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Innovative Nuclear Reactor Technology Elements

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INNOVATIVE SAFETY FEATURES

TASK 2.4
SOURCE TERM REDUCTION/
CONTAINMENT DESIGN

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1. Introduction

Attention to the Containment issues have dramatically increased in the development of criteria for new reactors. The application of a defense in depth approach has been extended to the consideration of severe accidents, against which the Containment system is the fundamental and the last barrier. Therefore design innovations for the Containment system have been introduced in practically all new designs, but it is also an area where medium and long term research may be warranted.

The technical requirements for the design of the Containment system are linked to a number of conditions under which the Containment is called to perform; the source term definition is of fundamental importance to define the performance required to the Containment. The conservatism that was used in the past, intended also to cope with events not yet occurred like the severe accidents, is now less justifiable since a tendency is in place to consider, even if at different degrees, the severe accidents in the process for the definition of the Containment required performance. However, some aspects of the source term definition are somehow complex from the physical and from the chemical points of view. Area for possible further research to reduce the quantifiable uncertainties and, as a consequence their relevant conservatism are delineated in the present work.

Finally there are possible designs where the role of the “classic” Containment, as a structural leaktight building, is not as important as for the present generation of NPP’s or may be even eliminated. Effective solutions have been proposed and in some cases are already available, to demonstrate that the fission products may be confined. This is the case for example of the HTGR, where the “Containment” function against the release of fission products in every condition is carried out by the fuel itself.

In the present TR different facets of this extremely important issue are discussed.

2. Requirements for innovation

The Containment is now required to be verified, early in the design process, for conditions that account for extreme situations where the pressure and temperature values may exceed the design values.

It is also required that the system functions without the need for immediate operator intervention and that a grace period is warranted instead to the operator.

The promising aspect is that the above situation does not represent in all cases an abrupt departure from the acquired experience. On the contrary the majority of the interventions are directed to extend the Containment performance in areas were already a lot of work has been accumulated (Containment resistance under deflagration conditions etc).

The conditions that determine the Containment sizing and design are the pressure, temperature, the source term and the environmental dose evaluation methodologies. The conservatism of the thermohydraulic calculation does not pose particular problems while for what concerns the uncertainties of the source term there are areas where further research could reduce significantly the conservatism.

However, the demonstration of Containment system performances is, anyway, complex, requires a number of assumptions and it is subject to a certain degree of uncertainty.

Therefore, in the long term, completely innovative approaches in fuel and in the Containment concept itself are justified.

For what concerns the source term the tendency, since the late 1970s, is to define, based on experience and research, a more physically based source term for the evaluation of the plant response to an accident, that would also account for the real behaviour of the fission products rather than a strongly conservative one, as it was originally done when such an information was not yet available or too costly to produce.

Along this path, as it will be seen in chapter 3, the tendency of the requirements posed by the utilities is to account for all the new information in the way the assessment of the plant response to an accident, even severe, is carried out. For instance the EUR has codified, taking advantage of the recent design and construction of nuclear power plants, some of criteria on how to calculate the source term, something that is not present to the same extent in the US correspondent of the EUR, due to the longer time period since design and construction took place.

3. Utility requirements

Utility requirements are based also on this matter on the double rail of improving safety margins and using proven technology.

In general the requirements are based on more realistic assessment with respect to the past of the available results of source term. The refinement in the knowledge of the source term is done to decrease the quantifiable uncertainties so, maintaining the same degree of conservatism, to reduce the adopted margins that are added in the design process.

The major features required by the utilities are:

- Large and robust Containment structure
- Double Containment with an annulus filtered ventilation system (**a requirement of EUR only**)
- Large reactor cavity for retention and cooling of core debris or an ad hoc feature considering vessel melt-through.
- A reactor cavity flooding system.
- A large cold water inventory inside the Containment (such as the IRWST in some PWR's).

The ultimate capability of the Containment should be evaluated by the designer.

Also, different levels of Containment performance are now distinguished and defined in EUR starting from normal condition up to the ultimate level. This progression helps designing the Containment more appropriately for the different conditions. It is in particular required by EUR:

- to prevent early failure of the Containment. The objective is to prevent, as far as possible, all Severe Accidents which might challenge and lead to early failure of the Containment. Degraded core accident sequences which might lead to early failure of the Containment shall be shown to be such that they must not be considered (this concept is developed in another section of this report.)

- to mitigate Severe Accidents. The Containment and the associated systems shall be able to mitigate the consequences of a degraded core, in particular with regard to retention and cooling of the core debris, core concrete interaction effects, limitation of leakages, loads associated with oxidation of the fuel cladding and hydrogen deflagration, extending the grace period for any operator intervention needed for accident management.

Severe accidents which might lead to early failure of the primary Containment that shall be specifically prevented or shown to be of such low probability that they do not need to be addressed in the design are :

- hydrogen detonation,
- high-pressure ejection of molten core materials,
- steam explosion that could threaten the Primary Containment*,
- reactivity accidents (including heterogeneous boron dilution specifically in PWRs).

