A New Generation of Pressurized Water Reactors

Une nouvelle génération de réacteurs à eau sous pression

Eine neue Generation von Druckwasserreaktoren

Günther KESSLER
Professor
Nuclear Res. Center
Karlsruhe, Germany

Wolfgang BREITUNG
Dr.-Ing.
Nuclear Res. Center
Karlsruhe, Germany

Josef EIBL
Professor
University of Karlsruhe
Karlsruhe, Germany

Günther Kessler, born in 1934 received his Mechanical Engineering Degree at the University of Aachen and his Dr.-Ing. Degree at the University of Karlsruhe, Germany, where he is now professor at the Mech. Eng. Dep. Since 1963 he is involved in reactor physics and reactor safety.

Wolfgang Breitung, born in 1944 received his Degrees in Nuclear Engineering and his Dr.-Ing. at the University of Karlsruhe, Germany. He is involved in reactor safety research at the Nuclear Research Center of Karlsruhe since 1977.

Josef Eibl, born in 1936, received his Engineering Degree at the Technical University of Munich, 1959, and Doctor Degree in 1963. He is Professor and Director of the Institut für Massivbau und Baustofftechnologie at the Technical University of Karlsruhe.

SUMMARY
The feasibility of a containment design is studied for future nuclear power plants which are able to sustain extreme loading cases caused by severe core-melt accidents, such as hydrogen-detonation or steam-explosions. Several measures are considered to achieve a deterministically 'safe' design.

RÉSUMÉ
Dans cette note on s'occupe de savoir si, pour les centrales nucléaires du futur, il est possible de réaliser des confinements qui puissent résister aux contraintes sévères d'un hypothétique et très grave accident de fusion du coeur, comme celui résultant de la détonation de l'hydrogène ou d'une explosion de vapeur. De nombreuses propositions constructives sont faites, en vue d'obtenir un confinement qui seriat "sûr" de façon déterministe.

ZUSAMMENFASSUNG
Der Beitrag geht der Frage nach, ob für zukünftige Kernkraftwerke Containments technisch realisierbar sind, die auch den starken Beanspruchungen eines angenommenen schweren Kernschmelzunfalles, wie sie etwa bei einer Wasserstoffdetonation oder einer Dampfexplosion auftreten, standhalten können. Es werden mehrere Konstruktionsvorschläge gemacht, um eine deterministisch, "sichere" Konstruktion zu erzielen.

1. FUTURE CONTAINMENT CONCEPTS FOR PRESSURIZED WATER REACTORS (PWR's)

In contradistinction to the numerous design proposals put forward for future small Pressurized Water Reactors, we aim our design criteria for future PWR's (beyond 2000) to reactors of a size similar to the existing 1300 MWe PWR's in Europe. In our design philosophy we eliminate in a deterministic way, i.e. beyond any reasonable doubt, the catastrophic consequences of containment destruction as discussed in the context of severe core melt accidents such as core melt-through of the containment basemat, steam explosion, H_2-detonation, high pressure failure of the reactor pressure vessel or other primary system components and containment bypass leaks. Our overall safety concept is designed to provide an ultimate barrier which envelops in a protective sense the spectrum of preventive and mitigative accident management measures. In the following we will define design specifications that will mechanistically prevent failure of inner and outer containment structures.

2. SPECIFICATION OF DESIGN MEASURES FOR THE CONTAINMENT STRUCTURES

In the very unprobable case of core melting at low system pressure (e.g. a leak in the primary system followed by failure of all emergency cooling systems and relevant accident management measures) the molten core would penetrate the bottom of the reactor pressure vessel (RPV) into the concrete structures below. The chemical reaction between steam and zirkaloy or stainless steel contained in the core will cause a release of about 1500-1800 kg of hydrogen into the containment. Various analyses have shown that despite the presence of steam, the detonability limits of H_2 with air may be reached and even exceeded in certain compartments of the containment. On the basis of theoretical and experimental results on hydrogen detonations [5] our containment design specifications require the containment to withstand a global shock impulse of about 0.2 MPas and a static pressure of about 2 MPa. With these design specifications the containment would not fail even if large scale hydrogen detonations occurred or if steam pressurization would develop.

