ANALYSIS OF CONFINEMENT STRATEGIES FOR A TOKAMAK FUSION REACTOR

SAFETY/ENVIRONMENTAL ASPECTS

KEYWORDS: *fusion reactor, confinement, safety*

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The Safety and Environmental Assessment of Fusion Power (SEAFP) was performed in the framework of the European fusion program, whose results have already been published. The European Commission decided to continue this program for some identified issues that required development. One of these issues was the analysis and specification of the containment concepts that minimize accidental releases to the environment.

To perform such an assessment, a methodology was followed to identify the most challenging accidental sequences in terms of containment integrity.

The results of the accident selection and analysis that were performed during the extension of the SEAFP-2 program are given. Preliminary recommendations for the definition of a confinement strategy for tokamak fusion reactors are established.

I. INTRODUCTION

A review of U.S. fusion safety work[1] and European tokamak reactor conceptual studies[2–5] show that a clear definition of a confinement strategy is required for compliance with nuclear safety objectives. This confinement strategy can be defined as an optimization between passive systems (container volumes or containment barriers) and active systems that are designed and set up to protect the containments from external or internal hazards.

The work presented in this paper is part of the Safety and Environmental Assessment of Fusion Power (SEAFP)-2 program entitled "Improved Coverage of Events." This work primarily consists of two tasks:

1. identification of sequences in which containment bypass is possible
2. calculations concerning certain complex sequences involving bypass of containment barriers (rather than a full breach), multiple failure sequences such as loss of heat sink, and failures that can be attributed to an electric arc on the magnets.

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Another objective of this program was to discuss the effect of the confinement strategy on the external releases for these complex and highly hypothetical sequences. Consequently, two reference designs for the containment were defined by using a bibliographic study of different containment concepts[6,7]: large containment and inner containment. Of course, the containment concept defined in the previous SEAFP program[3] was kept as reference.

The selection of the containment design was based only on volumetric and topological considerations; i.e., suggested pressure suppression systems were added only if shown to be necessary by the results of the assessment. On the other hand, two plant models were used to perform this evaluation. They were defined with the goal of reducing doses to the public in case of external releases and reducing the volume of active waste.

The process selected to define the most important sequences is based on a top-down approach, which was recognized as a more general methodological approach when detailed data on the reactor outline are not available. The top event was defined as excessive external radioactive releases, and the use of a top-down reasoning process (deductive) was followed, leading to the identification of events that could initiate a sequence that causes external releases.

II. DEFINITION OF ACCIDENT SEQUENCES

II.A. Methodological Approach

The top-down approach, using master logic diagrams[8] (MLDs), is used to help update the accident initiating event list previously identified by different techniques (hazard operation and functional failure mode and effect analysis) in the first SEAFP program.

The MLD technique has been used in this study to verify, update, and complete the initiating events list. This approach formally organizes the search for initiating events by constructing a top-down logic model and then deduces the appropriate set of initiating events.

The top event of the MLD represents the undesired event, i.e., excessive radioactive release for a nuclear installation. MLDs are constructed from the top down by postulating an excessive release at the site boundary and by considering all possible failures that could lead to this event using logical AND and OR gates. To ensure completeness, different levels are considered, the bottom one being constituted by the initiating event of the possible sequence. An example of the principal MLD of this analysis is shown in Fig. 1.

Following the SEAFP-2 program specification,[a] attention was focused on those accident scenarios that can challenge the containment integrity. This is why, taking advantage of the MLD performance, it was decided to analyze different types of containment concepts. All accident scenarios were investigated by considering different containment schemes to contribute to the best containment concept selection.

Two different types of containment have been considered for this SEAFP-2 assessment: (1) type B, based on the idea of containment foreseen for the International Thermonuclear Experimental Reactor[9] and called the inner containment option, and (2) type C, based on the idea of a large containment at the building level as the containment concept used for a pressurized water reactor (PWR) and called the large containment option.

For each containment concept, two plant models have been considered for the internal components: (1) model 2 is similar to the SEAFP water-cooled model, but with a new reference low-activation martensitic steel (^{17}Li^{83}Pb is the breeder/multiplier material), and (2) model 3 is similar to the helium-cooled, pebble-bed, martensitic steel DEMO blanket concept, with the same steel as model 2. The major features of the concepts related to the different options are as follows:

1. Model 2—type B containment concept (Fig. 2)
    a. a pressure suppression system (PSS) for the vacuum vessel (VV) that operates when vacuum vessel pressure rises up to 200 kPa
    b. no expansion volume
    c. a filter scrubber to protect second containment for ultrasevere accidents (it opens at 140 kPa and limits the pressure below 160 kPa)
2. Model 3—type B containment concept (Fig. 3)
    a. expansion volume (designed at 500 kPa) as foreseen for SEAFP model 1 design
    b. a filter scrubber to vent the expansion volume to the stack (when expansion volume pressure exceeds 140 kPa)
3. Model 2—type C containment concept (Fig. 4)
    a. no PSS
    b. no expansion volume
    c. no filter scrubber for the second containment; a filter scrubber to protect second containment for ultrasevere accidents (it opens at 140 kPa and limits the pressure below 160 kPa)
    d. the second containment with a double-walled structure and controlled atmosphere in the interspace; the maximum pressure for a PWR containment is ~500 kPa

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[a] For the SEAFP-2 program, the highest-level objective is as follows: Public evacuation is never required in case of accidents, even in the event of the worst physically possible accident (ignoring external hazards).