Measures to prevent high-pressure ejection of molten core materials, which could lead to direct Primary Containment heating, shall include reliable means of depressurisation of the RCS. The pressure shall be less than 20 bar at the time of any molten material ejection from the reactor vessel.

It has been chosen to require that no overpressure protection shall be needed during the first day.

The Severe Accident evaluations in the design process shall use realistic assumptions and best-estimate calculations

The SASS[1] should be reached before 30 days with a goal of 1 week.

The probability of vessel failure and consequential early Containment failure shall be demonstrated to be well below the design probability Targets for DEC releases.

An approach is required for the design of the Containment system which mitigates the consequences of a degraded core, in particular with regard to :

- retention and cooling of the core debris,
- core/concrete interaction effects,
- limitation of leakages, taking into account the source term, the loads associated with oxidation of the fuel cladding and hydrogen deflagration (allowing for measures provided to eliminate hydrogen), local detonations and other loads in the more probable Severe Accidents.

The mitigation measures shall be designed on the basis of the representative Severe Accidents to be addressed as DECs. Generally, Severe Accidents with highest probabilities shall be selected as DECs and taken into account and mitigated as appropriate until the probabilistic

[1] In EUR SACS and SASS are defined. Referring to a severe accident SACS indicates a Controlled State, i.e. a phase during the development of the accident, at which the plant stopped going where it wanted. The SASS indicates a Safe State, i.e. a phase during the development of a severe accident, starting right after the SACS, when the plant starts going where the operator wants. The main physical parameters on which to determine if a SACS or a SASS is reached are the reactivity control, the radioactivity confinement, the heat removal and the corium stabilization.

targets are met. However, care must be taken not to discard Severe Accidents of lower probability but involving significantly greater challenges.

At least one Severe Accident sequence shall be addressed in the design regardless of its probability of occurrence calculated by PSA. If the core melt frequency is lower than 10^{-6} ev/yr, and therefore the Limiting Release target is already met, the most representative low-pressure core melt sequence shall be selected as DEC. In general, this sequence will be the sequence with the highest probability. Reference is generally made to core-melt events, but design requirements shall be used also for other DEC, like the complex sequences (severe accidents with no core damage), as applicable.

A single design Reference Source Term (RST) for core-melt sequences shall be determined by the Designer for each standard design examined. The RST shall include also the evaluation of coolant inventory and gap content releases. The design RST shall be representative of all Severe Accidents addressed and evaluated in the PSA.

The in-Containment Source Term (or Source Term) is defined as the release into the Containment from the RCS and in the case of Severe Accident, from the molten core outside the reactor vessel Source Term is defined eventually as release from the sumps in case of revolatilisation of the fission products due for example to depressurisation after Containment failure, in case of a Severe Accident.

The source term shall be characterized by the definition of times and rates of appearance of radioactive fission products in the primary Containment, types and quantities of the species released, and other important attributes such as their chemical and physical forms.

According to EUR the quantification of the Source Term shall be made in accordance with requirements reported in an ad hoc appendix to the EUR document. Exceptions to the rule of the appendix must be identified and adequately supported on the basis of internationally recognized codes and/or experimental data.

All assumptions, parameters and computer tools used by the Designer to derive the RST or to calculate PSA Source Terms shall be based on a widely recognized experimental database or they shall be adequately supported.

It is in this area that the opportunity is found to further reduce uncertainties that could bring about significant reduction of burden in the design process and hence economic advantage.

Still in EUR, the Containment system shall be designed in such a way it can withstand any of the Severe Accidents considered in DEC, without the operator action during the first 12 hours. The designer should aim at extending this period up to 24 hours.

The Designer shall provide the reference core inventory and an evaluation of the Reference Source Term released to the primary Containment during a Severe Accident for the entire accident period, or until the corium has reached a stable, cooled condition and solid state and the primary Containment has been depressurised. The Designer shall provide the concentration of the isotopes in the primary Containment taking appropriately account to the source term reduction effects. The releases to the environment and the location of such releases in the entire accident period shall be provided. In this type of evaluation indication shall be given of the fraction of organic iodine that is expected to be released with respect to the total iodine.

In EUR, since it is recognized that the estimate of the elemental and organic iodine releases has been reduced based on research results obtained during the years following the late 1970s, it is required to demonstrate that credit for charcoal adsorption of these iodine forms shall not be necessary in Severe Accidents to meet the Limiting release criteria.

Releases can be assumed to occur at the height of the plant stack only for that fraction that is assumed not to bypass the secondary structures and for the time in which the secondary Containment is maintained at sub-atmospheric pressure. Bypass releases shall be assumed to occur at ground level.

The most current version of the computer code employed and available to the analyst at the time the assessment is performed, shall be used for source terms calculations.

However, for EUR, it may be appropriate for the analyst to consider other information (e.g. predictions of more detailed mechanistic codes) in evaluating the source term.

If the molten core cannot be proved with a high level of reliability to be coolable inside the reactor vessel, preventing vessel failure, then specific provisions are needed to assure its coolability outside the vessel. The Designer shall prove that corium would relocate in the reactor cavity in a coolable configuration. As an alternative the Designer can include a Corium Collecting and Cooling Device (CCCD), usually called a core-catcher, provided with a Corium Cooling System. The Corium Cooling System shall not have any active component inside the Containment. In all cases the Designer shall also demonstrate that, in the most unfavourable cases, re-criticality cannot occur.