For the unlikely case of failure of heat removal via the steam generators and subsequent failure of depressurisation of the primary system, the core would melt and heat the bottom of the RPV until it fails. The multi-phase water-steam mixture together with the molten core would flush out of the RPV downwards into the reactor cavity. The main results of a recent analysis [6] show that thrust forces of about 300 MN would act initially and decay within 100 ms. To prevent an upward movement of the RPV, the vessel support structures must be designed to withstand 300 MN. Additional structures must be provided above the reactor vessel to keep the RPV in its original position.

After a core melt down at relatively low primary system pressure, the molten core masses may come in contact with water remaining underneath the core support structures inside the RPV and will eventually cause a steam explosion. This steam explosion may destroy the RPV and create missiles (e.g. pressure vessel head) that could penetrate the reactor containment (α-mode failure). A preliminary assessment regarding the mechanical strength of the upper part of the RPV indicated that even an energy release of 3 GJ would not produce missiles that could endanger the integrity of the outer containment. However, additional inner containment structures will be provided to retain missiles released from the RPV. These inner containment structures would need to be located, most likely, both underneath and above the RPV.

After release of the core melt from the RPV into the reactor cavity, the molten core material would erode the concrete basemat of the containment. Recent experimental and theoretical studies on molten core-concrete interaction, performed mainly in the USA and Germany, have quantified the process of basemat erosion. A new containment design concept has to resist basemat erosion. This can be achieved by introducing a molten core retention and cooling device underneath the RPV [4].

An overall safety concept must also contain the prevention of bypass leaks, e.g. through pipes. All tubes and pipes penetrating the containment walls should be assembled in a few groups.

COMPOSITE CONTAINMENT

FILTER

① INTERNAL PRESSURE

RPV ENVIRONMENT

②

DECAY HEAT REMOVAL ④

CLOSURE MECHANISM

⑤

③ CORE MELT COOLING DEVICE

⑥ REMOVAL
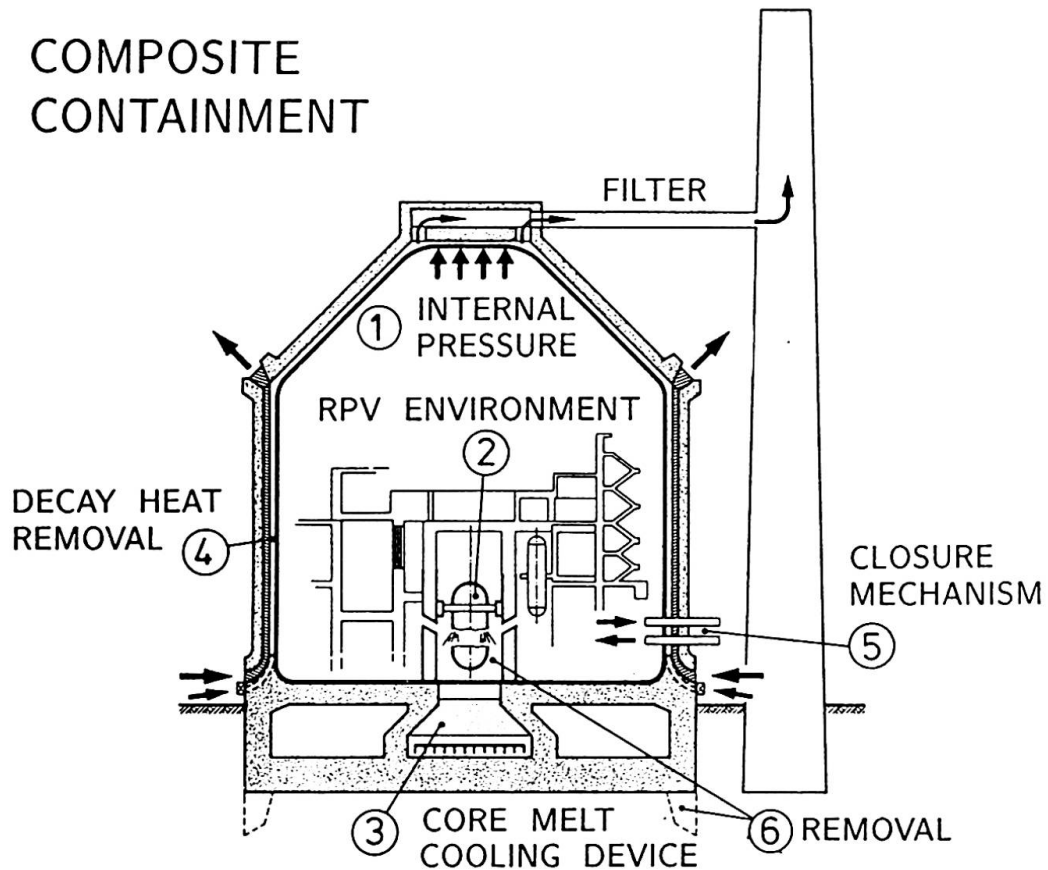
Figure 1 : Composite containment for a pressurized water reactor

