCOR model of the primary system comprises 15 control volumes, 30 flow paths and 34 heat structures. The control volumes with associated flow paths and heat structures are discussed below.

5.2.1 Lower Plenum (CV110)

The lower plenum is bounded by the spherical bottom head, the cylindrical moderator tank support and at the top, the upper side of the core support plate (CSP). The free volume is reduced by the CSP, the control rod guide tubes and drive pistons, neutron and temperature measurement tubes and belonging penetration studs welded to the lower head. These heat structures are specified in the input to the COR package.

The inlet flow path is from the eight recirculation pumps (RCPs) is in the lower part of the downcomer. The RCP is modelled as pump flow path of type “QUICK-CF” for which the pump head is given by a Control Function. The water flow passes through a number of slots, about 530 mm high, in the bottom of the moderator tank support where it rests on the bottom head. The water from the lower plenum enters the fuel assemblies through the 700 inlet nozzles in the core support plate. The flow paths to the bypass are through eight 14.6 mm diameter holes in the lower part in each of the 125 inner of the totally 169 control rod guide tubes. Five inlet flow paths to the fuel channels and five to the bypass are used in the MELCOR model, corresponding to the number of radial rings in the core region.

5.2.2 Fuel Channels and Bypass (CV121-125 and CV131-135)

The core region was divided into a five MELCOR rings. For a BWR each ring comprises one fuel and one bypass parallel flow channel. One control volume was used for the whole length of each channel, which makes totally ten CVs (axial division can be made for more detailed calculations, but extends the execution time). The core region has a height of 4.165 m and goes from the upper side of the core support plate to the top ends of the fuel pins inside the upper core grid. The 700 fuel assemblies were distributed with respect to the different inlet flow restrictions in the following way:

Table 2. Characteristics of the core rings

Ring No.	1	2	3	4	5	Total
No of fuel assemblies	176	176	176	80	92	700
Inlet flow restriction, v. h.	39.6	39.6	39.6	62.8	92.5	-
Flow area in fuel channels, m ²	1.7395	1.7395	1.7395	0.7907	0.9093	6.9187
Flow area in bypass, m ²	0.8398	0.8398	0.8398	0.3817	3.8650	6.7660
Number of control rods	44	44	44	20	17	169

Figure 5 below shows a cross section of the vessel at core level.

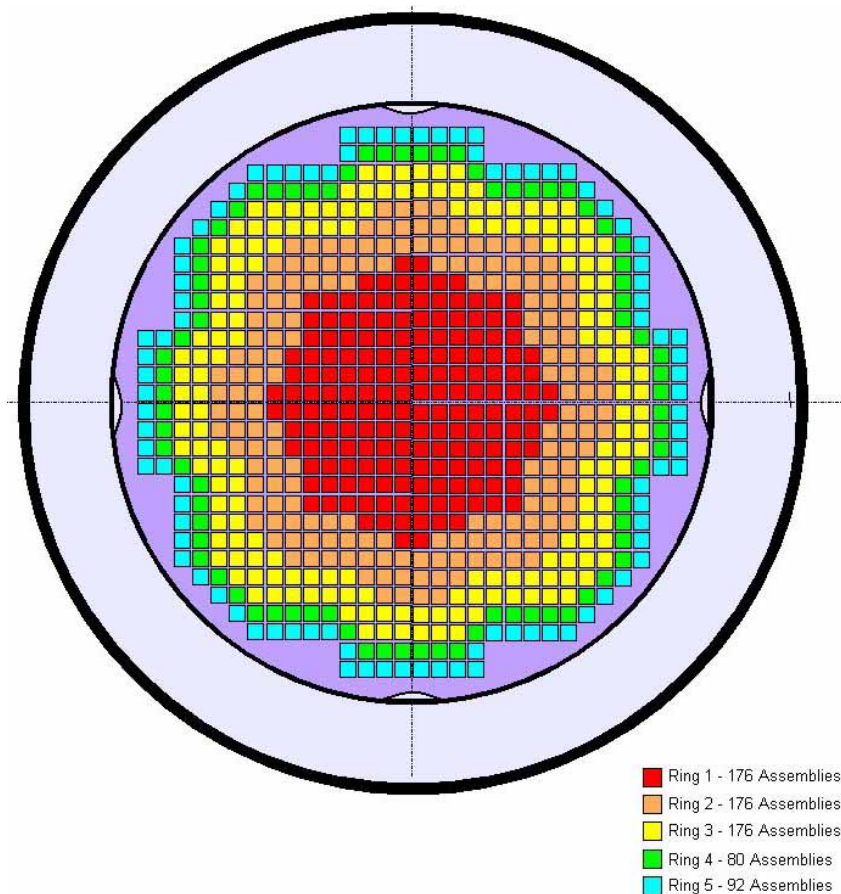


Figure 5. Cross section of vessel showing radial ring division

The bypass area is large in ring 5 since it includes the space between the outermost fuel assemblies and the moderator tank wall. The area is reduced to take into account the

four inward bends along the periphery of the moderator tank, and therefore an effective, smaller inner diameter is used in the input for the heat structure. The inner bypass areas are reduced by the space occupied by the control blades as it is assumed that the reactor is scrammed in the accident cases to be studied. The fluid volume inside the water crosses is included in the bypass volume.

The SVEA-96 Optima2 fuel bundle has three axial zones with rods of three different lengths. The full heated length is 3.68 m, but some fuel rods are shorter, 4 of 1/3, and 8 of 2/3 of full length. There are thus 96 fuel rods in the lowermost zone 1, 92 rods in zone 2 and 84 rods in zone 3, which gives a flow area that varies with height. The values given in Table 2 are average values.

There is one inlet and one outlet flow path to each fuel and bypass channel. In order to simulate free exchange of water in the moderator volume, cross flow paths are modelled between the five bypass channels.

All heat structure data of the core inside the moderator tank are specified in the COR input.

5.2.3 Upper Plenum (CV140)

The upper plenum is defined as the volume between the lower part of the core grid and the moderator tank lid at the top. The half-spherical shaped lid is penetrated by the 165 inlets to the steam separators. The free volume is limited by structures as the core grid, top ends of the fuel bundles and above them the piping of the core spray system 323 with supporting structures. The inner volume of the 323 pipes is included in CV140 since the check valves are on the outside.

5.2.4 Standpipes, Risers and Steam Separators (CV150)

This control volume consists of the inner volume of the 165 steam separator systems surrounded by the upper part of the downcomer region. A set of 5 separators forms a package enclosed by an outer steel wrapping. The geometry is rather complicated and the pipes have different lengths so the definition of the bounds can be discussed. It was decided to let the upper boundary to the steam dryer volume be at the steam outlet from the central separators.

MELCOR has no special separator model like RELAP5 with its carry-over and carry-under parameters. Some enhancement of the separator function was instead tried to be achieved by using the flag IPFSW=2 on record CV15001, that means that all fog is returned to the pool, and the flag KFLGFL=2 on record FL17002, which implements “pool-first” in the flow path from the separators to the downcomer.

5.2.5 Steam Dryers and Dome (CV160)

This is the largest control volume in the vessel and comprises the steam dryer region and the dome volume upwards limited by the vessel upper head. In the lower part is the steam dryer package. Its volume was estimated from the weight of totally 48 000 kg.

Some of the mass consists of support structures that are assigned to the downcomer volume. In the upper part there are the dome spray piping which occupy a minor fraction of the volume.

The outer boundary of the dome volume is formed by the reactor pressure vessel. Two heat structures are defined, one consisting of the upper part of the cylindrical shell, and the other by the upper head. The wall thickness in the upper head HS is increased to take into account the large mass of the vessel flanges.

5.2.6 Downcomer

The downcomer control volume is defined as the region outside the steam separators out to the reactor vessel wall and downwards comprising the annular space between moderator tank and reactor vessel. The upper elevation is at the steam outlet from the separators and the bottom at the edge where the moderator tank support skirt is welded to the reactor vessel lower head downstream the RCPs.

The water level in the downcomer is controlled by the feed water flow and its set point is 4.2 m above the active core at normal operation with 3300 MW_{th}.

Heat structures in the upper part of the downcomer comprise separator wrappings, skirt and support for the separator and dryer systems, piping for core spray and auxiliary feed water and feed water spargers. In the downcomer bottom are the RCP impeller and casing. The outer boundary heat structure consists of reactor vessel wall. The mass of the various nozzles connecting to the downcomer is accounted for by increase of the wall thickness.

5.2.7 Steam Lines (CV180)

Four steam lines lead the steam from the dome to the turbine. The nozzle inner diameter is 354 mm after which the diameter increases to 530 mm in the steam pipes. It is assumed that the isolation valves at the inside of the containment close in the studied accident cases. The internal volume in four pipes is estimated to agree with the value 23 m³ used in the SCDAP/RELAP5 file [Ref. 5].

Heat structures are the 50 mm thick pipe walls with heat insulation on the outside.

To each one of the steam lines are four valves to system 314, the pressure control and depressurization system, connected.

5.3 Reactor Containment, Spray and Cavity input (File *O3cont*)

This file contains CV, FL and HS input for the containment building and input to the SPR package for the containment sprays and to the CAV package for the reactor cavity. The nodalization of the containment comprises five control volumes. Another external volume simulates the MVSS scrubber and still another volume is used for the environment. The nodalization scheme is shown in Figure 6 below.