EUR requires that the designer provides information on the leakage area versus pressure correlation at pressures up to the DEC pressure. This requires R&D to be carried out, especially for steel Containments. Leak rates at pressures lower than design pressure and, even more important, at pressures slightly higher than design pressure are very difficult to assess both at the design stage and during plant operation. EUR introduces specific requirements to reduce these uncertainties.

Design of large penetrations (i.e. equipment hatches and personnel locks) shall assure that the required leaktightness is maintained during DECs in the harsh environment associated with these conditions. This shall apply at least until it is reasonable to expect that the Primary Containment is fully depressurised. On this subject for example, activities in experimental research are underway to verify the personnel air lock and equipment hatch performance.

In EUR the role of the secondary Containment is recognized also if the secondary Containment volumes are not under depressurization giving credit to hold up and deposition. More precise data on Decontamination Factors achievable in these ways might be valuable.

In the following some elements are given from the Utilities Requirement Document URD coordinated by EPRI. These must not be intended as difference with the EUR requirements. In fact in many cases EUR position is on the same line as the URD. In a further refinement of the present work, the differences of the treatment of the issue of the source term and Containment design could be highlighted. The same applies also for other paragraphs in this report.

For the URD, the plant shall be designed with specific features to minimize challenges to the Containment following a severe accident. Specific features shall be incorporated to address the following: features to handle the pressure and temperature resulting from generation of combustible gases, features to limit the generation of non-condensable gases as a result of corium-concrete interaction and features to reliably depressurize the reactor pressure vessel or limit the magnitude of the pressure rise in Containment resulting from ejection of core debris at elevated RPV pressure.

For the URD for passive plants, Containment performance shall assure Containment leaktightness sufficient to meet off-site dose limits, including dose limits associated with simplified emergency planning, for at least 72 hours without the need for off-site assistance. Beyond 72 hours, only minimal off-site assistance (e.g., commercial supplies and components which are readily available, easily transported, and easily installed, such as a portable ac generator with its fuel and connection cables) shall be necessary to maintain required Containment leaktightness.

In URD, the passive systems that are specified for Containment decay heat removal are effective means for aerosol fission product removal. This capability shall be evaluated and utilized in defining the suspended fission product concentration that is available to leak from the primary Containment. R&D could be worth in this area.

For URD the plant shall include design characteristics and features to address a comprehensive set of severe accident challenges to the Containment. Design characteristics and features shall include features to limit the generation of non-condensable gases as a result of corium-concrete interaction and features to handle the pressure and temperature resulting from generation of combustible gases.

The URD for passive plants lists some examples of Passive ALWR mitigation features which provide the high assurance of Containment integrity and low dose; they include:

- . Passive Containment heat removal;
- . Passive means of cavity/drywell flooding of core debris;
- . High reliability Containment isolation (many fewer penetrations and fewer yet normally open penetrations);
- . Increased design pressure of systems which interface with the RCS;
- . Gross, periodic, on-line Containment integrity check.
- . Increased RCS coolant inventory which tends to delay fission product leakage:
- . Steam condensation inside primary Containment which removes fission product aerosols.
- . Significantly reduced leakage through leak paths directly from primary Containment to the environment;
- . Secondary building design to hold up fission product leakage from the primary Containment.

The plant shall include design characteristics and features to address a comprehensive set of severe accident challenges to the Containment. Design characteristics and features shall include features to limit the generation of non-condensable gases as a result of corium-concrete interaction, features to handle the pressure and temperature resulting from generation of combustible gases and features to assure Containment integrity including isolation and precluding steam generator tube rupture and other Containment bypass scenarios.

Protection of the Containment for overpressurization beyond 24 hours shall be provided. Overpressure protection beyond 24 hours may be provided simply by the size and strength of the Containment by demonstrating that the ASME limits are not exceeded for approximately two to three days after the beginning of the accident.

For URD the Plant Designer shall perform an analysis of anticipated Containment airborne activity levels, estimated extent of personnel entries during normal plant operation, and radiation protection (ALARA) measures. This analysis shall determine whether a separate Containment cleanup system is cost effective or whether the Containment low volume purge better provides necessary Containment cleanup prior to shutdown. Experience from operating PWR plants indicates that installed Containment cleanup systems are seldom operated because they are not effective in removing noble gases. Routine operation of a Containment low volume purge system controls Noble gas concentration along with control of Containment pressure.

As a conclusion note it shall be underlined that utilities are industrial enterprises, and, therefore, would like to minimize the risks associated with the construction of plants, which implies enormous investments. Therefore the keyword for the utilities is innovation but with prudence.

4. Economic requirements

The Containment is also an important component because it plays a role in the economic evaluation of the design and it contributes to the overall competitivity of a design. Its importance on this regard, however, is limited to a few percent of the the plant total direct overnight cost.