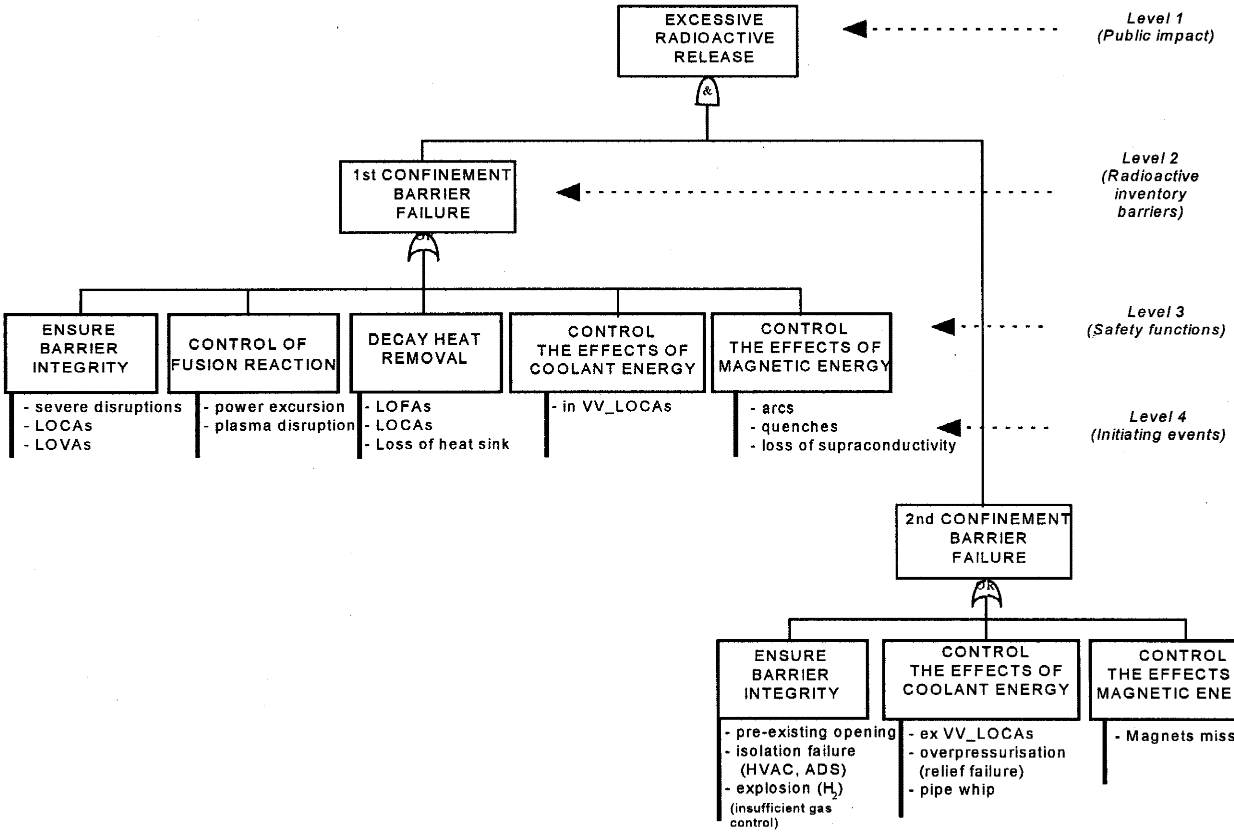

Fig. 1. Example of MLD for a fusion reactor.

4. Model 3—type C containment concept (Fig. 4)
   a. no PSS
   b. no expansion volume
   c. same conditions as for model 2 but with a controlled venting to the atmosphere for ultrasevere accidents, and a filter scrubber to protect second containment for ultrasevere accidents (it opens at 140 kPa and limits the pressure below 160 kPa)
   d. the second containment with a double-walled structure and controlled atmosphere in the interspace; the maximum pressure for a PWR containment is ~500 kPa.

II.B. Selected Sequences

II.B.1. Bypass Sequences

Possible bypass of the first and second containment has been emphasized because it can result in direct environmental releases. Furthermore, release into the second containment could cause release to the environment through leaks, through the ventilation system, or through a preexisting opening.

1. For plant model 2/containment type B, the most relevant bypass events are those involving the higher radioactive inventories, such as loss-of-vacuum accident (LOVA), loss-of-coolant accident (LOCA) in secondary cooling loops, large primary heat transfer system (PHTS) LOCA to secondary cooling loop, PHTS LOCA to LiPb circuit, and magnet energy release. Other bypass events, such as cryogenic circuit breach inside the main vacuum cryopumps, will involve a lower amount of radioactive material or they will have a lower cross-section area for environmental release (e.g., through piping). To limit the number of possible bypass events, the PSS must be designed to withstand overpressure in the plasma chamber.

2. For plant model 2/containment type C, the most relevant bypass events are a LOCA in the secondary cooling loops and a failure of the plasma shutdown. To avoid that, a PHTS LOCA to the LiPb circuit results in a containment bypass, so the LiPb circuit should be completely inside the second containment.