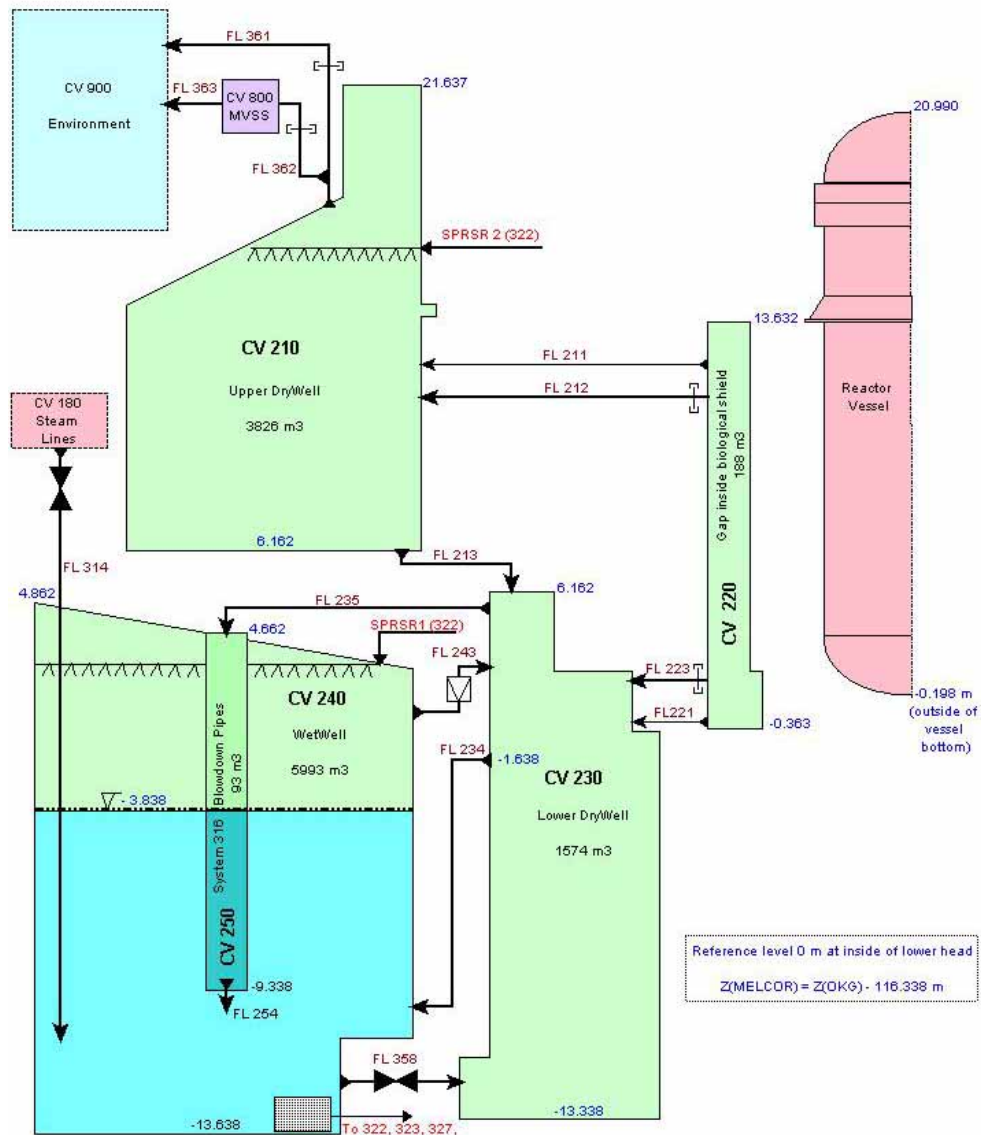


Figure 6. MELCOR nodalization of the *O3* containment

The model and the measurements are based on original drawings obtained from OKG AB. The MELCOR reference elevation is at the inside of the reactor vessel bottom which is at elevation 116.338 m according to the elevations on the drawings. There are three large volumes, the Upper Drywell, the Lower Drywell and the Wetwell. Two of

the control volumes are considerably smaller. These are the gap region around the lower part of the reactor vessel and the volume inside the blowdown pipes. The gap region, CV220 is an almost closed volume inside the biological shield with the thermal insulation on the inside wall and is furnished with channels to facilitate separate cooling of the gap atmosphere. The volume in the blowdown pipes, CV250, is modelled separately to simulate the level behaviour at clearing of the pipes during blowdown.

The free volume was calculated from the drawing measurements taking into account the interior structures. These structures consist, in addition to concrete walls, of a large number of steel structures as pipes, pumps and valves, support steel bars, gratings, etc. The rather complicated geometry results in an uncertainty of the figure of the free volume, but the figures arrived at here are used rather than the figures from “2003 Störningshandboken” [Ref. 6]. The following values were used:

Table 3. Free volumes in the containment

CV number	Name	Volume in MELCOR (m ³)	Volume in Ref. 6 (m ³)
210	Upper DryWell, UDW (Total Drywell)	3826	(5662)
220	Gap volume	188	-
230	Lower DryWell, LDW	1574	-
240	WetWell, WW (Incl. BD pipes)	5993	(6016)
250	System 316 blowdown pipes	93	-
240 + 250	Gas volume in WW at normal water level	2745	2670
240 + 250	Water volume in WW	3341	3346
210 to 250	Total fluid volume	11 674	11 678

Normal, initial water level in WW is 9.8 m above bottom. The atmosphere is all nitrogen. The temperature of the WW pool is kept at maximum 20 C° at normal operation by cooling through the system 322 spray. There is also another branch of system 322 with spray nozzles in upper drywell which is activated under accident conditions. Other safety systems related to the containment considered in the MELCOR model are:

- System 316, the pressure suppression blowdown system. Twenty-four 600 mm pipes go from the steam collecting cubicles in the upper part of the LDW into the WW pool ending 5.5 m below the water surface. In case of a LOCA steam blown into the UDW or LDW increases the pressure there and the steam is discharged into the pool where it will be condensed. The cold water with its large mass will effectively reduce the pressure. Pressure increase will mainly be caused by clearing of the blowdown pipes and by heating of the non-condensable nitrogen gas in the containment.
- System 314. This pressure relief system has several functions, among others for pressure control and ADS, Automatic Depressurization. Totally sixteen DN 250 and DN 300 mm pipes go downwards in UDW from the four valves on each steam line. Each of these pipes branches into four DN 150 mm pipes above the floor to the WW, so there are totally 64 blowdown pipes leading into the WW pool. The submergence depth is there 6.9 m.

- Breakable sealing sleeves in the biological shield around pipe penetrations. The pipes for main feed water, ECCS and some other pipes go radially from the reactor vessel through the gap space, CV220 and through the thermal insulation to the UDW. In case of a pipe break close to the vessel overpressure will create a flow path through the sleeves. An opening differential pressure of 0.5 bar and a maximum flow area of 1 m² are assumed for FL212 going from CV220 to CV210.
- Blow-out panels in the thermal insulation in the bottom of the gap volume which will burst at overpressure. An opening differential pressure of 0.2 bar and a maximum flow area of 22 m² are assumed for FL223 going from CV220 to CV230.
- Overflow pipes from LDW to WW. There are four 600 mm pipes connecting LDW with the WW pool. If the spray is activated in the UDW, or water is blown out from a LOCA it will flow down to the LDW through the large openings in the floor between these two compartments. When the level rises to 11.7 m above the bottom of LDW water will begin to overflow to the WW (Flow path FL234).
- Vacuum breakers are installed in pipes between the gas volumes of WW and LDW to prevent overpressure in the WW. There are eight DN 450 mm pipes each with double check valves. The opening differential pressure is 0.02 bar. This flow path between CV240 and CV230 is modelled by FL243.
- System 358 – Transfer of water from WW to NDW. Two separate pipe lines each with two valves in series facilitate filling of NDW up to a level of minimum 4 m. The system is designed to open the valves automatically in case of a severe accident at an early phase to provide cooling of falling debris from the vessel. It is here modelled by flow path FL358.
- System 361 – Venting of the containment directly to the ambient atmosphere. This is an ultimate way for pressure relief of the containment. A rupture disk in a DN 800 mm pipe that goes from the top of UDW will break at a pressure of 6.5 bar (Flow path, FL361).
- System 362 – Filtered venting to the atmosphere through the Multi Venturi Scrubber (MVSS). A DN 300 mm pipe is connected to the system 361 pipe upstream the rupture disk. The rupture disk in the pipe to the MVSS bursts at a pressure of 5.0 bar. The MVSS is assumed to have a volume of 500 m³ and the blowdown pipes be submerged about 4 m in the water pool. The MVSS is then vented to the ambient air (Flow path, FL362).

The various control volumes are described briefly in the following.

5.3.1 Upper Drywell (CV210)

The Upper DryWell (UDW) is the large annular space between the inner biological shield and the outer cylindrical containment concrete shell, plus the space above the reactor vessel upper head to the containment steel cupola. It is limited by the thick floor to the wetwell and lower drywell at the bottom (OKG elevation +122.5 m). The

concrete ceiling has a conical shape towards the opening in the centre on which the large steel cupola is mounted, which is sealed against the fuel service pool on top of the containment.

The free space is reduced by the main steam lines and a number of other insulated pipes which go from the biological shield to the isolation valves before they go through penetrations in the outer wall of the containment. The space around the top of the reactor vessel is partly occupied by thermal isolation panels. In addition, there is a substantial mass of steel from support bars, staircases, gratings and certain equipment as coolers, etc which reduce the gas volume.

Two open flow paths were defined. FL211 is a flow path from the gap volume which simulates a small leakage from the otherwise closed gap volume (CV220). FL213 models the large openings in the UDW floor next to the biological shield going down to the LDW and to the steam collecting cubicles below the floor.

5.3.2 Gap inside the biological shield (CV220)

The reactor vessel rests with its skirt on the top of the inner biological shield. Between the reactor vessel cylindrical wall and the inner surface of the 1.3 m thick biological shield there is a 0.775 m wide, annular gap, narrowing at the top. The space is partly occupied by the thermal insulation that is placed against the concrete wall leaving a gap of 0.58 m to the vessel wall. The gap volume is sealed at the bottom with insulation panels tightening around the motor cases of the RCPs and around the penetrations for control rod drives and neutron detectors. The panels are supported by the bottom radiation shield made of 120 mm thick steel plates.

The pipes for feed water, auxiliary feed water and the system 323 pipes from the vessel go through the gap and occupy, with their nozzles, some of the gap volume. In case of a pipe rupture within the gap area overpressure will open up the sealing sleeves around the pipe penetrations towards the UDW. The insulations at the bottom are designed as blow-out panels and will open a flow path to the WW.

Small leak areas are assumed to exist under normal conditions to UDW (FL211) and to LDW (FL221).

Since the thermal insulation is not placed on the vessel surface but on the inside of the biological shield the temperature of the atmosphere in the gap volume is higher than in other parts of the containment. The insulation and a cooling system are designed to limit the temperature in the concrete to maximum 65 °C. The insulation is taken into account in the MELCOR model, but not the cooling system.

5.3.3 Lower Drywell (CV230)

The Lower DryWell (LDW) consists of the central cylindrical room below the bottom radiation shield and goes down to the lower floor of the containment. The outer diameter of the cylindrical wall is 13.8 m and the wall thickness 0.8 m. The circular shape on the inside is interrupted by eight vertical strengthening bars of concrete, 1 m thick and stretching 1.6 m inwards. In the upper part the spaces between the bars are

enlarged sideways to form the steam collecting cubicles. Above them are the openings to the UDW. In the bottom of the LDW connects a duct that goes under the WW to the manhole with an air lock to the outside of the containment.

The space in LDW is occupied by various equipment. Below the reactor vessel are the RCPs and the control rod drives. There are then a large mass of structures in piping, cables, staircases, service floors, etc. which further reduces the free gas volume.

Like in all outer walls, except in the WW pool, a tightening plate of carbon steel is embedded about 300 mm from the inner surface. The bottom of the DW forms the “cavity” in the MELCOR model. In case of a severe accident the cavity will be flooded from the WW by automatic opening of the valves in the connecting pipes (System 358).

5.3.4 Wetwell (CV240)

The WetWell (WW) is the largest volume of the containment. It comprises the annular space between the outer shell and the wall to the LDW. The outer diameter is 25.5 m and the inner 13.8 m. The top of the WW is limited by the ceiling to the UDW that has a conical shape which is lower at the inside to give room for the steam collecting cubicles. From the cubicles the 24 blowdown 600 mm I. D. pipes hang down into the WW pool. Further out are the penetrations for 64 DN 150 mm pipes of system 314. The WW is filled water to a depth of 9.8 m at normal conditions.

There are relatively few components occupying the volume. The major reduction, about 164 m³, is due to the duct in the bottom to the manhole leading to the outside of the containment. Reduction of the WW volume is done for the system 314 pipes which have an average length of 15.4 m, hanging down to 2.9 m above the bottom of WW. The volume of the blowdown pipes of system 316 is subtracted since it is defined as a separate control volume, CV250. Other structures for which reduction of the volume was made are for various staircases, gratings, and support structures and for the suction strainer packages to systems 322, 323 and 327. In the gas volume is also the other branch of the containment spray, system 322.

The concrete on the floor and a large part of the walls up to 2 m above the water surface are lined with a stainless steel plate.

The flow paths connecting to WW were mentioned before and are listed below.