Containment indirect costs are, however, greater. In particular containment design may significantly affect the overall plant construction schedule and have a consequence on the costs. For example Containment structures designed to withstand very high pressures (> 7 bar_r) may imply a big step up in plant costs, since construction techniques that would be required would exceed the current practice.

A difficult balance exists between the need for cost control and the new requirements in terms of safety. It is of paramount importance that innovative technology take into account cost factors since the beginning in order to favor those R&D lines that are more promising also in terms of economics.

For the Containment system in particular attention must be paid since there could be instances where increasing safety, even though already satisfactory, may imply an increase of cost. The areas where the potential exists for an increase in costs are those where the Containment is called to: withstand a wider range of accidental situations; incorporate extra equipment to cope with the additional treats to be taken into account; comply with modified (and possibly more complex) licensing and assessment procedures; need to develop and test innovative components and systems.

The use of proven technologies, methods and codes, whenever compatible with the new goals is a fundamental means for cost control and, more important, control of the uncertainties. There are both design and management issues which affect the cost of Containments. Measures to minimize costs which are part of the design include: use of proven materials (concrete, steels, etc.); detailed planning of construction schedules to avoid interference between Containment construction and that of its content; optimization of construction techniques for instance by the use of modularization; early formulation of design criteria to allow integration of the design of all systems from the beginning taking into account the need for access and maintenance requirements; simplification of design, e.g. reduction of the number of penetrations, avoidance of over-specified features; design for long plant lifetime and including provisions for decommissioning.

On line monitoring of the leak rate may change the burden of the periodical test and hence reduce the costs also during operation (as the reduction of the number of penetrations for passive plants).

Factors that arise from management including the overall management of the industry and its regulatory environment include: assuring regulatory stability, assuring design stability to share development costs over several stations, assuring construction schedules, minimizing operation and maintenance costs.

In EUR it is required that the design life shall be capable of extension to 60 years without refurbishment for the components and the structures which are not replaceable (reactor vessel, Containment structure, major civil structures); all other structures and equipment shall be replaceable; the Plant Designer shall identify the provisions and extra investment costs that would be necessary to reach 60 years. So EUR requires the plant to be designed (including the Containment) to permit expeditious replacement of all operational components and equipment, especially heavy components, except the reactor vessel and all major structures which are not replaceable, such as the Containment, shall have a design life of 60 years. There shall be a plan for replacement of those components which may be subject to obsolescence, or to avoid early failure due to fatigue. This plan for replacement, refurbishment or repair shall ensure that the design life of the plant is achieved at minimum cost, and will be submitted to the Owner for early approval. Where appropriate, provision shall be made to allow, inspection, maintenance and replacement of seals between different buildings.

In order to improve the coherence of the study and to avoid undue conservatism, it is recommended, to the extent possible, that the same computer code be used for plant response analysis to support success criteria definition and for Severe Accident progression assessment in the Containment and source term analysis. A Severe Accident integrated computer code shall be the primary tool used to assess thermal-hydraulic and other physical processes and phenomena such as core heat-up and melting, Containment loading, release of radionuclides, molten core, concrete interaction, and combustible gas generation and ignition.

The computer code used for these calculations shall be internationally recognized and adequately supported by documentation including code validation against experimental data or international benchmarks.

For economy of resources the analyst may choose to apply conservative criteria. In this case, the analyst shall identify where conservative assumptions have been introduced and shall review the results to ensure that such conservatism does not obscure insights from the results.

The pressure at which the ability of the Containment System to maintain Containment integrity and leaktightness is threatened shall be assessed using the method discussed in a chapter written in EUR specifically for the Containment system, which includes discussion on phenomena to be taken into account to estimate the Severe Accident thermal and pressure loads on Containment.

In URD for maintainability it is required that the ALWR will be designed for ease of maintenance to reduce operations and maintenance costs, reduce occupational exposure, and to facilitate repair and replacement of equipment.

In URD for safety it is required that the ALWR design will achieve excellence in safety for protection of the public, on-site personnel safety, and investment protection. It places primary emphasis on accident prevention as well as significant additional emphasis on mitigation. Containment performance during severe accidents will be evaluated to assure that adequate Containment margin exists.

In URD for design basis versus safety margin it is required that the ALWR design will include both safety design and safety margin requirements. Safety design requirements (referred to as the Licensing Design Basis [LDB] are necessary to meet the NRC's regulations with conservative, licensing-based methods. Safety margin requirements (referred to as the Safety Margin Basis [SMB] are Plant Owner-initiated features which address investment protection and severe accident preventetion and mitigation on a best estimate basis.

In URD constructibility is stressed: design attributes of the ALWR that provide a substantially improved construction schedule and a basis for investor confidence in this schedule, are sought.

The choices that have more direct impact on the economics of the Containment are the decision to adopt a steel or a concrete Containment, a single or double Containment, with or without liner, large or small.

To pursue the reduction of liabilities very expensive Containments could be built but this would increase too much the cost of the Containment especially for the NPS to be built in the developing countries.

To have a clear demonstration of success under sever accidents conditions, requires large design margins. So it is important to decrease uncertainties.