3. For plant model 3/containment type B, the most relevant bypass events are LOVA, cryogenic circuit breach

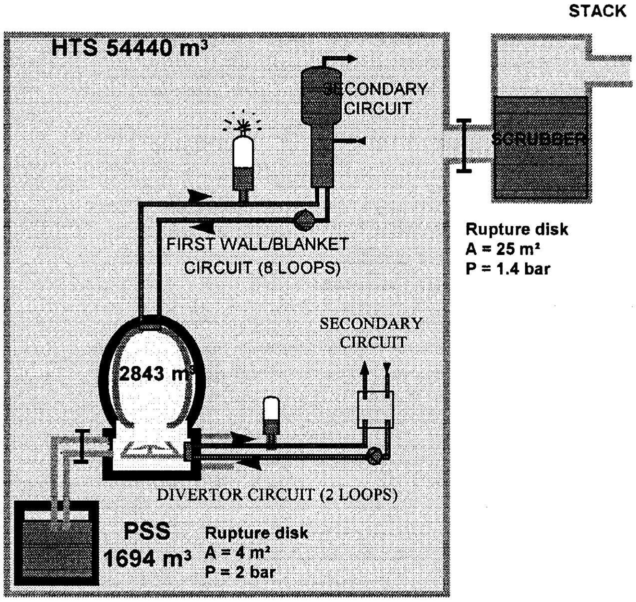

Fig. 2. Inner containment with PSS (type B) model 2, water cooled.

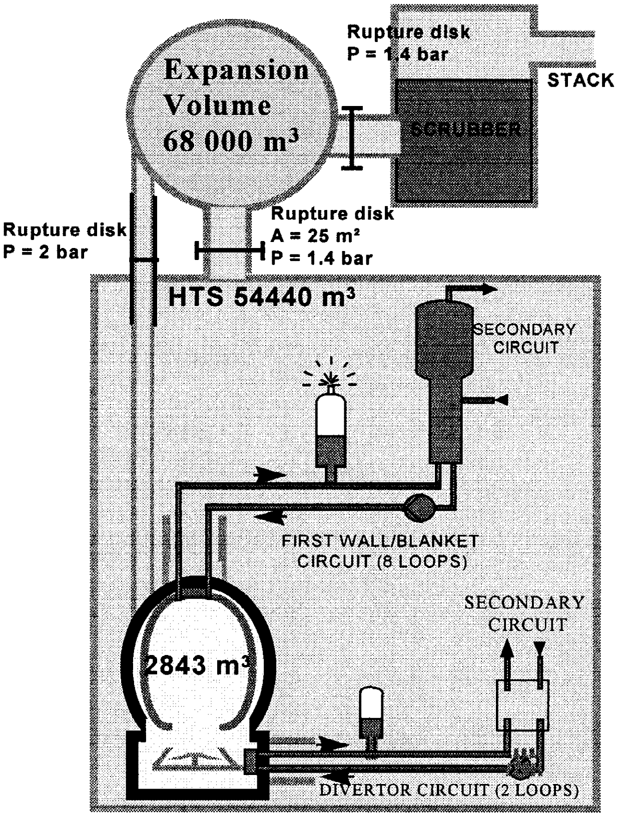

Fig. 3. Inner containment with EV (type B), Model 3, helium cooled.

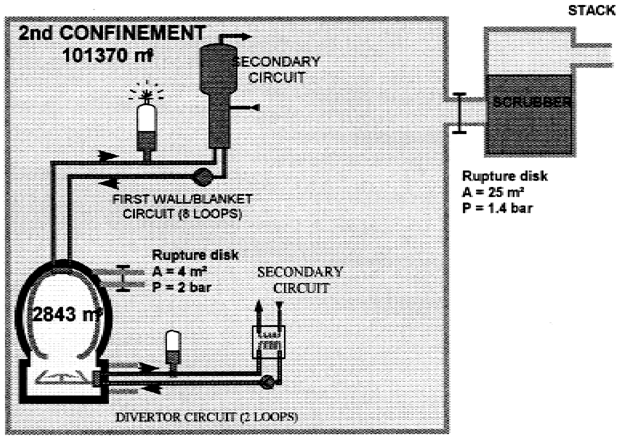

Fig. 4. Large containment (type C), models 2 and 3.

in the main vacuum cryopumps, LOCA in secondary cooling loops, large PHTS LOCA to secondary cooling loop, PHTS LOCA to helium purge gas circuit, and magnet energy release. To limit the number of possible bypass events, the expansion volume (EV) must be designed to withstand overpressure in the plasma chamber.

4. For plant model 3/containment type C, the most relevant bypass events are a LOCA in the secondary cooling loops and a failure of the plasma shutdown. Other possible bypass events [such as heat transfer system (HTS) LOCA to purge gas circuit or cryogenic circuit breach inside the main vacuum cryopumps] will involve a lower amount of radioactive material, or they will have a lower cross-section area for environmental release (e.g., through piping).

Bypass sequences can be split into two categories:

1. those that can be eliminated by design, such as LOCA to residual heat removal system, emergency cooling system, LiPb circuit, or purge circuit. The most straightforward approach is to terminate the auxiliary circuits in question within the secondary containment.
2. those that need detailed analysis such as LOCA to the secondary circuit where precise description of the pipes is necessary to get accurate results.

   This comes in two forms: (a) steam generator tube rupture and (b) secondary circuit break within the containment, inducing an ex-vessel LOCA of the primary circuits.

To correctly predict the consequences of such accidents, the appropriate analysis may be to use a less conservative mobilization analysis than is usually done in fusion safety and use PWR studies to estimate retention fractions in piping and auxiliary buildings since no fusion project has enough details on these fractions.

II.B.2. Important LOCAs

The term "important LOCAs" is used to denote complete losses of the coolant inventories for all loops that, if no credit is taken for the operation of any active safety system, might potentially be the consequence of loss-of-heat-sink events (of various types), loss of site power, or human actions. The appropriate response may vary according to whether the cooling is by helium or water:

1. *Model 2*. If the coolant is water, there are many ways to maintain a closed containment strategy by means of condensing arrangements. This should be combined with less conservative mobilization analysis.