①

②

③

SECTION A – A

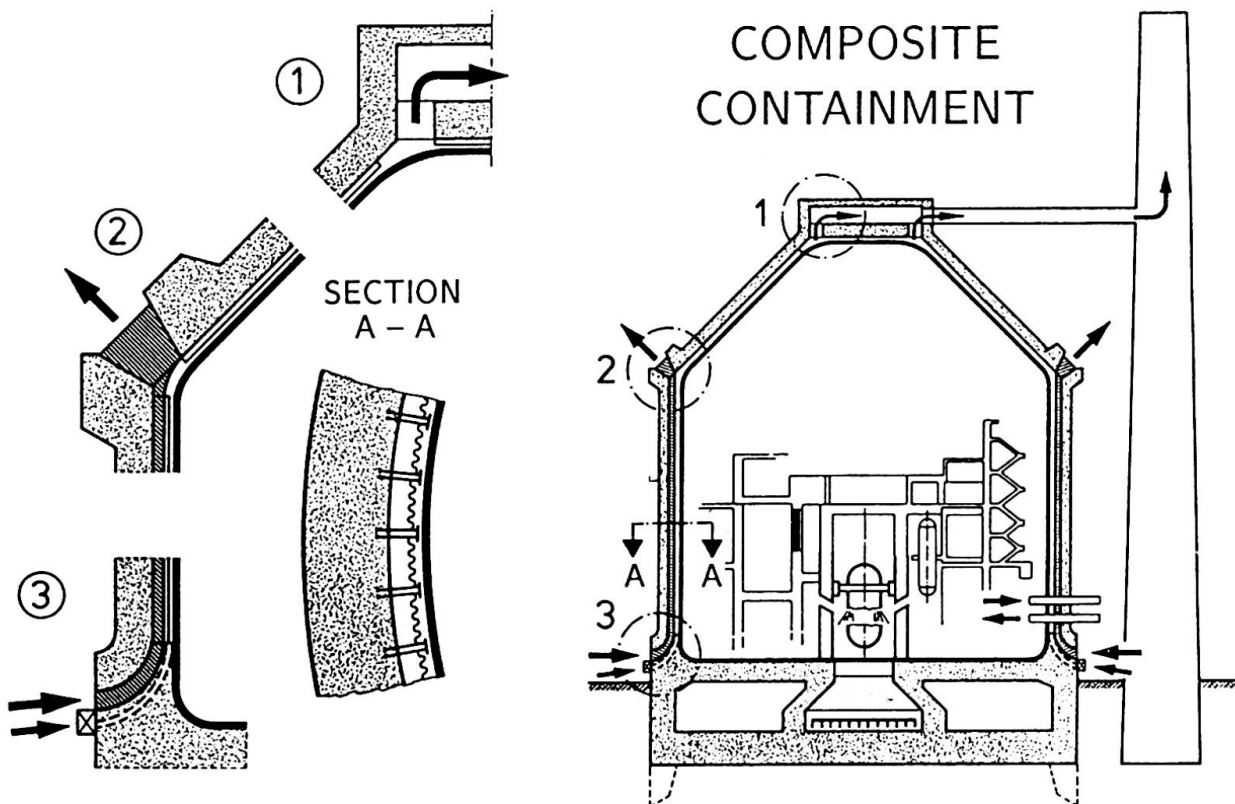## COMPOSITE CONTAINMENT

1

2

A A

3

Figure 2 : Separation of the cooling air stream from the filtered air stream

External accident management measures must be made available to seal any pipes or valves whose closure mechanisms may fail in a severe accident.