In terms of economics it shall also be mentioned the costs associated with the licensing process. Construction delays, design changes, plant “patchwork” may be a consequence of a difficult licensing process. Also for the containment it is very important that all the fundamental elemenst of the design be agreed upon with the Safety Authority. To achieve this and reduce the time needed, the “proven technology” criterion helps.

5. Licensing requirement

In the past years a licensing activity for new designs has taken place in the USA with the certification processes of ABB CE 80+, W AP600 and GE ABWR and in Europe in France, Germany and UK with the N4 the EPR and Sizewell B, respectively.

The scenario shows both traditional and more innovative (AP600, EPR) Containment concepts finding their way. The source term calculation, for instance for AP600 where due credit is taken for deposition mechanisms specific of the AP600 passive Containment, the EUR requirements themselves, show innovative approaches being currently adopted. As it was pointed out previously, the determination of the requested performance of the

Containment, for instance in terms of leak rate, depends on the source term and on its calculated impact on the environment.

In particular the French and German requirements for EPR are basically in line with the utility requirements.

An important aspect that is highlighted more in the licensing processes than in the utility requirement is the function of the containment as a protection against external events. This in particular applies to the aircraft crash protection. While the utility are reluctant to include this requirements as a standard requirement for international projects, in several countries licensing authorities insist to considered the aircraft crash either probabilistically or deterministically. It can be expected that, also because the uncertainties associated with the development of air traffic and aircraft characteristics in the future and because of the need to provide a solid shell to protect the reactor from other events, this requirement will be maintained in a more or less deterministic way.

It shall be noted that in general Licensing Authorities are the latest to respond to innovations. This is because of their responsibilities also in regard to the other existing plants.

However, from current difficulties in the few undergoing licensing processes needs for R&D activities may be identified. It should be said, however, that most of these points are exactly the ones addressed by the utilities.

6. Social requirements

For what concerns both the requirements from the society and the requirements for the society, the good neighbor policy brings the necessity to make the NPP “disappear” from the consideration of the surrounding populations. This means that in normal operation the need for land, the need for limitation of industrial and agricultural activities, the involvement of population in emergency planning exercises shall be reduced to a minimum. Moreover in case of accident it shall be absolutely avoided the disruption of the social texture caused by permanent population resettling and the permanent loss of large portions of territories. In addition an important objective is to avoid in any cases the involvement of the population in the emergency protection actions, particularly the emergency evacuation.

In EUR for the good neighbor policy releases in normal operation and accidents are required to be limited. For Severe Accidents, a threshold of activity release to the atmosphere is established. It is referred as Limiting Release in the document.

• minimal emergency (i.e. within 24 hr) protection action shall be necessary beyond 800 m from the reactor during early releases from the Containment;
• no delayed action (i.e. within 1 month involving temporary transfer of people) shall be necessary at any time beyond about 3 km from the reactor;
• no long term action, involving permanent (longer than 1 year) resettlement of the public, at any distance beyond 800 m from the reactor.

In addition, restriction on the consumption of foodstuff and crops shall be limited in terms of time and extension of the impacted area.

In URD also the releases for both the normal operation and accidental conditions are limited and, for the passive plants, URD poses the requirement that the plant shall be designed to provide a technical basis for simplification of plume exposure pathway-related-off-site emergency planning. The intent is to retain an on-site emergency plan and certain elements of the off-site plan, but demonstrate that doses are low enough that early notification, evacuation planning of the public, and provisions for exercising the off-site plan are not necessary. So in URD the simplification of the Passive ALWR emergency plan would apply primarily to plume exposure pathway off-site emergency planning and would primarily be in the area of eliminating early notification of the public, dissemination of emergency planning information to the public, and provisions for exercising the off-site plan. Furthermore, necessary emergency planning elements would be retained so as to provide a basis for expansion of response efforts in the event such expansion is necessary. This expansion would involve ad-hoc evacuation, i.e., use of state and local government plans that already exist for dealing with natural and technological hazards. A significant difference with EUR, is that URD is focused more on the "short" term (up to 24 to 72 hr) and less to the long term and accident termination.

However, the designer must take into account that the Containment structure, because it is presented as the last barrier against the fission products release in case of a severe accident must also be judged credible by non-technical people. This implies that: explanations dealing with the overall performance of the Containment should be simple and easily understandable; information should be given in such a way that non-technical people can easily understand that the design provides clear and straightforward solutions for the accident scenarios which have happened in the past and for any other conceivable. To obtain public support the public should perceive that a consensus, possibly at an international level, exists between the designers, the utilities, the public authorities and the scientific community on design bases, licensing criteria and performance assessment.

So the approach is to provide protection "in any case" and avoidance of the necessity of public evacuation, to provide for rapid depressurization, a strong and effective Containment in the long term, together with predefined recovery strategies and tools.

7. International trends

7.1. Containment design.

The nuclear plants being build today continue to have the traditional Containment's but also other solutions are proposed by the PRISM, HTGR and PIUS where the different design of the primary circuit allows for a relaxation of the requirement for the Containment.