- FL234 – Two overflow pipes from LDW
- FL243 – Eight vacuum valves to prevent overpressure in WW, part of system 316. The opening pressure difference is 0.02 bar.
- FL254 - System 316 – Exits from the 24 blowdown pipes in the PS system
- FL314 – System 314 – 64 blowdown pipes from the steam lines for pressure relief
- FL358 – System 358 – Two pipes for filling of water from WW to LDW
- SPRSR1 – System 322 – Containment spray to WW

5.3.5 System 316 Blowdown Pipes (CV250)

The 24 blowdown pipes are arranged in six bundles with four pipes in each. The bundles are evenly distributed in the area not occupied by the transport duct. The pipe dimension is D.I./D.O. = 600/612 mm. Since the pipes are mounted in the sloping roof to the steam cubicles the inlet elevation differs somewhat. Four of the outer pipes have a 90 degree bend at the inlet end, otherwise the inlet is downwards.

The water level in the blowdown pipes is the same as in the surrounding pool at normal conditions.

5.3.6 Containment Spray Package (SPR) input

The Spray Package models the heat and mass transfer between the spray water droplets and the containment atmosphere. The input specifies the location of the spray nozzles, the source volume (sump) and the control of the flow. Other input data defines the spray water temperature and droplet size and distribution.

5.3.7 Cavity Package (CAV) input

Input to the cavity package is needed for the modelling of core debris concrete interaction by the CORCON-Mod3 code in MELCOR. The concrete type is given, either as one of the built-in compositions, or as here by specifying the constituents and physical properties, which were supposed to be same as in the Ringhals 3 MAAP input.

Input is also required to define the geometry of the cavity which is based on CORCON and different from the MELCOR geometry. The resolution of the nodalization is given as number of "rays". Test runs showed that using a large number of rays, close to the maximum of 100, made the calculations more stable.

5.4 Core model. Input to COR and to TP, the Transfer Process Package (File *O3cor*)

The input to the COR Package specifies the material in fuel, fuel boxes, control rods, guide tubes, etc. that is present in the core and lower plenum. These are the structures which can melt and relocate during a severe accident. They constitute the “virtual” volume in MELCOR which, when it disappears, leaves place for fluid, or when it moves can reduce the flow area of another volume. COR also includes the part of the vessel lower head directly below the core and models heat-up by the debris of the vessel wall and its penetrations, melt-through and ejection of core debris into the cavity.

The nodalization of the COR region is shown in Figure 7 below:

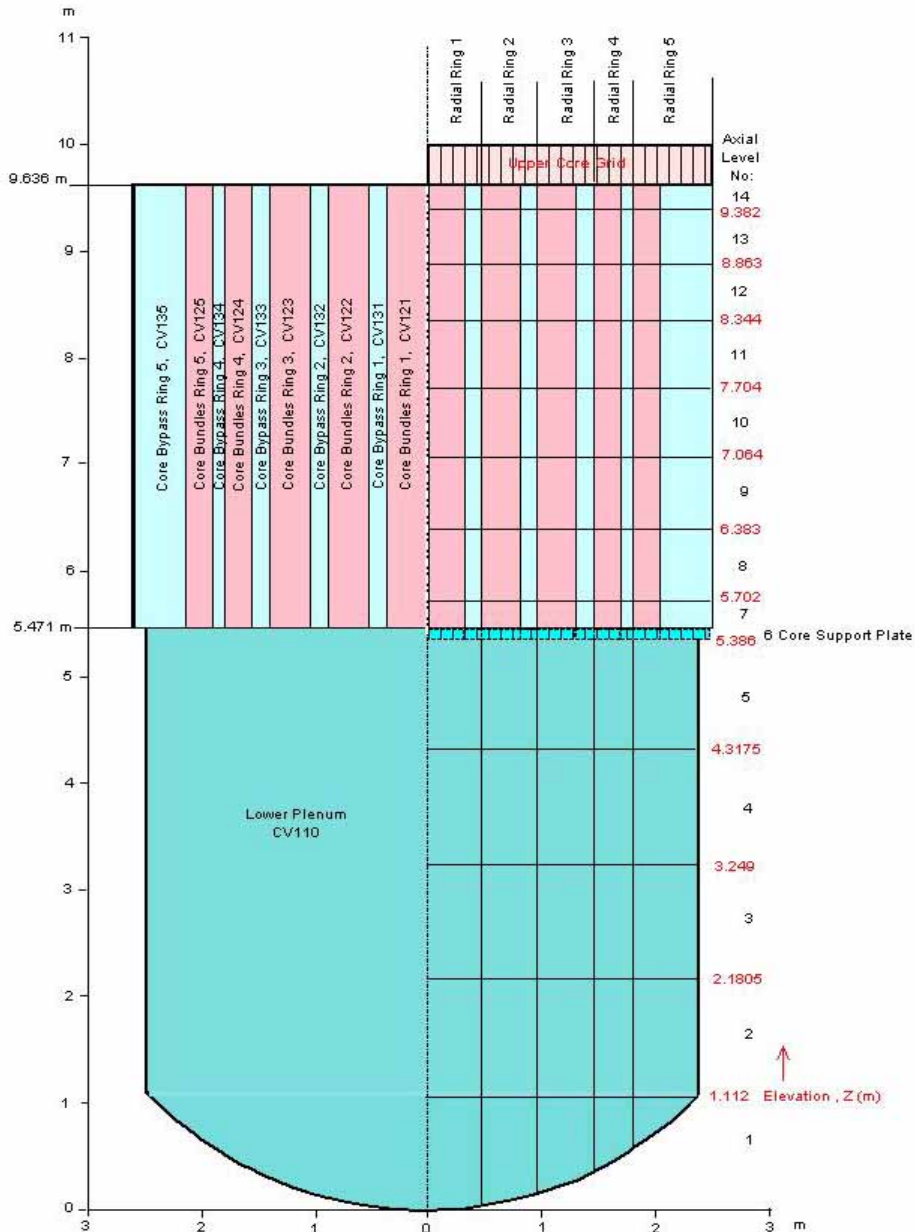


Figure 7. MELCOR Diagram of Core Model

The radial division is the same as for the hydrodynamics control volumes, i. e. into five concentric rings which here also includes the lower plenum and goes all the way to the vessel bottom. An axial division into 14 parts was applied. The numbering is from the bottom.

Six parts were assigned for the lower plenum, one at the spherical lower head, 1.112 m high, the following four equally high, 1.0685 m and the uppermost volume containing the 0.085 m thick core support plate. The latter must not belong to the core part since it can not have both a fuel and a bypass flow channel.

The core between the core support plate and the upper core grid was axially divided into eight parts of which the middle six constitutes the active core. These are adapted to the three different zones of the SVEA-96 Optima2 fuel and each zone is divided into two equally long parts.

In MELCOR 1.8.5 there is a distinction between Supporting Structures, SS and Non-Supporting Structures, NS. NS can only support itself and failure criteria are a critical thickness and the default, or input, melting temperature. SS supports not only itself but also structures in a cell above it. For a BWR two types of SSs are valid, "PLATEB" and "COLUMN". PLATEB applies to the core support plate. The model implies, however, that it can support only particulate debris. Support of the core in cells above requires that COLUMNS, i. e. the control rod guide tubes, below are still intact. The PLATEB can fail by yielding from the weight above when the yielding temperature is reached.

5.4.1 COR input

Input data for the core are mainly based on information from OKG. The order and structure in the input file follows the MELCOR 1.8.5 user's Guide, Rev. 2. The groups of required input data are:

- 2.1 *General Core/Lower Plenum Input.* Some global, geometrical and nodalization parameters are given here, among others the fuel pin cross section measurements, melting parameters for materials and especially for penetrations. Some conditions for lower head failure and characteristics for debris are also input here.

Default values were generally used with a few exceptions; Radiative exchange factors on record COR00003 for radiation upwards between cells (FCELA) and for radiation from liquid pools to the core components (FLPUP) were reduced from 0.25 to 0.05 as recommended in the Workshop 2000 papers which says "DEFAULTS SHOULD NEVER BE USED FOR RADIATION PARAMETERS". On record COR00009 the penetration failure temperature (TFAIL) was increased from 1273 K to 1625 K in order to avoid too early melt-through. ("Matweb" data sheet for SS304L gives a melt temperature of 1672 to 1727 K.)

- 2.2 *Axial Level Input.* This input section comprises specification of the axial cell division and boundaries and axial power distribution (The latter is overridden by the RN input).

- 2.3 *Radial Ring Input.* The only input blocks needed are the radial ring cross sectional area, the upper boundary heat structures and the radial power factors. Like for the axial input, the ultimate power distribution is given by the RN input.
- 2.4 *Specific Cell Input.* This is the more comprehensive part of the COR input. The coupling between core cells and the hydrodynamic control volumes is defined here. Then, for each COR cell is given the mass of all structure materials in the cell, e. g. for fuel, spacers, fuel boxes, control rods with guide tubes. Geometric data as component and debris equivalent diameters, flow areas and surface areas are specified needed for calculation of heat transfer, flow resistance and interactions between individual cells and between cells and control volumes.

Some masses of structures used in the O3 COR input are summarised in Table 5 below. Masses were calculated from component volumes using the following constant density values listed in the MP MELCOR manual:

Boron Carbide, B₄C, 2520 kg/m³
 Carbon steel, 7752.9 kg/m³
 Steel = Stainless Steel, 7930 kg/m³
 Zircaloy, 6500 kg/m³

Table 5. Masses for O3 specified in the COR input (kg)

UO ₂ in fuel (Optima2)	139 510
Zircaloy in fuel cladding	28 731
Zircaloy in fuel boxes	22 050
Total Zircaloy mass	50 781
Inconel in spacers	604.6
Boron carbide in control rods	1706.9
Stainless Steel in lower plenum supporting structures	34506.3
SS in core support plate incl. outer fix flange	8779.4
SS in LP Non-Supporting structures	24253.6
SS in fuel assembly inlet parts	7700.0
SS in control rod blades	18303.3
Total stainless steel, core and LP	93542.6

- 2.5 *Lower Head Input.* Here is given the ring radius', lower head nodalization (if not same as in the HS specification) and material specification. A simplification was made by assuming the whole inner 12 mm cladding consist of stainless steel, even though 7 mm between the basic wall material of carbon steel and the stainless steel surface is made of manganese steel. Data of the penetrations are also specified here. Two penetrations were defined, one representing a control rod and one a neutron detector stud. Input data which determine the failure behaviour are; location, mass represented by the penetration, surface and conduction area, and initial diameter of failure opening. Note, that heat transfer coefficients for lower head and the penetrations are specified on "general input" record COR00009.

- 2.6 *COR Material Input.* This input is optional and if not given the default material and properties are used, which were adequate here for the O3 case.

It should be noted that failure of a penetration or of the lower head initiates ejection of debris, but not of coolant from the reactor vessel. In order to simulate loss of coolant through the break a valve flow path has to be defined, the opening fraction of which is given by a control function. The argument is then the parameter “COR-ABRCH”, that is the break area calculated by the code.

Attention should be paid on the accuracy in input of cell measurements and volume data with respect to agreement with the figures given in CV and HS input. A consistency check in MELCOR tells if any deviation is too large. The COR volume must in any cell not exceed that specified in CV, otherwise the code aborts.

5.4.2 Transfer Process, TP, input

The Transfer Process, TP package provides an interface for a physics package to transfer mass and energy to other packages. In current case it is prescribed to be used by the COR, CAV, FDI and RN packages to facilitate transfer of radioactive masses from the core to the cavity.

The input is given as matrices for “In” and “Out” transfer, here to/from COR and FDI (Fuel Dispersal package) and to/from FDI and CAV. The “In” transfer process number (011) for the core was input on card COR00004 in the COR package, and as “Out” transfer process number on FDI card FDI0100 for transfer from core to FDI (The FDI package input is located last in the file “O3cont”). The “OUT2 Transfer Process No. from FDI to cavity is given on record TPOT01200.