3. CONTAINMENT DESIGN

Our novel containment design has been developed to achieve a deterministically 'safe' concept for nuclear reactors. The concept of safety has always been based on a purely probabilistic approach but, in reality, a possibility of failure still exists no matter how low the level of probability is. This applies even when the probability is reduced by a few orders of magnitude.

A reinforced concrete containment structure has a probability of failure of about $p_C = 10^{-7}$. Since the reactor must fail first, with a probability of less then $p_R = 10^{-6}$, then the probability of the two systems failing together will equal the product of the individual probability levels. In this case $p_f = p_C \cdot p_R$ has a value of 10^{-13} which is at least 6 orders of magnitude lower than current values which have been able to be reached up until now. A probability level of this order can be considered deterministically safe.

Beginning with the worst case scenarios discussed earlier the following must be considered (see also labels in Fig. 1) :

1   A static internal overpressure of 20 bars caused by decay heat development, and a dynamic one of 230 bars occurring within 5 ms that may result from a hydrogen detonation,

2   Pressure vessel failure under either a high system pressure or steam explosion,

3   Prevention of basemat erosion by retention and cooling of the molten core,

4   Passive removal of decay heat,

5   Closure of all tubes and pipes penetrating the containment wall, and

6   Removal of the pressure vessel, when the design life is exceeded, should be considered at the design stage.

Internal pressure problems resulting from either a static or dynamic loading case are well covered by the principal design of the proposed containment (Fig. 1). The building consists of a cylindrical wall structure covered by a conical shell. Both are divided into an inner steel shell and an outer reinforced concrete shell. The steel shell has a thickness of 38 mm, similar to those currently used for Convoy-reactors built by Siemens KWU. The concrete shell is about 2 m thick and protects the reactor against environmental threats, such as an airplane crash or gas explosion.

An 80 cm gap is provided between the inner steel shell and the outer concrete shell (Fig. 2). The gap is divided in the hoop direction by about 290 steel contact ribs which result in 50 cm×80 cm compartments. These contact ribs ensure that both shells will act together as a composite structure when loaded by internal pressure. This also applies for the case of an inner hydrogen detonation. The inner steel shell does not touch the contact ribs under serviceability conditions. However, for extreme internal loading cases the steel shell will expand and come into contact with the ribs so that the steel and concrete shells will act together. A large opening in the two shells, about 9 m by 11 m, is needed for the material transportation lock and poses a design problem that is presently being studied.