At present the following Containment design concepts have already been adopted in existing NPS in the world.

Single dry Containment. The Containment is large enough to withstand the short term pressure and temperature from the largest pipe break without pressure reduction systems. Typical applications are in PWRs and Candus.

Dual dry Containments. The primary dry Containment structure is surrounded by a second Containment which provides protection against external missiles and allows for detection and filtration of radioactive elements leaking from the first Containment. Typical applications are in PWRs.

Pressure suppression Containments. The Containment is so devised that the fluid that exits from a break inside the Containment must pass through a water pool where the steam part condenses.

Ice condenser Containments. The Containment is so devised that the fluid that exits from a break inside the Containment must pass through a rack of ice where the steam part condenses. Typical applications are in PWRs.

Negative pressure Containment's. In multiple reactor stations each individual reactor building can be connected via a duct to a large building maintained at low pressure to relieve the pressure resulting from a pipe break. Typical applications are in Candus.

Particular features that are being employed in current Containment designs are active igniters to burn hydrogen (in several plants), passive recombiners for hydrogen (e.g. AP600), inertization (BWR-90, ABWR), corium catcher/cooling features (System 80+, EPR, VVERs), filtered venting (VVER, Swedish and Finnish plants), passive Containment cooling (AP600, in EP1000 optional, SPWR), gravel bed pressure suppression (B&W B-600) and internal Containment cooling spray.

In most cases many Containment designs tend to avoid the implementation of provisions for filtered venting. This is to prevent spurious actuation's in case of a severe accident. Containment filtering devices of various design have been introduced as a backfitting and in some current Containment's as a last resort feature to avoid loosing Containment integrity in a beyond design basis event.

To allow passive Containment heat removal also in case of a double Containment, one of the options in the EP1000 design is the adoption of the heat pipe principle and the removal of the heat through completely passive means. The heat pipes carry the heat to an external pool where the heat pipes fluid is condensed to return into the Containment.

From the above description both large structures that rely on robustness and small structures that address more the specific of the course of the accident (steam condensation and inerting against hydrogen) are pursued. Also other innovative concepts are present like the case of the HTGR where the Containment function is demonstrated by the fuel that is irradiation and air cooled.

7.2. The source term.

A recognizable international trend is an enhanced importance associated to the severe accidents. In some cases the response is assessed through probabilistic studies and in other as part of the design process. The developing countries are not willing to pay all the money necessary for a super Containment, so the use of passive systems could help limit the problem.

For the determination of the source term, some uncertainties could be decreased for the deposition, resuspension and, especially, the revaporization. Full-scale testing, modelling and small-scale separate effect tests have all parts to play in reducing the uncertainties. Some full scale retention tests in complex circuit components under prototypical conditions indicate that significant net retention does occur.

Resuspension and revaporization have a major impact on the source term and the impact depends on the specific features of the plant and on the accident scenario examined. Areas like the size of the resuspended particles and the formation of agglomerates in the deposit layer still need further development. Work must still be done to delimit the important parameters that affect resuspension.

Semi-empirical and mechanistic resuspension modeling are in progress to address parameters such as surface roughness, bed porosity, chemistry on the surface and stickiness of the particles. Measurements on actual aerosols are supporting the model development.

The revaporization experiments on specimen from PHEBUS cam contribute significantly to the base knowledge on revaporization.

8. On-going activities

8.1. The Containment.

At present the innovative Containment designs concern a) the improvement of current designs; b) new Containment concepts; c) a new concept for the final barrier. The improvement of the current designs is sought in areas like the leaktightness, the design robustness and the passive operation.

Under some postulated accident conditions an in-vessel fuel-coolant interaction could occur. The resulting steam explosion is generally not considered to be sufficiently energetic to cause failure of the Containment. However, combining several conservative assumptions, some authors believe that there is a potential for rupture of the upper or lower head of the RPV, possibly causing damage to the Containment internal structure or essential safety equipment within the Containment.

In-vessel steam explosion defense strategies are: a) to exclude the possibility by design or by other physical considerations in demonstrating that the vessel would not fail [1], or to require, if the vessel has to be assumed to have failed, a reinforced reactor pit design able to withstand the consequential loads, possibly including an upper shield slab to protect the Containment from induced missiles, if the structures already present (e.g. refueling machine etc.) are not already enough to prevent the Containment perforation [2].

Specific measures to prevent in-vessel FCI have not been developed. It should be pointed out that some FCI models indicate a greater probability of in-vessel steam explosion if the vessel is at low pressure at the time of the event. This situation is much more likely in many next generation reactors since primary system depressurization is part of the prevention strategy. However this event is not likely to cause Containment failure.

If a substantial portion of the molten core comes into contact with an equivalent mass of water in the reactor cavity, a steam explosion could occur. Particularly in small Containments, local failures of the Containment structures may occur. Several preventive features are possible.

If the vessel is externally flooded there is the possibility to demonstrate that a molten corium resettled at the bottom of the vessel would not fail the vessel wall, rather the water outside the vessel will remove the generated heat. Westinghouse AP600 has demonstrated this capability.

Experiments have been carried out and other are in program to be performed at the Kurtchatov Institute in Moscow.