The options of input to the TP package are restricted to a few combinations of data sets. The input here was built from the examples in the manual, pages TP-UG-12—16. Note, that the transfer process numbers for radionuclide transfer must be COR and CAV numbers +500.

5.5 Decay Heat and Radionuclide Package Input (File *O3dch-rn*)

5.5.1 Decay Heat Package Input

The decay heat package in MELCOR models the decay heat power resulting from radioactive decay of fission products. Decay heat is evaluated for reactor core material and for suspended or deposited aerosols and gases. MELCOR couples thermal-hydraulic processes and fission product behaviour during the calculation.

Input data specifies the type of reactor, here BWR, and give the basis for decay power of radioactive fission products after shut down. A scram trip number has to be specified. The default ORIGEN decay curve was chosen. The other option is ANS.

The total initial reactor power is given as a sum of power from thermal fission of U^{235} and Pu^{239} plus fast fission of U^{238} . The default values are for a BWR with a total thermal power of 3578 MW, and each of the contributing three fractions are here scaled to the actual power $3300 MW_{th}$. The default operating time, 80 % of two years was chosen.

There are built-in decay heat tables in MELCOR for a large number of elements, however not for CsI, which is used in the RN input. A new class, No. 16 had therefore to be defined on the “DCHCLSnnn0” and “DCHCLSnnnm” records. The decay heat power as a function of time must then also be specified on the “DCHNEMnnmm” records. These values for CsI were taken from the Surry input file in [Ref. 7].

5.5.2 Radionuclide Package Input

The RN package has models for calculation of radionuclide release from the fuel and debris, of transport, deposition and removal by engineered safety systems of radionuclides in the various reactor systems. The RN package operates on the basis of material classes, which are group of elements that have similar chemical properties. Notice must be taken to the fact that some models in MELCOR use other grouping of elements, which is the case for VANESA. In these cases special mappings for transfer between the classes is needed. The following groups of data were entered according to the manual (RN-UG, section No. in brackets)

General control, Options and Mapping (3.1.1); Default values are employed as far as possible for definition of material classes. Thus number of sections (size bins) was set to 10. The default number of classes is 16, including CsI. The hygroscopic model is turned on. The default transfer fractions for mapping of non-radioactive masses to RN material classes are applied. Mapping of the new RN class 16 for CsI to a VANESA class must, however, be specified.

Initial Radionuclide Inventories (3.1.2) is specified for the fuel only, and must be input for each active core cell. The values are per unit mass. Axial variation is proportional to the axial power distribution taking into account the different lengths for the three axial zones in the SVEA-96 Optima2 fuel. The values are normalized to 1.0 for each radial

ring. The radial ring node multiplier is in proportion to the number of fuel assemblies in each ring. Since the power distribution varies with time during a fuel cycle a tentative distribution with a near symmetric axial shape was chosen. The form factor, not taken into account the internal pin power factor, is $F_{ax} = 1.21$, $F_{rad} = 1.506 \Rightarrow F_f = 1.822$, that is relatively low. The resulting power distribution as is shown in Figure 8 below.

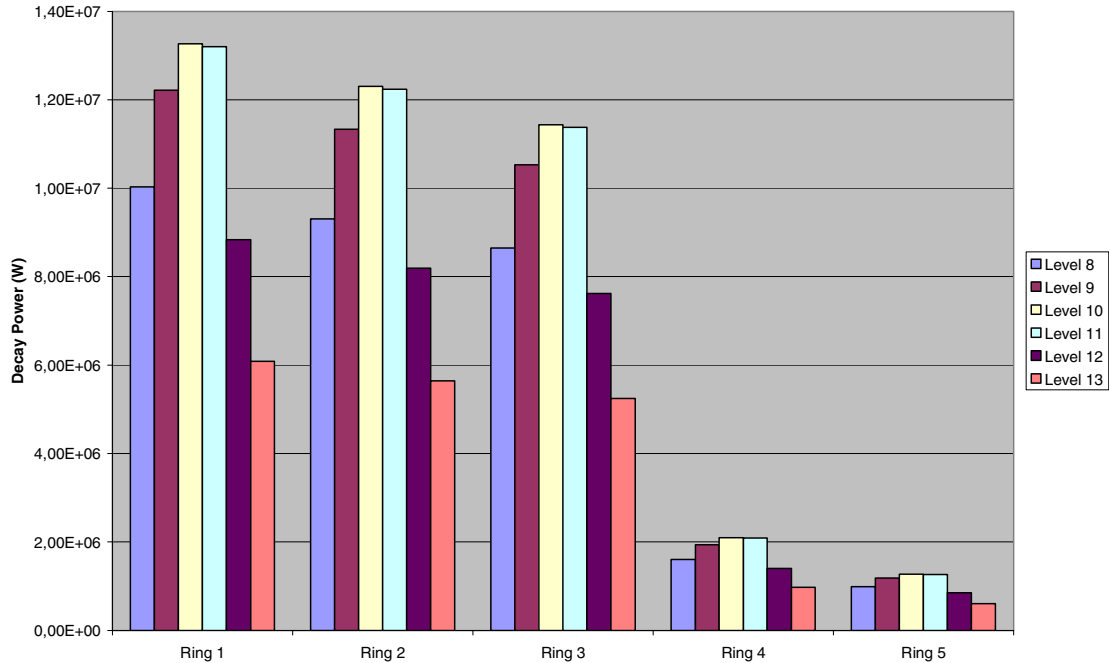


Figure 8. Decay power per MELCOR COR cell at time zero after scram

The power distribution also applies to the fission power before scram.

Release Model Parameters (3.1.3); The default CORSOR-M model with surface-to-volume ratio was selected, and the default for gap release temperature (1173 K). There are five additional CORSOR models to choose among.

A new acceptor class (#16) had to be defined for CsI.

Aerosol Modelling Parameters (3.1.4); Default values were used for the aerosol size and density parameters. Only two other input groups were applied, these are for redefinition of vertical surfaces to horizontal (RNDSxxx records), and for definition of intervolum settling (RNSETxxx). The RN models require each control volume to have at least one horizontal surface otherwise redefinition has to be made through the RNDS input. Here it was necessary only for the downcomer volume, CV110. (Another way to sidestep this is to introduce a horizontal dummy heat structure in the control volume).

The RNSETxxx records facilitate settling of aerosols from volume to volume without bulk flow, which is in addition to, and independent of transport by inter-volume flow. These were here used for all vessel volumes. For the environment volume, CV900 settling into the same volume was used to keep track of radionuclides released from the containment.

Aerosol Condensation Index (3.1.5); Default “ICOND” = 0 lets condensation take place on all aerosols.

Decay Heat Distribution (3.1.6); No redistribution was made.

ESF Parameters (3.1.7); The Engineered Safety Features (ESF) applied here is the pool scrubbing model which facilitates wash-out of aerosol and/or Iodine vapour. The SPARC model must then be activated in the flow path input, which is here done for the system 314, 316 and the MVSS blowdown pipes. RN input parameters on record RN2PLSxx describe the type of vent and the vent pipe geometry, e. g. number and diameters of holes in the nozzle.

The containment spray input on records RN2SPRxx defines a spray partition coefficient, here set to 5000.0, which is the ratio of concentration of iodine in the liquid droplets to that in the gas under equilibrium conditions.

There is also a block of input parameters that can be used for specification of filters for aerosols and fission product vapours. This could be used for the MVSS filter but is not applied now, since the effect of the scrubber model should be evaluated in the first place.

Radionuclide Chemistry (3.1.8); No chemical reactions were defined now.

Chemisorption (3.1.9); Activated by letting ICAON = 1.

Iodine Pool Model (3.1.10); Not activated here (default).

5.6 The ORNL Bottom Head Model (File *O3bh*)

The Bottom Head (BH) model is an extra feature originally developed for BWR applications, but can in MELCOR also be used for PWRs. The BH model is an option that replaces accident progression modelling of the debris interaction in lower plenum including failure of the lower head otherwise done by the COR model. The BH package is intended to give a more detailed simulation of phenomena in this region than the COR package. The description in the input manual is adapted to the jet-pump BWR which leaves some questions in the interpretation and application for Swedish BWRs with internal RC pumps.

The BH calculations are activated only provided that sufficient solid debris has accumulated in the lower plenum to adequately define the initial debris bed structure as required by the BH package. Otherwise the COR models will continue to calculate the bottom head phenomena and the BH modelling will be precluded. It is therefore necessary to change some melting parameter values in COR to inhibit COR to continue. In order to preclude prediction of penetration failure by COR an artificially high failure temperature is recommended on record COR00009. Here, this temperature was increased from 1625 to 10000 K, and furthermore were the HTC values decreased from 1000 to 100 W/m²K.

Other recommendations with the same aim are to use low debris quenching heat transfer coefficients, and to increase the minimum allowed debris particle diameter to 0.4, in order to mitigate the maximum pressure spike that might cause premature vessel failure.

Since one of the purposes with the BH package is to specifically consider the curvature of the vessel bottom head and its effect upon the shape of debris bed control volume boundaries more detailed nodalization is required for the lower plenum and lower head than for the CVH package. Accurate agreement between volume-to-elevation input in CVH and BH is necessary.

Some parameter values are not accepted by the BH package, e. g. was a heat structure multiplicity factor less than unity not accepted for the part of the lower head that belong to the downcomer (HS17001). It was therefore changed from spherical to cylindrical geometry. For the lower head below the lower plenum, however, a smaller multiplicity factor was accepted.

The following input sections are described below:

2.1 – Lower Plenum and Debris Bed Parameters.

Here is given the bottom elevation of the DownComer (DC) and the number of entries (nodes) in the specification of free fluid volume versus height in DC and Lower Plenum (LP) and of the stainless steel structure in LP. 31 and 22 nodes, respectively, were given going from the zero elevation to the underside of the core support plate. Shorter layers were used near the bottom where the curvature makes more difference. Nodes in the CV volume/elevation input had to be entered in the table for compliance with the CVH data.

Other input here is a table of melting temperature, molecular weight and heat of fusion for debris constituents. Default values were applied. Input parameters for LP debris are also specified here such as porosity and particle diameter.

2.2 – Vessel Wall Reaction Parameters and Metal/Water

A nodalization of the debris bed above the lower head in LP with three layers and five radial zones is inherent in the BH package and is independent of that in COR. The radial zones 4 and 5 exist only in the two upper layers 2 and 3. The outermost zone 5 next to the vessel wall is thin. The thickness is specified here and a value of 0.05 m was applied. Other input data are the vessel wall thickness at the penetrations and in the cylindrical part, and temperatures for creep rupture. The latter were taken from the input example in the manual and are lower for high pressure than for low pressure conditions.

2.3 – Eutectic Mixtures

Input values from the manual example were used. Melting temperatures and mole data for four constituents and a matrix for their interactions are specified. The materials are boron-carbide, cadmium-indium, chromium, iron, nickel, uranium, zirconium and their oxides.

2.4 - Parameters for Material Ablation.

This input has application to the melting of penetrations and ablation of surrounding materials. The number of penetrations and diameters and melting temperatures should be given for the three central zones. According to the manual, only instrument tubes are considered for a scrammed BWR, since “the control rod guide tube passageways would remain almost completely blocked by the internal control blade index tubes.” Thus a number of 22, 20 and 26 instrument tubes were defined for radial zone 1 to 3.

2.5 – Identification of the CVH Control Volumes that Interface with the BH Package.