2. *Model 3*. If the coolant is helium, it cannot be condensed, so containment of the coolant by decreasing the pressure may require an uneconomically large expansion volume. Realistic mobilization analysis may show that it would be perfectly acceptable to vent the outer containment in these cases. For example, venting could be envisaged, at low overpressure, through a tower of prerefrigerated, insulated stones.

II.B.3. Magnetic Energy Releases

Two (hypothetical) threats to the containment were identified as follows:

1. *Energetic fragments*. The most unlikely possibility was eliminated by detailed analysis in SEAFP, but the issue is not completely resolved. A robust rough analysis is needed to scope the containment structures needed.

2. *Major arcing*. Bypass possibility from arcing events is being discussed for ITER, and up to now, no decisive answer is given to eliminate this possibility. However, in a project such as SEAFP-2, i.e., in a design stage, it seems likely that this can be eliminated, provided that there are fewer space constraints.

II.B.4. Hydrogen

The topic of potential hydrogen generation and combustion raises issues related to the interaction between containment strategies and restrictions on material combinations.[7] Inerting of containment volumes, which is an option available to SEAFP-2 (as in SEAFP), could be a large part of the solution as well as the use of hydrogen inhibitors. The presence in a design of both oxidizable beryllium and water is certainly contraindicated. In the case of model 3, it may be possible to eliminate water (from the shield and the secondary circuit). In the case of model 2, it may be possible to eliminate beryllium by using tungsten (or some other candidate material) as the armor. For model 3, the possibility of replacing metallic beryllium by a nonoxidizable beryllium compound should be explored.

III. DESCRIPTION OF THE SELECTED ACCIDENTAL SEQUENCES

Using the top-down approach, a number of accidental sequences were identified to be assessed in detail. It was found that because of the number of failed barriers, the sequences involving bypass and the sequences with an important LOCA were the most crucial as far as excessive radioactive release was concerned. It was also found that an assessment of magnet energy hazard–induced sequences had to be performed to complement previous SEAFP works.

III.A. Bypass Sequences (Bypass Through the HTS)

The sequence to study is initiated by a steam line rupture which induces a 10-tubes steam generator tube rupture (SGTR) and leads to an in-vessel break. The goal is to (1) quantitatively evaluate whether the initiator could really induce the bypass of containment, (2) determine both the pressure loads on containment and the radioactive release through the individuated paths, and (3) perform a sensitivity analysis (to give an assessment on important parameters to take into account in next design), both to mitigate the accident consequences and define retention features.

The times when the different ruptures occur will be considered as parameters as well as the time of plasma shutdown.

III.B. Loss of Heat Sink

This case is treated as a highly hypothetical sequence in conventional nuclear reactors, but a suitable confinement strategy could control the releases and keep them below the evacuation limits.

This sequence involves the loss-of-heat-sink event, which leads to a complete loss of coolant inventories for all loops after opening the different pressure relief valves. The energy released and the decay heat removal strategy thus have to be controlled by other means (active or passive).

This study will propose different mitigating alternatives related to the type of coolant (helium or water) and to the containment concepts defined in the task.

III.C. Magnet Accident Sequences

In some confinement strategies, the cryostat is all or part of the second barrier; therefore, damage of this barrier as a result of magnet accidents must be investigated. Two mechanisms of damage are possible: damage due to mechanical interaction and damage due to thermal interaction.

Mechanical interactions can be missiles (i.e., loose metal parts accelerated by the magnet field) or a helium release from the coolant system of the magnets pressurizing the cryostat. Those mechanisms have been investigated under SEAFP, so the missing part is the thermal interaction between the magnet system and the cryostat.

In a previous study,[10] ten different electrical faults of the toroidal field circuit were investigated and evaluated in terms of maximum consequences of the cryostat. It was found that a double short to ground at the bus bar of one coil probably has the most severe consequences on the cryostat wall. During the dump of the coil energy, such shorts can ignite at the bus bar because of a multiple insulation failure.

IV. EVENT SEQUENCES ANALYSIS

IV.A. Bypass Through the Heat Transfer System

The accident scenario studied for model 2 is initiated by a steam line break, which leads to an SGTR and eventually a first wall break.[11] The steam line break occurs on the secondary side and within the second containment (see area 1 in Fig. 5). (Failures outside the second containment are controlled by isolation valves preventing release of the secondary coolant into the buildings.) It is assumed to be a double-ended guillotine break, and the steam line diameter is 0.6 m. The break results in a rapid secondary-side depressurization and is assumed to cause ten steam generator tubes to rupture (see area 2 in Fig. 5). Coolant from the primary circuit will escape to the steam generator secondary side, and the subsequent loss of primary cooling will lead to a break in the first wall (see area 3 in Fig. 5). It is assumed that all first-wall cooling pipes in one segment are ruptured.

Steam coming from the steam line break will cause a pressure increase in the second containment. Activated materials contained within the vacuum vessel will be transported to the secondary circuit and from there directly to the second containment.

The study of the pressure transients and the characteristics of the releases have been the main objectives of this work. The code used for the analysis is MELCOR 1.8.3 (Ref. 12).

IV.A.1. Pressure Loads

The pressure in the second containment exceeded the design pressure for both the type B and type C containment concepts (Fig. 6). The maximum pressure greatly depends on the design of the scrubber. Parameters seen in this study to affect the second containment pressure are PSS rupture disk area, vent pipe diameter, and pool depth. A sensitivity study was performed using the parameters given in Table I, and the results are shown in Figs. 6 and 7.