The estimated extreme loads acting within the reactor pressure vessel cavity are labelled in Fig. 3 and are still under further investigation, as discussed in Section 2. For a pressure vessel failure, the upper vessel-head will be held in place using a restraining steel device connected to the upper concrete ceiling which is fixed with unbonded prestressing cables. The high pressure generated from large amounts of energy release will accelerate the lower half sphere into the reinforced concrete grid below. This allows the melt to reach the core catcher device that is located in the lower compartment. The pressures acting inside the pressure vessel cavity and the core catcher cellar are resisted by the reinforced concrete.
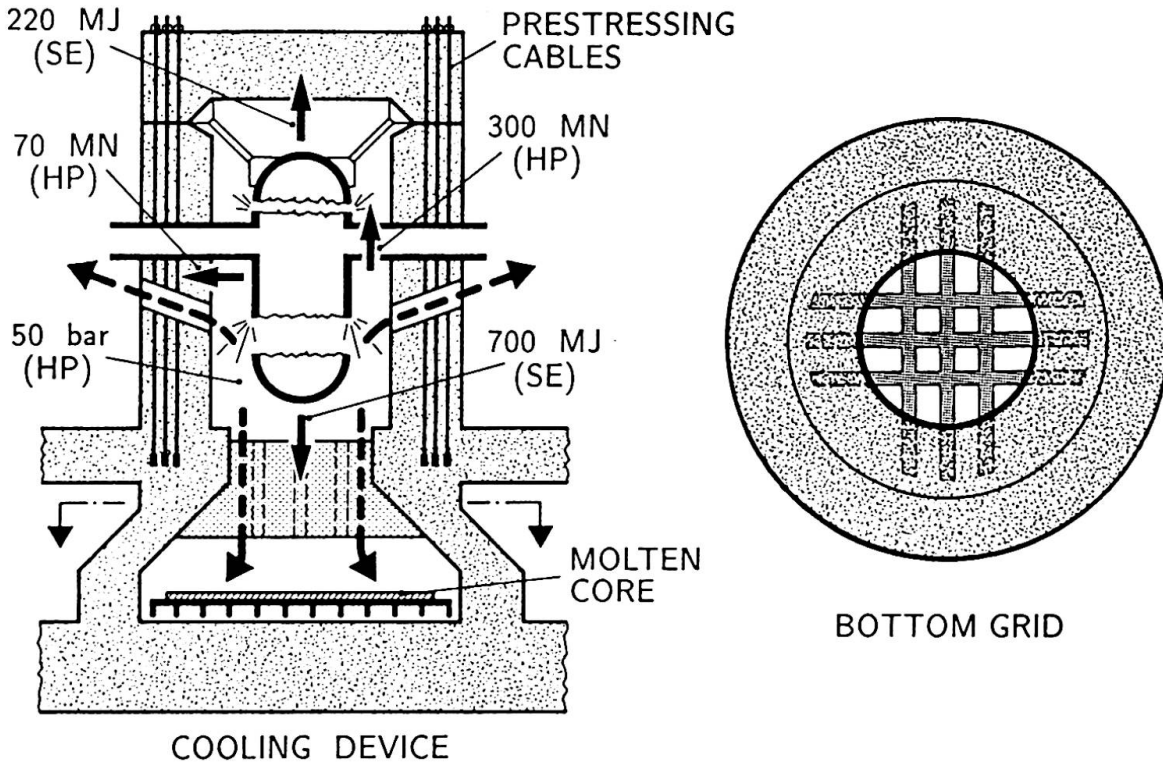
REACTOR PRESSURE VESSEL ENVIRONMENT

Figure 3 : Reactor pressure vessel environment and core-melt cooling device
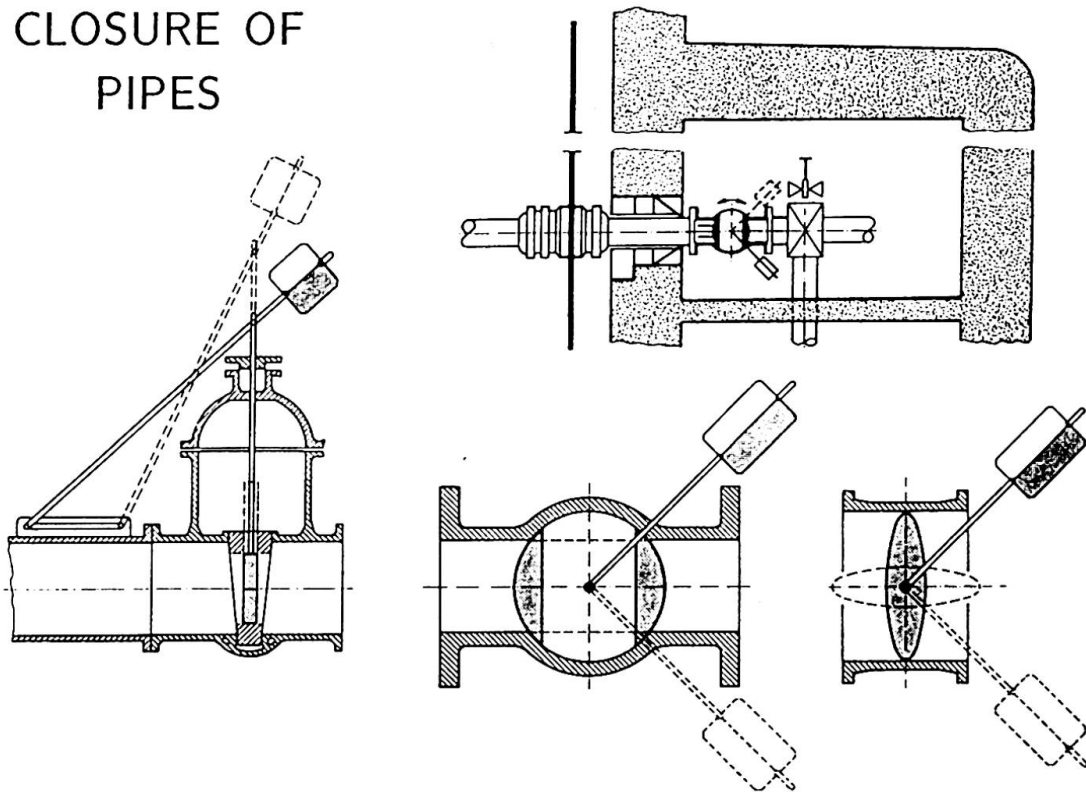
CLOSURE OF PIPES