Here are the control volume numbers given for the downcomer, the containment volume surrounding the vessel and the lower plenum. The flag ICVHBH has to be set to 1 in any case to avoid abort, even if CVH and BH volume data are consistent.

2.6 – BH Package Print Edit Intervals.

This input is required. The heading is somewhat inadequate since one input value is DBDRPR that defines the maximum rate in which debris will be added to the BH package debris bed from the core region. By this input the user can distribute the falling debris over several time steps when large instantaneous mass of debris occurs.

There is one input record that is required which is not mentioned or explained in the input manual, UG. This is record BH1301 containing two time values, BHTIME and DTPNTB, which were copied from the manual example.

2.7 – Failed Core Boundary to Vessel Wall Radiation model Input.

Radiation heat sink boundaries to the failed core model are the adjacent vessel wall, which is here the cylindrical part, HS17002.

2.8 – BH Package Right (Outside) Surface Data for Reactor Vessel Bottom Head.

The bottom head is divided into 18 nodes of which node 1 is the lowermost. In addition to flags indicating boundary heat transfer type and condition, the critical fractions for pool and atmosphere heat transfer should be given (corresponding to the HS input parameters CPFPL and CPFAL).

2.9 – HS Package to BH Package Modelling Transfer.

This input is required in order to avoid duplicate modelling of the bottom head wall by both COR and BH packages after activation of the BH calculation. Two heat structures represent the bottom head in the O3 model, HS11001 and HS17001 and will be deactivated in COR.

Attention must here be paid to the fact that as these heat structures are decoupled there might be no area for aerosol settling which would lead to abort of the calculations by the RN package. Tests with dummy heat structures in LP showed that they are also deactivated. The only way to avoid abort is then to introduce a RNSET record enabling settling of aerosols in LP to the volume itself (CV110) and put IVOLF = IVOLT (which, however, generates a “Warning” in the MELGEN .DIA output file).

2.10 – BH/HS Package Structure.

Two values are given. IHSBOT is the HS number that is turned off and is also represented as node NWALL, which is here HS17001. IHSTOP is the vessel wall HS above, here HS17002. The IHSBOT structure begins at the lowest elevation of the DC. The border between the two heat structures should be at $\text{Max}(\text{DRXID}/2, \text{HBSB}+0.076)$ above vessel zero. DRXID/2 is here the largest = 3.2 m (DRXID is the inner diameter of the spherical part of the reactor vessel bottom head).

To facilitate IHSTOP (HS17002) to receive conduction energy a control function for internal energy source must be introduced, according to the manual, p. BH-UG-29.

It is recommended that the inner surfaces IHSBOT and IHSTOP are identified to receive radiative heat transfer from adjacent surfaces, and therefore a number of related HSRD records were added in the O3primysyst file.

2.11 – BH Package Lower Plenum Debris to Overlying Surface Model Input

These records identifies input required to evaluate the heat transfer associated with radiation from the surfaces of the lower plenum debris bed to selected overlying structures prior to core boundary failure. It defines the temperature at which the core boundary is assumed to fail and the HS package structures to be deactivated. In the O3 case ten surfaces are considered; the four HSs of the moderator tank support structure (LP shroud) and at the top the five rings of the core support plate. A small fraction of the vessel wall below the LP shroud is included as well to comply with the model in the manual, and is denoted a minor view factor in the view factor matrix.

The failure temperature of the LP shroud is set to 900 °C, which is higher than the value in the manual example, 577 °C, which seems surprisingly low.

Last in this input block is a list of the heat structures which will be deactivated after core boundary failure. These are four HSs of the LP shroud, one at the core support plate and eight of the moderator tank in the core region.

2.12 – BH Package Lower Plenum Vessel Penetration Break Size.

A control function, in this input CF196, is given to specify the break area at failure of the instrument tube penetration. The recommended value of 0.0005 m² is input.

2.13 – Fission Product Release

This is for mapping of the BH materials to RN classes, other materials are set by the RN package as before. No input was made, so the default mapping scheme was employed.

Similar to the case in COR a flow path has to be specified to facilitate flow of water and steam through a gross head failure break area. The output parameter “bh-fflag” (Note that lower case is used for output variables in the BH package and upper case in other packages) is a flag whose value changes from 0.0 to 1.0 to indicate gross head failure of the bottom head, either by creep rupture or by ablation. A flow path, FL701 was defined to model this type of BH break.

5.7 Control Function Input (File *O3cf*)

The Control Function (CF) input, except that which is especially related to the initiation and to the definition of transient run, is placed in this separate file. Two kinds of control functions are included here:

- CFs for control of FL-valve input in the containment, as for rupture of the blow-out panels between the gap volume and UDW, opening of the vacuum valves and valves for LDW flooding, rupture disks to the MVSS and to the environment.
- CFs set up to produce plot variables not directly available in the MELCOR plot file. In addition to these inherent plot variables the output from most of the MELCOR packages contains a large number of control function arguments which can be utilized to compose new, user defined plot variables. One reason for creating the separate *O3cf* file was to facilitate introduction of complementary plot variables required for special calculation sequences.

5.8 Input to Materials Properties Package (File *O3material*)

Thirty-five materials are defined in the Materials Property (MP) package with their physical properties implemented in the MELCOR code. These are called in the other MELCOR packages by use of mnemonics. In some cases the default properties can be changed by the user by inputting table values which replace the default table function.

The user can also define a new material giving it a unique name and by input of table values for the desired property. Three new materials were specified this way; 'INCONEL X750' for the material in the spacers, 'insulation' for the thermal insulation of the reactor vessel and pipes in the containment and 'O3concrete' for concrete in the containment walls. The properties specified are density, specific heat and thermal conductivity. Constant values were given except for Inconel for which specific heat and thermal conductivity were given as functions of temperature.

5.9 Initialization, boundary conditions and transient definition input (File *O3init*)

File *O3init* contains the following general and case-specific input data:

- Executive Package (EXEC) input as run title, file names and time data.
- Assignment of control volume types. This facilitates grouping of some output variables. Here type 1) is for primary systems, 2) containment, 3) MVSS, 4) environment and 5) for the feed water source control volume.
- Non-Condensable Gas (NCG) input. These are numbered starting with #4 (1 to 3 are reserved for water, i. e. liquid, fog and steam, respectively). Here nitrogen, oxygen, hydrogen, carbon-dioxide, carbon-monoxide and methane were assigned numbers 4 through 9.
- Calls to all other input files for the MELGEN run by the R*I*F command.
- Input for smooth initialization and initial conditions for a steady-state period to be calculated by MELCOR as starting conditions for the transient run.
- Input for the transient case to be calculated by MELCOR. This comprises control functions to define the transient conditions and to activate and deactivate the safety functions under consideration.

Thermodynamic initial values must be given to the CVH package for the control volumes (records CVnnnAk) and initial temperatures for core cells (records COR ijj03). Initial structure temperatures for heat structures are normally determined by the MELGEN steady-state initialization calculation provided that the initialization flag $ISS \geq 0$, otherwise the temperature data must be specified on records HSCCCC8NN. Initial fluid velocities in volumes (on record CVnnn02) in the CVH package and in flow paths (record FLnnn04) in the FL package are optional and can also be calculated by the code.

Since the exact values are not known in all volumes, cells and heat structure nodes, and in order to tune the boundary conditions to given operating data a steady-state period was introduced foregoing the transient calculation in MELCOR. A time period of 600 s was shown to be sufficient to reach stable conditions. A time shift was made so that the steady-state period is negative from -600 s in order to let the transient begin at time zero.

For the *initialization and steady-state* calculation the following systems were introduced and with variables adjusted to their set values:

- The fission power was gradually increased from zero to 3300 MW during the first 50 s and thereafter held constant.
- The RCP pressure head was increased simultaneously from zero to 0.37 MPa.

- A feed water source was defined as a time-independent control volume having a pool temperature of 490.15 K (217 °C), with a flow path to the DC. The volumetric flow was controlled to maintain the nominal water level in the DC.
- A turbine valve whose opening fraction was increased at the same rate as the power and giving a maximum steam flow rate corresponding to 3300 MW.
- Pressure control was made by a table function with the system 314 valve opening area as a parabolic function of the dome pressure, starting from zero area at 7.00 MPa. A combined set of control functions was designed to handle both the pressure control and the ADS function, the latter only for the transient.

The *transient* part of the O3init file defines the conditions for the actual severe accident simulation. Besides some general input data are here placed case specific conditions for the various systems that are activated during the transient. The accident conditions have to be checked once more against plant data when the input is to be applied on analysis of more realistic cases decided upon later. Two tentative accident sequences were chosen for demonstration of the O3 input. It should be emphasized that the conditions here are only preliminary. The two cases are:

Case 1. Total loss of all AC power. This implies that neither the emergency core cooling, system 323, nor the auxiliary feed water system 327, nor the containment spray, system 322, are activated. Other conditions set by the O3init input are:

- RCP coast down starts at time zero.
- Power decay due to void feed-back from 1 to 10 s.
- Closure of feed water after 10 s during 5 s.
- Isolation signal and closure of turbine valve after 10 s in 1 s.
- Scram signal after 10 s initiating fast decay of fission power.
- Pressure control at 7.0 MPa through opening of system 314 valves.
- ADS depressurisation by system 314 initiated upon low DC level, L4, and with a delay of 600 s.
- Activation of system 358 after 5000 s which opens the valve between the WW pool and LDW and fills LDW with water to a depth of at least 4 m.

Case 2. Large steam line LOCA with total loss of AC power. A flow path, FL710, from the steam line to UDW was added with an opening area of 0.22 m², corresponding to the pipe inner diameter of 0.53 m. The maximum break flow is limited by the smaller area in the steam nozzle at the vessel having a minimum diameter of 0.354 m. Systems 323, 327 and 322 will not work as in case 1. Other conditions in the input are:

- Break opens at time zero and full area is obtained after 1 s.
- RCP coast down from 0 to 10 s.
- II isolation simulated on high containment pressure > 0.15 MPa initiating:
- Scram signal and fast decay of fission power.
- Closure of turbine valve and feed water after 1 s during 1 s.
- Activation of system 358 at low DC level L4 + 600 s which opens the valve between the WW pool and LDW.

5.10 Input to MELCOR (File *O3melcor*)

While MELGEN is the pre-processor to which the majority of the input is written, MELCOR is the very MELCOR program which executes the transient calculation from a restart file originally created by MELGEN. The input to MELCOR is therefore rather short and the main part consists of instructions to the Executive Package EXEC. Among these, utilized here are:

- TITLE and JOBID records for naming and identification of a run.
- RESTART number if restart is to be done from a certain stage in the calculation, or with a “-1” from the last restart.
- Naming of the output files if others than the default names (RESTARTFILE, OUTPUTFILE, DIAGFILE, MESSAGEFILE AND PLOTFILE)
- Certain timing information such as TEND, end time of calculation, CPULIM maximum CPU time allowed. SOFTDTMIN record facilitates a reduction of the minimum time step and the number of times it can be applied, and is useful to avoid abortion at critical events when the code cuts the time step below what is normal minimum. CYMESF sets the frequency of log information presented on the screen.
- TIMEk, time step control record. A number of records can be given here for an arbitrary number of time periods into which the total time to TIMEND can be split. Each record specifies the maximum and minimum time steps, and frequencies for writing to the output file, plot file and restart file.

For most of the basic MELCOR packages very few variables can be input or changed in a MELCOR run after having once been defined in the MELGEN input. One useful variable that can be changed is the initial value of a Control Function. Another input to MELCOR utilized here is the COREDV01 to the COR package which can be used to control the printed edit and enable some plot variables to be added to the plot file.