In the strategy of defense in depth various means of cooling the corium in the reactor cavity after RPV failure have been proposed. Most of these measures involve allowing the corium to spread out either in the vertical or horizontal direction and to cool the corium by flooding with water or allowing heat transfer to water without flooding. Active and passive systems have been proposed for removing heat from the corium.

In the area of Containment leak-rate assessment under severe accidents, experiments are on-going that involve personnel air locks and the equipment hatch.

On-going activities concern the core-catcher design, corium spreading and penetration behaviour.

8.2. The source term.

The determination of the source term is at the basis of the design of the Containment system. As a consequence important efforts are being developed both in the USA and in Europe to further enhance knowledge on the behaviour of the corium basically for addressing a) its cooling (FARO, ACOPO), Finland (COPO) , Kurtchatow Institute RASPLAV, the UK, Germany, France, etc.) to further define the issue and so reduce the uncertainties and b) to study the fission products evolution in the Containment atmosphere. Safety standards being the same, less expensive Containments can be built once the knowledge on the above areas is improved and the known uncertainties reduced.

In the following some considerations are given for what concerns the issue of the fission products evolution inside the Containment.

Dry aerosols or aerosols in presence of steam (condensation) have different deposition rates. Different approaches to steam condensation on aerosols in some cases have a strong impact on predicted aerosol growth. There is evidence that a non-equilibrium treatment is necessary for proper assessment of the condensation rate.

PHEBUS results indicate that all elements are removed from the Containment atmosphere at approximately the same rate in medium-humidity conditions.

Two KAEVER tests with mixed CsI/Ag aerosols observed unexpectedly low depletion rates. The chemical composition of prototypic aerosols and the resulting degree of hygroscopicity, appears to play a strong role in the depletion behavior.

Aerosol deposition on condensing surfaces of a heat exchanger component test, has been shown to depend not only on the solubility but also on the nature of the aerosol.

High quality data are now available for the droplets size distribution and other parameters following flashing jets from the primary circuit breaks. Models predict that the resulting liquid aerosols can be effectively removed by impacting and are confirmed by integral experiments.

Experiments show strong decontamination and partial plugging by aerosols in leak paths through electrical penetration and flanged gaskets. SESA experiments in France are on going to determine the degree of plugging of the cracks by condensation of the steam into water. If the water can be demonstrated to remain in the crack long enough the mechanism can be used to reduce the leakage calculated to the outside of the Containment. The long term reduction that can be credited to this mechanism will be addressed.

The use of hydrogen recombiners may have implications for the aerosol growth and depletion, as it affects local thermal-hydraulic conditions.

The experimental database on natural aerosol depletion mechanism for Containment code assessment is of good quality and sufficient. Recent experiments have employed much improved instrumentation for the characterization of both thermal-hydraulics and aerosol physics. The PHEBUS results indicate that the deposition rates in the Containment can be well predicted. An important effect is water condensation on aerosols, which under medium to high relative humidities (RH>70%) can significantly accelerate the fission products removal. The KAEVER experiments have confirmed that hygroscopicity can strongly enhance aerosol deposition in the Containment.

Another indication from the PHEBUS experiments is that the chemistry of Cs and I is more complex than expected. More data on this subject are needed.

Modeling of aerosol growth in the Containment is judged satisfactory when the thermal-hydraulic conditions and aerosol properties are well known.

9. Overview on R&D proposals

Further study on the in-vessel FCI phenomenon to determine all the relevant governing variables is needed. The loads consequent to such an event should be better defined and the survaivability of the Containment demonstrated.

In-vessel corium coolability has been demonstrated for W AP600. The possibility to relay on this mechanism also for higher power reactor exists. Activities, including experimental, must be performed to decrease the uncertainties.

Further study on the governing variables in case of ex-vessel corium-concrete interaction steam explosion should be carried on and the maximum loads better defined decreasing the uncertainties. Research is needed for ex-vessel corium coolability. Here a configuration is needed to be taken as a reference for the corium spreading and the coolability and crust formation demonstrated.

Research on materials that can minimize the gases emission is also worth pursuing.

Research to correlate the leakage area versus pressure correlation at pressures up to the DEC pressure, in particular for steel Containments is necessary.

Of great importance for the Containment cost reduction is the research on the seismic loads to justify the reduction of margins and to reduce the role of probability.

For what concerns the source term determination, it can be said that several source terms scenarios (on the order of the tens) can be envisaged depending on the plant and severe accident scenario. It is necessary to improve the confidence in the prediction of the flow paths, velocities and temperature distributions in the primary circuit under severe accidents conditions.

There is still a need to investigate aerosol deposition in complex geometries and singularities such as valves and bends. An important removal mechanism in sequences with steam generator tube rupture is flow across tube bundles and experiments are planned. Evidence was found that in superheated conditions chemical reaction between aerosols take place, influencing the deposition rate. This needs to be reproduced by other experiments.

Deposition/resuspension in by-pass sequences with very high flow rates (hundreds of meters per second) has not been studied. In this area more experimental data and understanding of deposition in compressible flows is needed. Currently no credit on deposition in safety analysis can be taken with the present level of knowledge.