The size of the scrubber rupture disk, instead of the scrubber vent pipe diameter, affects the speed of depressurization of the second containment. The area of the vacuum vessel rupture disk (see B_{ref}, B_{05}), does not affect the maximum pressure in the second containment because the vacuum vessel pressurization is limited by the choked flow at the in-vessel break, and consequently, the ex-vessel break has the same flow rate in both cases.

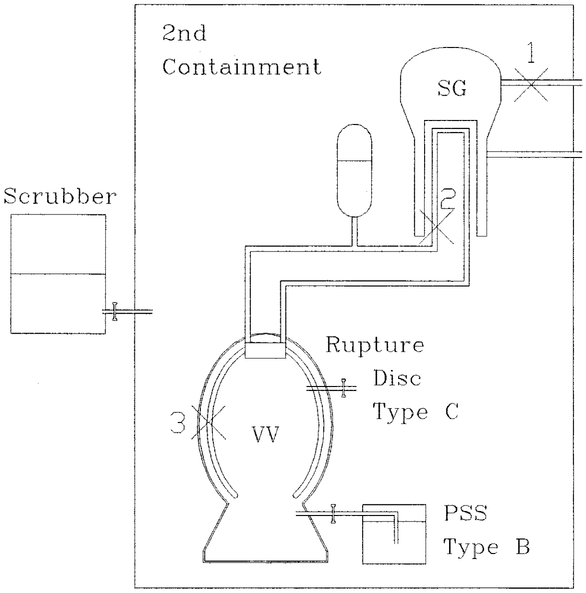

Fig. 5. Bypass accident scenario representation.

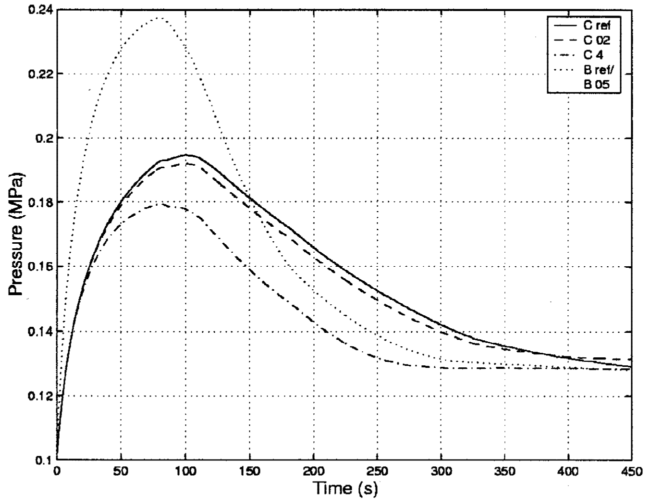

Fig. 6. Pressure in second containment, all cases.

TABLE I

Sensitivity Study Parameters

Case	Description
B_{ref}	Reference case: Type B containment concept; Scrubber rupture disk area, 2 m^2; Scrubber vent pipe diameter, 0.1 m; PSS rupture disk area, 2 m^2
B_{05}	Type B containment concept; Difference from reference case: PSS rupture disk area, 0.5 m^2
C_{ref}	Reference case: Type C containment concept; Scrubber rupture disk area, 2 m^2; Scrubber vent pipe diameter, 0.1 m; Vacuum vessel rupture disk area, 0.6 m^2
C_{02}	Type C containment concept; Difference from reference case C_{ref}: Scrubber vent pipe diameter, 0.2 m
C_4	Type C containment concept; Difference from reference case C_{ref}: Scrubber rupture disk area, 4 m^2

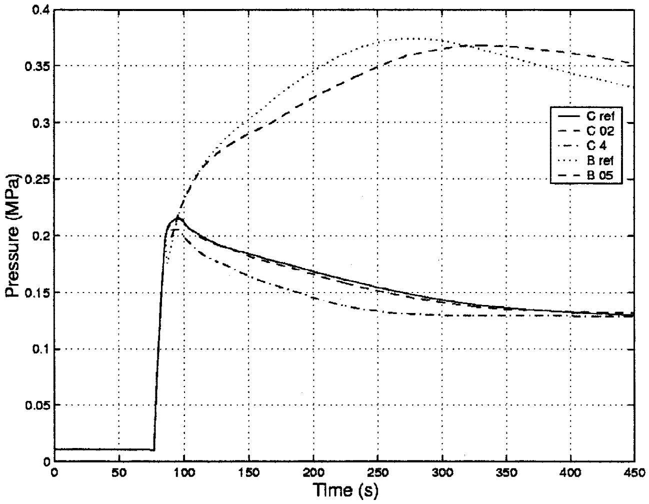

Fig. 7. Pressure in vacuum vessel, all cases.

In the type C case calculations, the vacuum vessel is vented to the containment, resulting in a fast depressurization of the vacuum vessel. In the type B cases, the vacuum vessel is vented to the PSS. For both containment concepts, the vacuum vessel pressure stayed below the design pressure of 0.5 MPa for all cases (Fig. 7).

IV.A.2. Releases

IV.A.2.a. Type B Containment Concept. For the type B containment concept, aerosols were initially transported from the vacuum vessel into the pressure suppression pool. When the pressures in the vacuum vessel and primary system have leveled out, the aerosols reach the second containment via the steam generator. This results in lower releases for the type B cases. However, leaks through the vacuum vessel walls occurring because of the pressure difference are not taken into account in this study. These leaks would be larger for the type B containment concept than for the type C containment concept because the vacuum vessel reaches atmospheric pressure considerably faster in the type C calculations (Fig. 7).

When the aerosols finally reach the second containment, the pressure here has decreased considerably, and there only remains a small mass flow into the scrubber. This results in small releases to environment, $\sim 10^{-16}$ kg of gaseous tritium (HT).