Figure 4 : Closure of penetrating tubes and pipes

The core-melt cooling and retention device (Fig. 3) is protected from the downward moving end-cap missile by the concrete grid. The molten core will be cooled from the top and bottom faces by using water evaporation to provide a circulation system that can operate completely inside the pressure resistant enclosure of the building. With this method the heat is transferred to the steel shell and then dissipated, via heat radiation, by the chimneys.

The compartments which are formed in the cylindrical part of the containment between the inner and outer shells, and seperated by the contact elements, will form natural draft chimneys about 40 m high. Thermodynamic calculations have shown that they are capable of removing the released decay heat exclusively by passive means.

Considering that small leakages are unavoidable not only during accidents, but even under service conditions, it becomes necessary to control these leakages by filtering the air in contact with the inner steel shell. It is assumed that a possible leakage will occur in the close vicinity of any penetration points. The huge amount of air necessary to remove the decay heat would have required extremely large filter units, the latter slowing down the speed of the air stream. Consequently, an airlayer of about 10 cm thickness is separated from the main chimneys by a flexible steel membrane (Fig. 2). The air stream that removes the decay heat is led only along the cylindrical part of the building, while the other air stream which could become contaminated is led along the whole inner steel shell and filtered at the top of the building. The inner air stream is joined with the conventional 150 m high chimney located next to the reactor building so that it will be under a lower pressure than the outer stream. This provides a passive way to prevent the cooling air from being contaminated, even under normal service operations. The separating membrane does not significantly influence the decay heat removal.

All tubes and pipes penetrating the inner steel shell have to be completely closed by mechanical means (Fig. 4) to ensure that no fission products will enter the environment. This system must be operable even under high pressure conditions. It is envisaged to concentrate these penetrations at a few points around the perimeter, similar to existing Convoy PWR's, and close them by devices currently used by conventional power plants [3].

In summary, a containment design which is able to contain a severe core-melt accident is feasible. This will protect the public by preventing any release of radiation into the environment. Since the cost of the reactor building for the last convoy PWR built in Germany represented only about 4% of the total costs, then the additional amount of money needed to strengthen the containment is not very hard to justify.

ACKNOWLEDGEMENTS

REFERENCES –

1.   HENNIES, H.H., KESSLER, G., EIBL, J. (1989). Improved Containment Concept for Future PWR's. 5th Int. Conference on Emerging Nuclear Energy Systems. Karlsruhe, FRG, July 3-6, 1989.

2.   EIBL, J. (1989). A new Containment Design for PWR's. SMIRT-Pre-Conference Seminar on Containment of Nuclear Reactors. UCLA - Los Angeles, CA, August 9-11, 1989.

3.   MANG, F. (1990). Private Communications.

4.   KUCZERA, B., ALSMEYER, H., KRIEG, R., EIBL, J. (1990). Considerartions on Alternative Containment Concepts for Future PWR's. 2nd Int. Conf. on Containment Design and Operation. Toronto, Canada, October 14-17 1990.

5.   BREITUNG, W. (1991). Conservative estimates for dynamic containment loads from hydrogen detonations. 11th Int. Conf. on SMIRT, Pre-Conference Seminar, August 14-16, 1991, Shanghai, P.R. China.

6.   JACOBS, G. (1991). Estimation of Loads Acting during Reactor Pressure Vessel Blowdown at High Pressure. Am.Nucl.Soc. Winter Meeting San Francisco, November 10-15 1991.

7.   EIBL, J. et al. (1991). Containments for Future PWR-Reactors. Int. Conf. Structural Mechanics in Reactor Technology (SMIRT 11), Tokyo, Japan, August 18-23 1991.