As originally being a parametric code MELCOR has still a large number of Sensitivity Coefficients, SC cards, by which certain constants and variable values can be changed in a MELCOR run. The SC records can also be used to change certain iteration parameters. This turned out to be useful since the default convergence criteria in some cases employ very small tolerances.

6. Demonstration runs for O3

Difficulties were encountered running to full time when the BH input file “O3bh” was added. The results presented here are therefore from calculations using the NONBH set of input files. The damage progression and lower head failure is then calculated by the COR instead of by the BH package. A discussion of the experiences from the BH runs follows later in section 6.3. Two demonstration runs were performed using the different “O3init” discussed above. Case 1 is total-loss-of-power case and Case 2 a steam line LOCA.

The initial conditions are the same in all runs and are presented below.

6.1 Initial conditions

Operating data for the rated power level of 3300 MWth were obtained from the OKG utility [Ref. 3]. MELCOR steady state calculations were carried out for 600 s, which was regarded as enough to obtain stable conditions as illustrated by the plots in Figures 9 and 10 below.

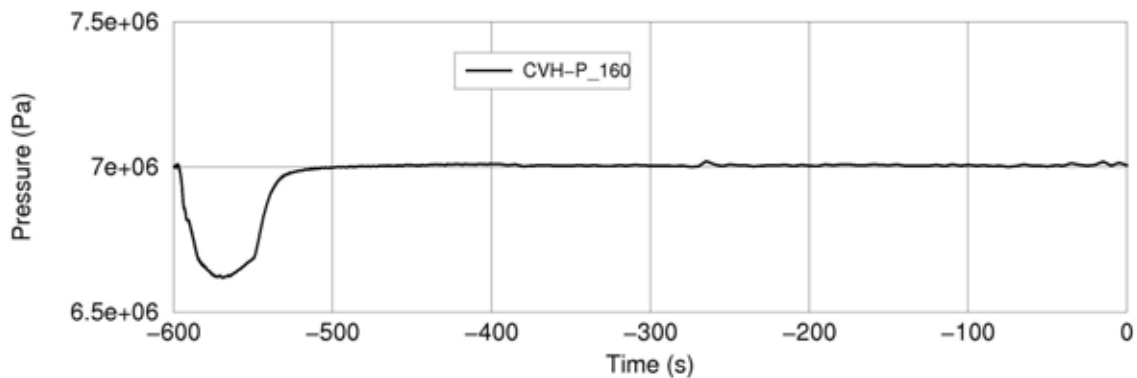


Figure 9. Steam dome pressure, from -600 to 0 s.

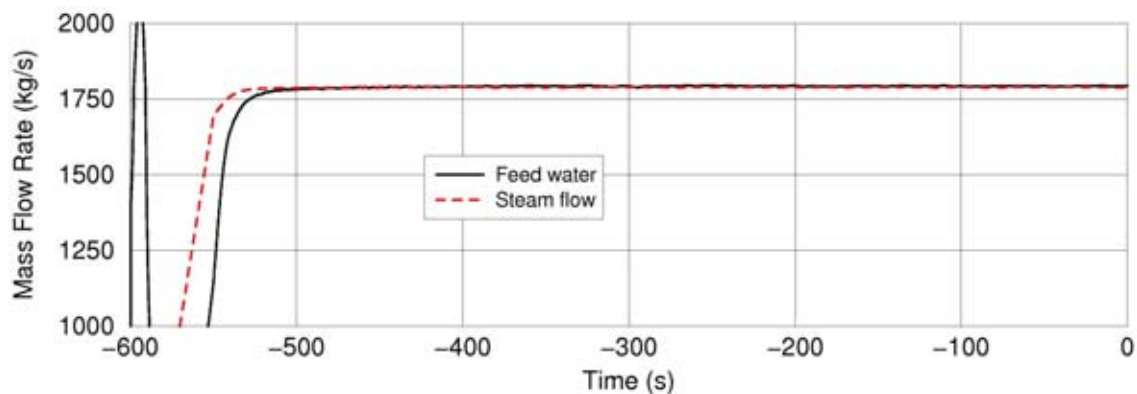


Figure 10. Feed water and turbine mass flow rates, from -600 to 0 s.

Values of some operating parameters at time zero, i. e. at start of the transient simulation are presented in Table 6.

Table 6. Initial conditions in the O3 MELCOR runs

Quantity	MELCOR	Plant data
Thermal power in core (MW)	3300	3300
Dome pressure (MPa)	7.007	7.00
Recirculation mass flow rate (kg/s) at Δp 0.37 MPa	12340	12100
Bypass flow of total (Incl. in water crosses)	0.120	-
Feed water temperature ($^{\circ}\text{C}$)	217.0	217.0
Feed water mass flow rate	1793	-
Steam mass flow rate to turbine	1790	-
DC water level above core active length	4.198	4.2

6.2 Case 1 – Total Loss of AC Power

The boundary conditions for Case 1 are described above. It was assumed that scram was obtained 10 s after the power loss and that there was an initial decrease in fission power caused by increased void in the core due to RC pump coast down. The initial power decrease from 0 to 10 s was taken from the SCDDAP/RELAP5 simulation [Ref. 5].

At 10 s also the steam lines and feed water were closed, and pressure control was maintained by the 314 valves blowing into the wetwell pool (Figure 15). Loss of water from the vessel led to a gradual decrease in DC level. At level L4, 0.5 m above the top of heated core, and after a delay of 10 minutes ADS (Automatic Depressurization System) was initiated. Water levels in the vessel are shown in Figure 11 below:

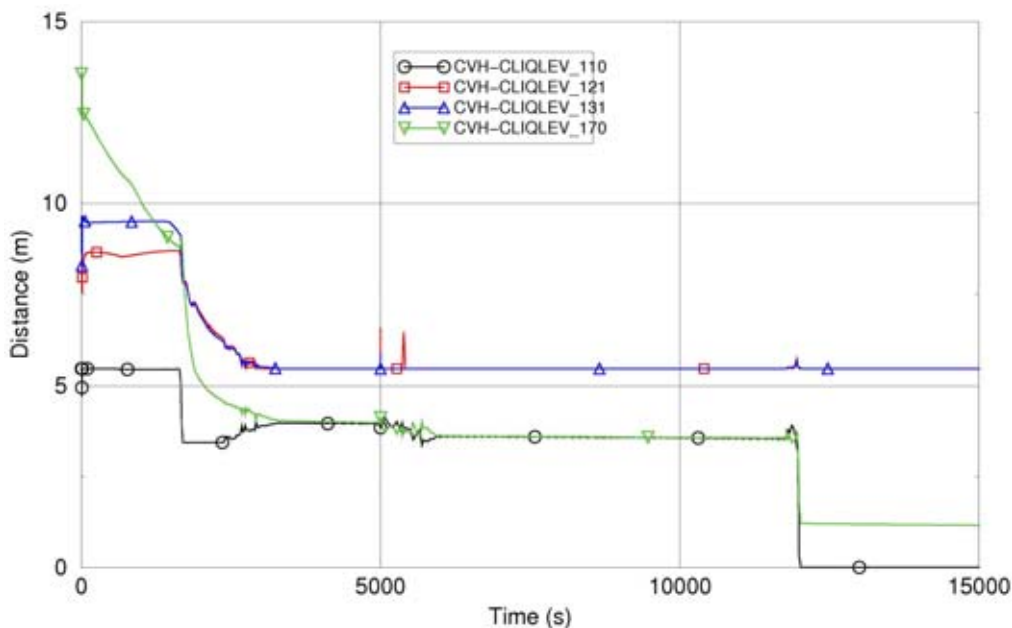


Figure 11. Collapsed water levels in LP, fuel and bypass channels and in downcomer

The ADS started a fast depressurization and led to uncover of the core which then was heated up by fission product decay as seen in Figure 12 showing the fuel temperatures. The temperature curves end when the fuel rods collapse as the Zircaloy cladding is oxidized and can no longer contain the fuel pellets.

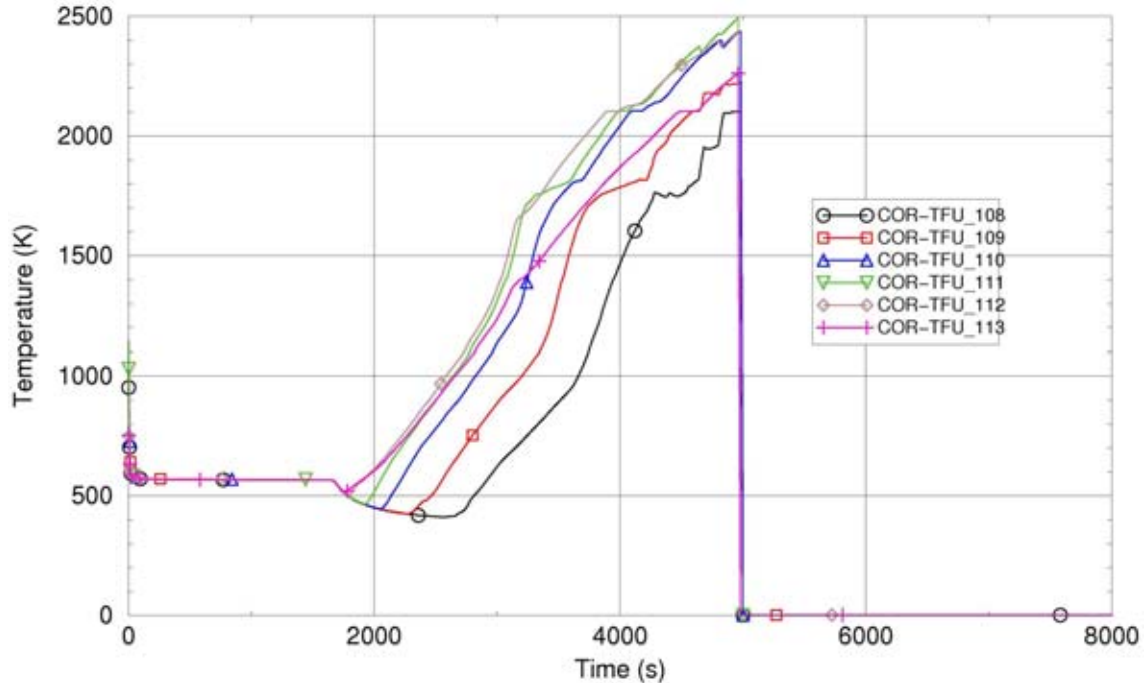


Figure 12. Fuel temperatures in the central Ring #1 in various axial cells.

The debris from the core was predicted to fall down on and heat up the core support plate, beginning at core ring 1. After 3 h 16 minutes it began to yield and core debris fell into lower plenum. There, the supporting control rod guide tubes were heated and gradually failed to support the rest of the core. There was still much water left in the lower plenum which limited heat-up of the vessel lower head. MELCOR instead calculated a rapid heating of the penetrations. These were calculated to rupture already at 3 h 19 minutes into the transient and started debris ejection into the cavity.

The strong ADS blowdown into the WW increased the pool water temperature and the containment pressure since the containment spray was assumed to fail. 5000 s into the transient the valve in system 358 was opened permitting overflow of water from WW to LDW cavity, which was flooded before the core debris ejection. The breach of the vessel emptied the water from the lower plenum adding water to the cavity. Heating from the debris increased the containment pressure in absence of external cooling so it eventually, at 18.9 h, reached the break pressure, 5 bar, of the MVSS rupture disk.