IV.A.2.b. Type C Containment Concept. For the type C containment concept, the releases reach the second containment mainly via the vacuum vessel relief valve but also via the steam generator tube rupture and steam line break.

A small amount of the HT entering the scrubber remains there, on heat structures and in the atmosphere above the pool, but not in the pool as scrubbing of vapors is not included in MELCOR models. The major part of the HT passing through the scrubber is released to environment.

The amount of HT escaping to the environment depends more on the duration of the flow out from the scrubber than on the mass flow rate (Fig. 8). Case C_4, with a large rupture disk and a faster depressurization, results in the lowest HT release (Fig. 8). Case C_{ref}, with the smallest rupture disk area and vent pipe diameters, results in a longer transient and a larger HT release to environment.

Compared with the HT releases, small amounts of beryllium are released (Fig. 9). This is because beryllium is removed by the scrubber. The scrubber works more efficiently when a small rupture disk is used, i.e., generating smaller mass flows.

IV.A.3. Conclusions on Bypass Through the HTS

The pressure in the second containment increases above the design pressure in all cases, even if systems to relieve pressure are in operation. In the sensitivity study,

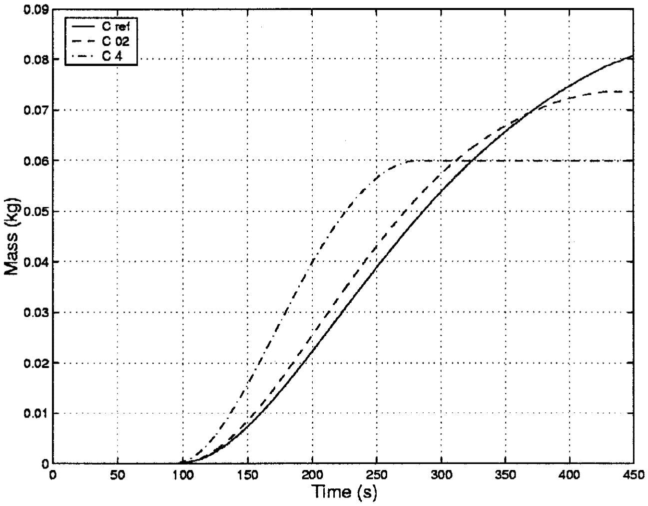

Fig. 8. HT releases to environment, type C cases.

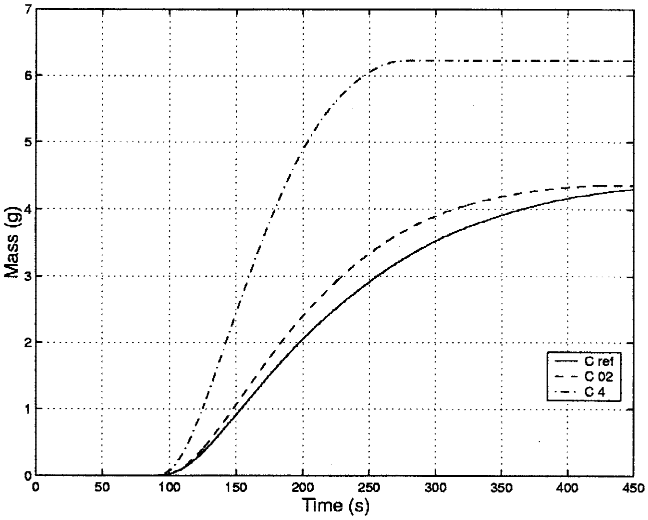

Fig. 9. Beryllium releases to environment, type C cases.

it is shown that increasing the size of the rupture disk decreases the maximum pressure reached during the transient. The type B concept, including a smaller second containment volume, results in a larger maximum pressure than the type C concept, which has a larger second containment volume.

In all cases, after the in-vessel break, the vacuum vessel pressure is relieved through rupture disks, and the design pressure is not reached.

The releases are considerably smaller for the type B containment concept than for the type C concept. However, it should be emphasized that leaks through the vessel walls, which are increasing with pressure differences, are not taken into account in this study. Such leaks would be considerably larger for the type B concept and might erase, or at least considerably decrease, the differences between the two containment concept in terms of release quantities.

IV.B. Loss of Heat Sink

This accident is analyzed using the CATHARE code.[13] This hypothetical accidental sequence (usually classified "beyond design basis") involves the leak of all primary and secondary cooling loops while previous LOCA studies assumed the failure of only one primary loop out of eight.[2,3] Consequently, this transient leads to the total dryout of the secondary loops and to a pressure rise within the primary circuits. The relief valves of the steam generators and pressurizers open. After ~1.5 h, because of the impossibility of removing decay heat, first-wall temperatures rise, an in-vessel break is induced, and steam is released into the vacuum vessel.

The results of the thermal-hydraulics simulation, i.e., mass and enthalpy flow rates, are used as boundary conditions for the containment calculations with the CONTAIN 1.1 code.[14]

The containment response of the SEAFP reference design is compared with two other's containment concepts: large containment (type C concept) and inner containment with pressure suppression pool (type B concept).

As pressure peaks exceed the design limit in most of the cases, the use of additional mitigation devices is discussed.

IV.B.1. Description of the Sequence

Two alternative scenarios were defined related to the use or absence of a mitigating system. Scenario 1 is the reference case.

1. *scenario 1*. A loss of the condenser induces the loss of the heat sink in eight steam generators of the first-wall/blanket cooling system. The first step of this study is the calculation of the transient on one cooling loop, using the Cathare2 V1.4E code. The transient progress is as follows:

   a. loss of heat sink at $t = 0$

   b. opening of a relief valve on the pressurizer if $P > 13.5$ MPa

   c. plasma shutdown is triggered by the first opening of the pressurizer valve

   d. pump stop if cavitation.