The flow conditions in the steam generators, depending on the accident situation could be from laminar to turbulent. Thus it would be useful if the TUBA tests could be extended to turbulent conditions.

On resuspension there are experimental results that show that the phenomenon is not understood well enough for application to plant analysis. The PHEBUS data indicate that reactor aerosols are rather easily resuspended. Also the determination of the size of the resuspended particles may pose problems. Measurements of parameters such as surface roughness, bed porosity, chemistry on the surface and stickiness of the particles are needed to support the modelling development. To quantify circuit retention, there is a need for specific experiments related to clearly defined accident sequences. Also, for resuspension, a separate effects tests program is necessary. Phenomena such as boiling pools, fast Containment depressurization or hydrogen combustion may promote the resuspension of the aerosols deposited on the Containment walls and sumps during the late stages of a severe accident. The aerosol sources resulting from these phenomena are quite uncertain and have not been systematically investigated. The presence of large amounts of water in the Containment may result in the revolatilization of iodine.

The only experimental program on revaporization is in Finland. Both theoretical and experimental activities are necessary to understand the revaporization process. To better understand revaporization it is necessary to identify the different composites that are formed and this cannot be done by spectroscopy alone.

For the spray efficiency in removing aerosols, both detailed and integral tests are necessary to support the modelling. PHEBUS experiments give indication that other mechanisms besides those already accounted for are at play in removing aerosols. These include turbulent impaction and charge effects and should be further investigated.

The effect of the spray on hygroscopicity and as a mechanical scrubbing effect can be better researched (most effective droplet size etc.) to design the spray system. Technical grounds to rule out that the spray actuation can turn the atmosphere detonable in condensing the steam should be stated.

The possible impact of hydrogen recombiners on aerosol depletion rates due to affecting local thermal-hydraulic conditions and to chemical effects have to be investigated.

Heat release by hydrogen burning may have a strong effect on aerosol characteristics as a result of the thermal-hydraulic transient that can possibly liberate volatile forms of iodine. Experimental evidence and thermodynamic analysis are inconclusive as to the magnitude of the effect.

Pool scrubbing models also need further development.

Modelling of re-entrainment from boiling pools (a weak but persistent late-phase source of fission products) performs well for ideal systems but currently lacks consideration of non-ideal effects like suspended materials, solute and surfactants. It has to be examined if re-entrainment from boiling pools may have a significant effect on offsite releases.

As far as codes are concerned, activity must still be done to determine if flow modelling in severe accidents is sufficient. The database on aerosol properties (important in dry atmosphere, while they can be neglected in wet atmosphere) such as particle shape factors, density and collision efficiencies, is very scarce. Uncertainties in modeling aerosol behavior in condensing atmospheres are so large (orders of magnitude in airborne concentrations) that predictions of the steam condensation models are not reliable enough for source term evaluation purposes.

10. Availability of necessary R&D facilities

There is a need for large scale experiments with combined effects to be financed.

A list follows of the facilities available for experiments on

A) in-vessel coolability:

- COPO
- ACOPO
- RASPLAV
- FARO

B) Containment

- SESA
- ATHERMIP

C) Containment atmosphere

- PHEBUS
- KAEVER
- PARESS
- STORM
- TRANSAT
- TUBA
- FALCON
- BTF
- CARAIDAS
- NUPEC
- POSEIDEN
- WAVE (JAERI)

11. Correlation of requirements and R&D proposals – Judgement on priorities

12. Recommendations on future R&D activities

Recommendations on R&D may be derived from the discussions developed in the previous sections. However in the following a summary of the most important needs is reported.

It shall be repeated that there are two lines of development. The first one is related to strengthen the containment as a structural leaktight building to make it more resistant and more reliable, and the second one in identifying new features or new designs to prevent in different ways the release of fission products into the environment.

The function of the containment as a barrier against external events may perhaps be improved and updated in the light of possible new challenges to be considered (e.g. new types of aircraft), but we believe that this aspect is of a lesser priority in terms of R&D.

The issue of Containment isolation, prompt as required, reliable and effective, is one possible area of development. The current Containment isolation system is still a complex system, that require sensing devices based on number of parameters and parameter combinations, a number of actuators with the necessary supporting system and the efficiency of valve closure and leaktightness could be increased.

The entire area of severe accident mitigation shall be further explored, in conjunction with the specific phenomenological research.

With the reduction of the uncertainties margins can be reduced and components can be made less expensive. The source term, that together with the pressure and temperature conditions, is the major contributor for the definition of the component, is the best candidate for the reduction of the uncertainties.

The fission products inventory in the fuel can be modified changing the fuel design. An activity to minimize the fission products and actinides content could find its role in the strategy of improving the performance of the Containment.

Also strategies to continuously recycle the fission products to minimize the inventory should be pursued.

13. References

[1] KUCZERA, B., "R&D investigations relating to future advanced PWR Containment concepts", paper presented at TCM on Advanced Containment Technologies, IAEA-TC-818, Aix en Provence, France 1992.

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