The results of Case 1 are discussed further in Section 6.5 in which a comparison is made with those of LOCA Case 2. The comparison includes a table of events and some additional plots in figures 15-19.

6.3 Case 2 – Large Steam Line LOCA

The initiating event is a full area break in one of the steam lines discharging steam into the upper drywell. A total loss of all AC power is assumed to occur simultaneously. The break flow is limited by critical flow in the steam outlet nozzle and reaches initially 1030 kg/s, but is then temporarily larger with decreased void as shown in Figure 13.

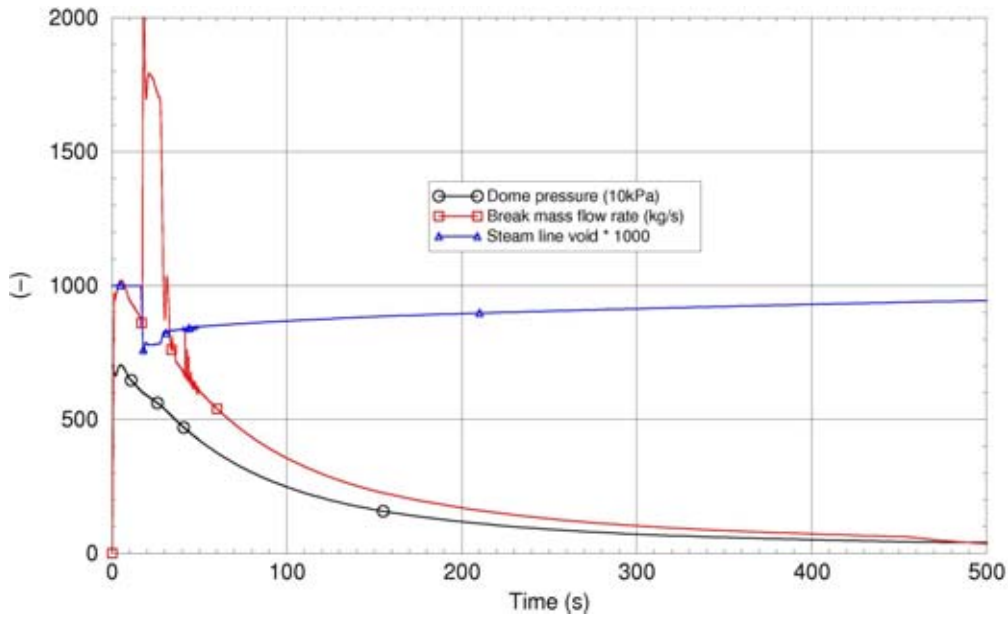


Figure 13. Break mass flow rate in Case 2; Large steam Line LOCA.

The drywell pressure increased rapidly due to the large break flow and triggered isolation signal and scram after 1.6 s. Core heat up started already at 180 s in the upper part of the core and rupture of fuel cladding began after about 19 minutes. Figure 14 shows fuel temperatures in Ring 1.

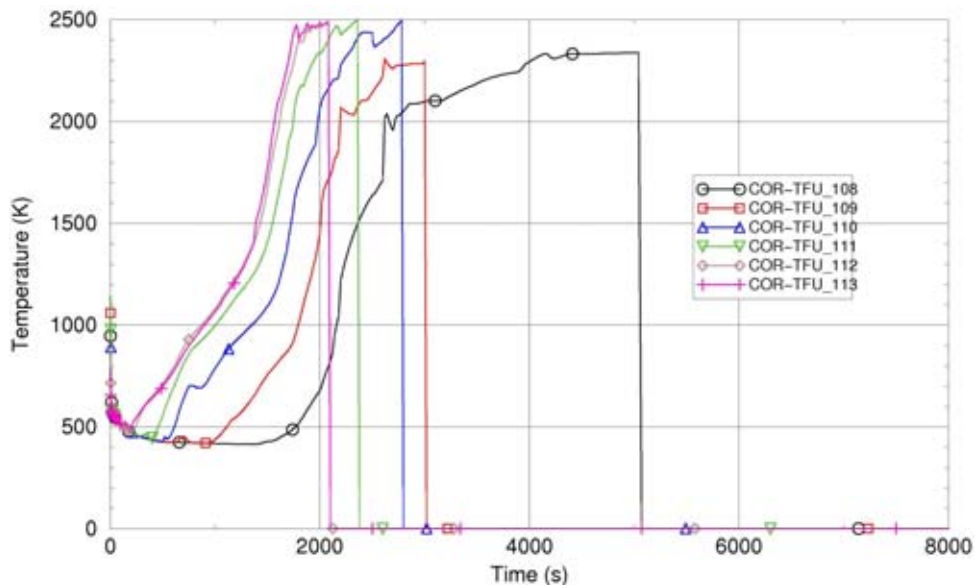


Figure 14. Fuel temperatures in the central Ring #1 in various axial cells.

After about 2 h and 15 minutes core debris fell into lower plenum and melted through the central penetrations only 3 minutes later. However, already before that a pressure spike (Fig. 15), caused by debris quenching in lower plenum, propagated to the containment exceeded the rupture disk set pressure of 5 bar and opened venting to the MVSS.

Additional results of Case 2 are presented and discussed in section 6.5.

6.4 Tests with the Bottom Head, BH model

The input to the BH package (Appendix D) was prepared according to the manual and following the input examples where they were applicable to the O3 case, as described in Section 5.6.

The test runs were made with boundary conditions identical to those for Case 1 in the “NONBH” run. The BH input was accepted by MELGEN without errors, but the transient run with MELCOR failed when it came to the debris quenching stage. The difficulty is that the code aborted without any error messages or any attempts to cut down the calculation time step. The only remedy seemed to be to reduce the maximum time step to small values, but then the computation time became unwieldy.

It looks as if the problem has to do with the decoupling of heat structures in lower plenum that is done in the transition from the COR to the BH package in the MELCOR calculation, according to the recommended input specification. This occurs when there is a certain amount of debris passed from the core to lower plenum. To avoid abort by the RN package due to loss of settling surfaces when the heat structures are decoupled, the manual recommends introduction of an RNSET record for the lower plenum, setting the *from* control volume equal to the *to* volume. However, introducing this caused the code to abort without error messages, as mentioned above. Without RNSET the calculations went on further, but stopped with the error message “No settling area ...”. The cause of the problem might be that the model in the BH package is adapted to the jet pump BWR which has a different configuration with a baffle plate in lower plenum which not exists in the O3 BWR.

After several attempts trying some recommended sensitivity coefficients and decreasing the candling heat transfer coefficient for steel from default 1000 to 10 W/M²K the code succeeded to continue behind the transition from COR to BH modelling. It then ran up to about 13 h into the transient until new convergence problems arose. Since the BH version of the code could be executed only with some variables set to unrealistic values the results might not be reliable either and any detailed evaluation and presentation of these are therefore not made. A few results are included in Table 7. The input used here is included in Appendix D.

6.5 Summary of the demonstration runs

The demonstration runs showed that the input deck without the BH package worked satisfactorily even if some results might be questionable, what is discussed in Chapter 7. Calculation times were reasonable, a factor of 1.2 real time in Case 1 and 0.92 in Case 2. For the BH version Case 1 was noticeable slower. The execution generally slowed down considerably during critical phases, such as during debris quenching and penetration rupture.

A summary of events, comparing the results of Case 1 with and without the BH package and Case 2 is given in Table 7 with times read from the Message output file .MES.

Table 7. Some time of events calculated by MELCOR.

Event	Case 1 NONBH	Case 1 BH	Case 2 NONBH
Start of transient	0.0 s	0.0 s	0.0 s
Scram	10 s	10 s	1.6 s
Low level L4 in DC	17 min 31 s	17 min 31 s	55 s
ADS initiation	27 min 31 s	27 min 31 s	-
First rupture of cladding	46 min 56 s	46 min 34 s	18 min 43 s
Failure of core support plate	3 h 16 min (Ring 1)	2 h 57 min (Ring 1)	2 h 15 min (Ring 1)
Start of debris quench in LP	3 h 16 min	2 h 57 min	2 h 15 min
Penetration failure in Ring 2	3 h 19 min	2 h 58 min	2 h 18 min
Gross head failure occurs	-	5 h 48 min	-
Containment pressure > 5 bar	18 h 55 min	11 h 25 min	2 h 17 min

A large number of variables are available for plotting from the output plotfile. A few plots for the NONBH cases are shown in the following figures 15 to 19.

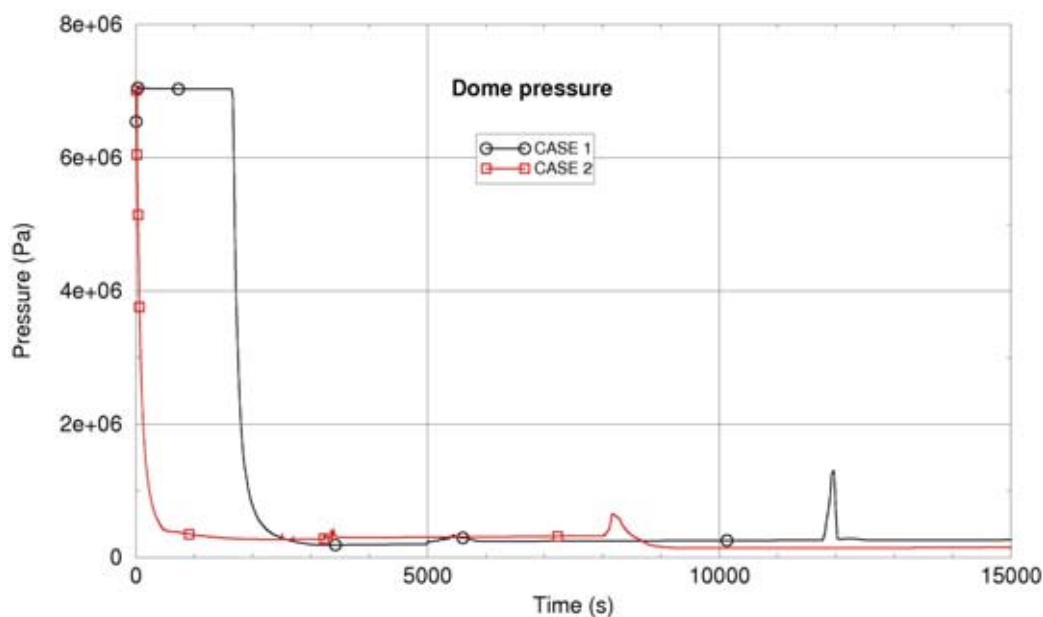


Figure 15. Pressure in steam dome in Case 1 and Case 2 (NONBH)

The pressure in the steam dome decreased to about 4 to 5 bar after steam blowdown, either by ADS relief as in Case 1, or through the steam line break in Case 2. The debris quenching caused temporary increase in steam production resulting in the pressure peaks around 12000 and 8200 s, respectively.