The second step is the calculation by the Contain V1.11 code of containment system pressurization with the heat sources of the steam generator, pressurizer valves, and in-vessel break enthalpic flows.

2. *scenario 2*. According to the results of the previous studies,[15–18] it seems interesting to use a steam generator auxiliary feedwater system (AFWS) to avoid an induced in-vessel break. In that scenario, we assume the availability of an AFWS that is able to remove 3% of the residual heat power, i.e., 20 MW. Consequently, the AFWS mass flow is 3% of the nominal flow (6 kg/s).

We suppose that an operator is able to actuate the AFWS 10 min after the plasma scram. Moreover, we suppose, that a sufficient amount of water is available so that the AFWS can operate as long as needed.

The transient conditions up to achieving AFWS operation are the same as for scenario 1.

IV.B.2. Containment Responses

IV.B.2.a. Pressure Evolution: Scenario 1. For the SEAFP reference design,[3] the pressure reaches 0.66 MPa in the containment and 0.42 MPa in the vacuum vessel. For type B, the pressure peaks are 1.3 MPa and 0.66 MPa, and for type C, because the containment is also used as the expansion volume for the vacuum vessel, the pressure peak reaches 0.58 MPa.

In every case the pressure design limits are exceeded except for the vacuum vessel of the type B confinement if the total area of the vent pipes is increased from 4 to 8 m^2. This means that to avoid the rupture of the containment, a vented scrubber should be used to mitigate the pressure in the containment. Even in the case of the SEAFP reference design,[3] we assume that a scrubber is available and connected to the expansion volume of the steam generator vault.

Using a vented scrubber avoids overpressurization. The pressure trends in the containment are shown on Fig. 10 for the different containment concepts.

For the three concepts, the rupture disk opening limit of 0.14 MPa is reached at the beginning of the transient. When the scrubbers and expansion volumes operate, the pressures stay below 0.135 MPa for SEAFP and type C and 0.125 MPa for type B. When the in-vessel break occurs (after 4400 s), a slight overpressure results for the type C concept.

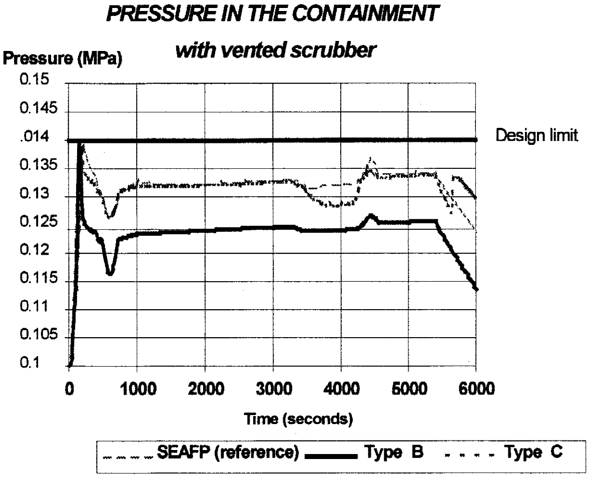

Fig. 10. Pressure trends when using a vented scrubber.

To overcome the overpressure in the containment, there is a choice between opening the rupture disk at a lower pressure (~0.13 MPa) or increasing the volume of the scrubber. Another solution would be to slightly increase the design pressure of the containment, e.g., to a value of 0.2 MPa. In fact, to operate correctly, a scrubber needs a driving pressure difference between the drywell and the wetwell volumes of at least 0.03 or 0.04 MPa. A design pressure of 0.14 MPa is therefore too close to the limits of the optimized operation and should be slightly increased.

IV.B.2.b. Pressure Evolution: Scenario 2. Using transients analysis, it can be seen that the energy released in the containment with scenario 2 is higher than in scenario 1. This is due to a continuous feeding of the steam generator relief valves by the AFWS that transfers energy to the containment. After 1 h, the pressure reaches 0.84 MPa (SEAFP reference design), 2.5 MPa (type B), or 1.1 MPa (type C). In every case, with no additional mitigation device, there is a rupture of the confinement.

However, milder consequences are expected for this scenario with respect to the previous: (1) There is no in-vessel break, and (2) the enthalpy and mass flow rate peaks are lower.

IV.B.3. Conclusions for the Loss of Heat Sink

This study provides an analysis of the consequences of the loss of heat sink leading to an induced in-vessel break.

The secondary AFWS has been assessed as a mitigating system. It was shown that in-vessel break can be avoided, consequently reducing the source term. It is also shown that for all the sequences, the design limits of the containments are exceeded for the three types of containment evaluated.

The use of a vented scrubber connected to the stack reduces the peak pressure below 0.14 MPa in both containments (inner and large). The pressure also decreases rapidly when there is a vented scrubber. This reduces the release of radioactive material through potential leaks to a level as low as reasonably achievable because most of the volume released to the surroundings is filtered.

The use of other mitigation systems such as spray and closed pressure suppression pool were also analyzed. These analyses show that the use of a spray is convenient to avoid exceeding the pressure design limits. However, the use of another heat sink like the AFWS for the secondary circuit is necessary to get spray mass flow rates at a reasonable level. Recalling that the use of AFWS avoids in-vessel breaks, there would be a lower radioactive inventory within the secondary containment.

IV.C. Magnet Accident Sequence

The thermal interaction between the magnet system and the cryostat has been identified as a phenomenon not previously studied in detail. The double short to ground at the bus bar of one coil has the most severe consequences on the cryostat wall. Its assessment is presented in this section.