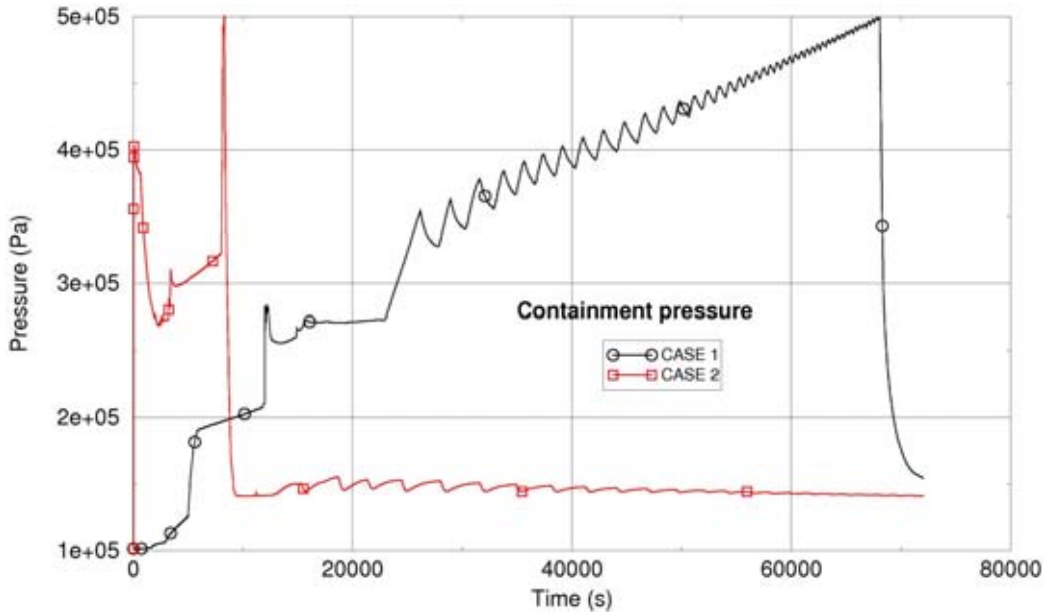


Figure 16. Pressure in the containment upper drywell in Case 1 and 2.

Figure 16 illustrates the different behaviour of the containment pressure in Case 1 and 2. In Case 1 the pressure increase is relatively slow as it is caused by release from the system 314 valves until the discharge from the vessel occurs. Boiling in the cavity then gradually raises the pressure until the release to the MVSS takes place. In Case 2 the large break flow directly into the upper drywell atmosphere, and then the debris quenching in lower plenum, caused sharp pressure spikes in the containment. The oscillations in pressure is probably caused by fluctuating flow and condensation in the wetwell pool.

Oxidation, primarily of zirconium, in the core generated totally 711 and 781 kg of hydrogen in Case 1 and Case 2, respectively, as seen in Figure 17. It corresponds to oxidation of about 56% and 62 % of the rod cladding, or 32 and 35 % of the total mass of zirconium. Since the atmosphere in the containment consists of nitrogen and steam no burning of hydrogen occurs. The volume of hydrogen is significant and as a non-condensable gas it contributes to the increase in pressure.

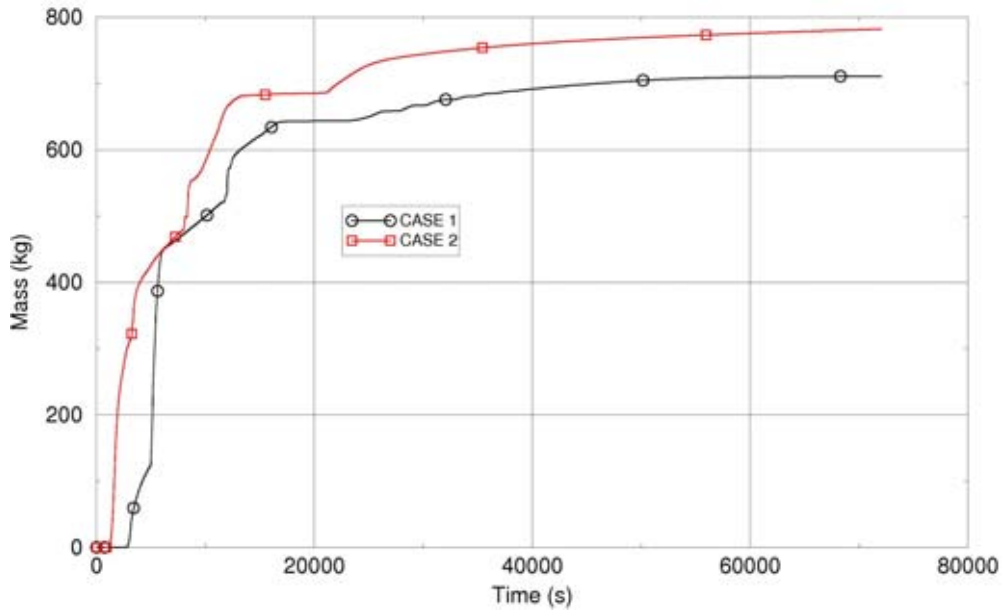


Figure 17. Hydrogen mass produced in the core in Case 1 and 2.

Release of fission products into the coolant started with the first rupture of the fuel cladding. Radioactivity was then transported by the steam into the containment, initially by 314 blowing into the WW pool in Case 1, or through the large steam line break in Case 2 into upper drywell. After failure of the lower head penetrations additional release took place into the lower drywell. Figure 18 shows the release of the caesium fraction.

MELCOR predicted that the major part of the Cs remained in the containment also after venting through the MVSS. This was especially so in Case 1 where the initial release was washed out in the wetwell pool. In Case 2 where the release was mainly into the drywell atmosphere a larger amount was blown into the MVSS.

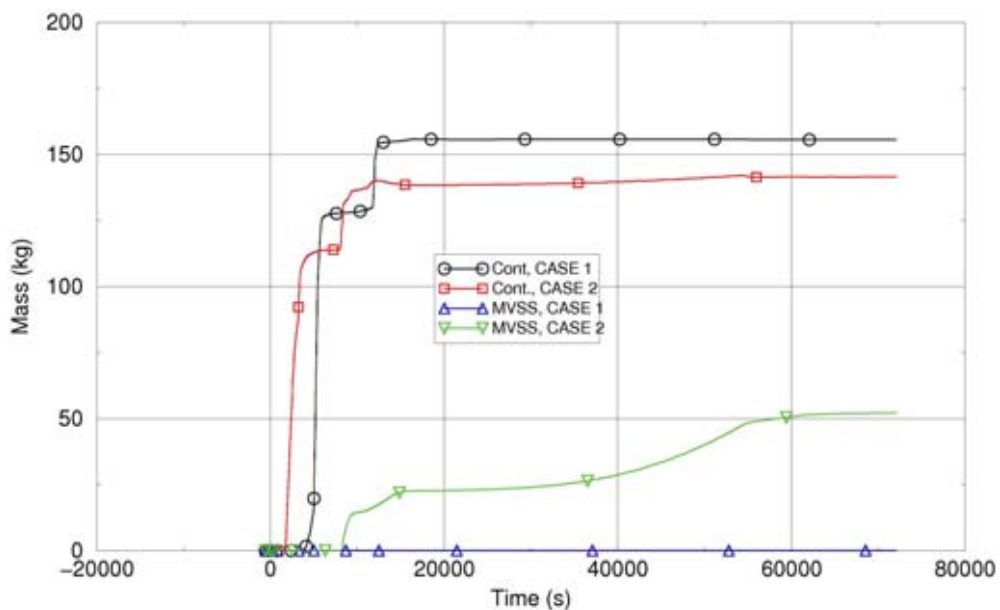


Figure 18. Mass of Caesium in containment and in the MVSS

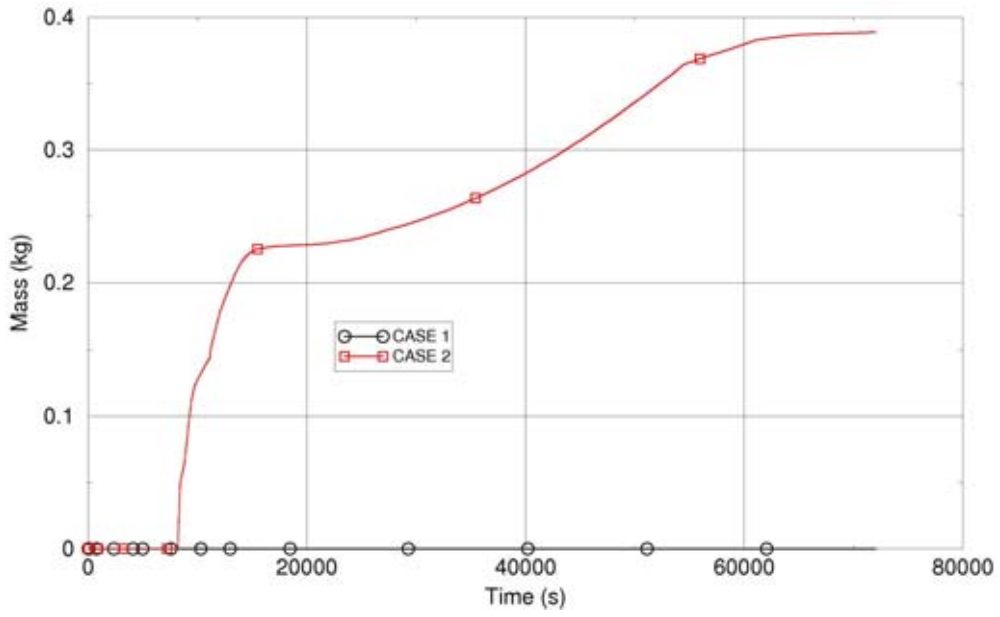


Figure 19. Release of Caesium through the MVSS to the environment

The modelling of the MVSS function has not been validated and is only made by application of the MELCOR pool scrubbing model. This shows a very good retainment of aerosols and a very small fraction of the Cs released to the environment as seen in Figure 19 above.

7 Conclusions and Recommendations

The input model of Oskarshamn 3 to MELCOR 1.8.5 has been completed in adequate detail for the reactor vessel with connecting systems and for the containment inclusive the MVSS. The input base model, i. e. without input to the ORNL Bottom Head package was tested and found to work satisfactorily for two tentative accident scenarios; Case 1, total loss of AC power and Case 2, large steam line LOCA.

The performed calculations of Case 1 and Case 2 should be regarded as demonstration runs only to test the function of the input. When the input deck is going to be used for actual severe accident sequences in future analyses review of the boundary conditions should be made. Although MELCOR seems to predict the severe accident phenomena qualitatively well there are questions concerning some quantities.

The melting of vessel penetrations arrived relatively early despite the conservative heat transfer areas and melting temperature that were assumed compared to default values. Penetration failure arrived with still a considerable mass of water left in lower plenum, the water level being about 4 m. In a test without penetrations, modelling “gross head failure”, the water level was about 2 m at vessel failure.

MELCOR gives the user wide possibilities to influence the calculated results. In addition to values which can be changed from default on many input records there is a large number of sensitivity coefficients aimed for parameter studies. Special attention should be paid on certain of the input variables in further applications of the O3 input model such as:

- Modelling of debris heat transfer in lower plenum. Variables are, among others, debris particle diameter and porosity, heat transfer coefficient, and falling velocity of debris particles.
- Modelling of vessel penetrations. It was noticed that the default conditions are more conservative in the BH than in the COR package. In BH only instrument tubes, not control rod penetrations are modelled as a rule. Parameters which have effect on penetration failure conditions should be investigated further.
- The concrete composition used in the CAV modelling is preliminary and is same as in the Ringhals 3 MAAP model. The composition should be checked against real data for the LDW floor, especially with respect to the mass of steel reinforcements. Tests without LDW flooding and application of the degassing model could demonstrate the effect of concrete composition and flooding.
- The fission product decay heat function is crucial for the heat-up in- and ex-vessel and thus for the accident progression. Review of the decay function and parameter studies are here recommended .

Since a new code version, MELCOR 1.8.6, was released just before the completion of this input deck and the separate BH package is there abandoned, it is recommended to convert the 1.8.5 input deck into the 1.8.6 version using the O3 data produced here for the BH package.

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