IV.C.1. Model

To represent an arc in the vicinity of the cryostat we first have to describe a scenario that can be modeled in a second step.

Figure 11 shows the geometry of the bus bar in the vicinity of the cryostat. From a coil connection box, a tube feeds through the cryostat wall and leads to the coil. From this view, we see that the bus bars, the cryogenic lines, and the instrumentation lines are contained in this tube. For the arc, we assume that three insulation barriers fail and there is a direct short between the bus bars.

During the accident, we assume that the energy converted at the bus bar melts the bus bar and the other lines completely through. With the broken bus bar, two separate arcs are formed, one closing the electrical circuit of the toroidal field system and the other shorting the failed coil. This is schematically shown in Fig. 12.

The effect of the arcs on the cryostat wall is determined by the radiation of heat. The cryostat walls are not cooled, so they will be heated up to melting temperature. The melted material runs off and a hole is formed

IV.C.2. Results and Conclusions

During the transient, two arcs are formed, one closing the circuit of the shorted coil and another closing the circuit of the residual coil system. While for the latter the energy dissipation at the arc is some tens of megajoules, for the former ~0.5 GJ were found because the shorted coil quenched during the transient and did absorb ~20 GJ. The massive quench is caused by the induced current in the shorted coil, increasing the magnet field at the shorted coil by ~10%.

How to translate the converted energy into a hole size in the cryostat was investigated. Pure heat radiation as the heat transfer mechanism was assumed. It was found that the hole area will be in the range of 0.3 to 0.5 m^2.

The analysis performed includes several assumptions to bridge gaps of unknown details. Therefore, the number calculated should be considered to be an approximate value than rather than a precise value.

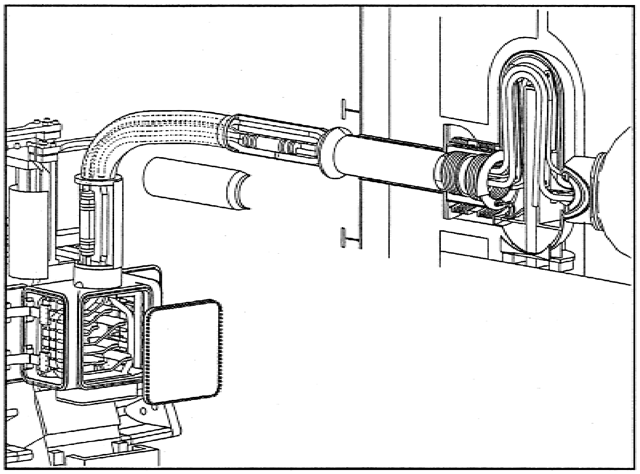

Fig. 11. Isometric view of a cryostat feedthrough of a coil connection tube.

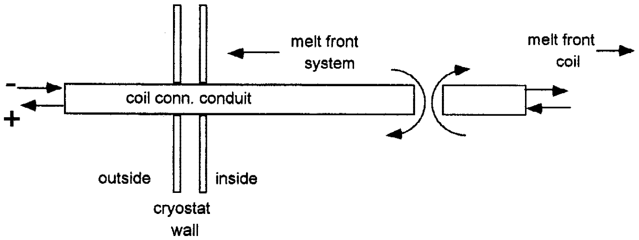

Fig. 12. Schematic representation of the double arc formation at a bus bar.

V. CONCLUSIONS

The purpose of this paper was to obtain better coverage of certain event sequences than was done in the previous SEAFP study. One particular goal was to provide recommendations for containment strategy selection.

The identified bypass scenarios suggest that to minimize the probability of related events, it would be preferable to have a large containment as in the type C option. Furthermore, this configuration decreases the number of penetrations and consequently the number of bypass possibilities.

When dealing with HTS bypass scenarios, it can be concluded that the criteria for confinement strategy selection are less obvious. The concern with HTS is that it carries a certain quantity of energy and that it links the vacuum vessel to the turbine building in all cases of confinement strategy. If the consequences are smaller in terms of releases for the type B containment concept, the pressures reached are much higher than in the type C concept, and special attention has to be given to containment strength. Finally, for these bypass scenarios, no definite trends can be outlined, and no recommendations for confinement selection can be made, provided the containments are designed with the standards assumed in our modeling.

The analysis of the loss of heat sink, which is at the limit of the beyond design-basis accidents, concludes that in any type of confinement option, a mitigating action has to be triggered to contain the overpressurization of the containment. A building spray system combined with an AFWS would be the most efficient strategy to prevent external releases. However, this analysis raises the issue of postaccidental recovery. In fact, using sprays when tritium particles are present in the containment has to be assessed, and the consequences on plant final state and recovery have to be studied.

The magnet accidents are certainly those that have been analyzed with the greatest number of assumptions. However, this study gives a preliminary evaluation of break size that can be induced by such accidents and also an idea of the bypass characteristics. Nevertheless, the cryostat is the piece of equipment most exposed to magnet accidents, and its role in the confinement strategy has to be considered when accounting for magnet accidents.

As a final conclusion, it can be stated that with respect to safety, all the confinement strategies investigated are able to handle highly hypothetical sequences involving bypass, provided adequate means are defined to lower the consequences of the accident. Such means as those that can control the pressure in the containments and trap the radioactive particles (such as filters or scrubbers) can have a strong influence on the definition of the confinement strategy.

It must also be stated that some other concerns for confinement strategy selection have not been reported. They are principally related to occupational doses to workers and ease of performing good maintenance and inspecting critical components.

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