REPORT

OF A CONSULTANTS MEETING ON

CONTAINMENT AND CONFINEMENT PERFORMANCE IN NPPs WITH WWER 440/213 AND 440/230 REACTORS

VIENNA, AUSTRIA, 29 NOVEMBER - 3 DECEMBER 1993

EXTRABUDGETARY PROGRAMME ON THE SAFETY OF WWER NPPs

International Atomic Energy Agency
CONTENTS

1. INTRODUCTION

2. POSSIBLE IMPROVEMENTS OF WWER 440 MODEL 230 CONFINEMENT

3. THERMAL HYDRAULIC BEHAVIOUR OF BUBBLER CONDENSER CONTAINMENT

Annex 3a Answers of Prof. Bukrinski to the questions referring to "The experimental and calculational investigations of processes in bubbler condenser containment systems of NPPs with WWER-440 reactors after LOCA" prepared by VTI and published by Sojuz-glav-zagran-atom-energo, USSR

Annex 3b Answers of Prof. Karwat to specific questions on thermal hydraulic behaviour of bubbler containment.

4. PROBLEMS OF MECHANICAL STRENGTH OF BUBBLER CONDENSER STRUCTURE

5. HYDROGEN PROBLEMS AND OTHER BDBA THREATS TO CONTAINMENT INTEGRITY

6. GENERAL CONCLUSIONS AND RECOMMENDATIONS

REFERENCES

LIST OF PARTICIPANTS

PROGRAMME OF THE MEETING

TECHNICAL PAPERS PRESENTED

BUKRINSKI, A.M. Review of experimental work for thermal hydraulics of the bubbler condenser system.

BALAZ, P., V-1 Accident Localization System Upgrading to Cope with Large LOCA Scenarios, VUEZ, Tlmace (Nov. 1993)

BALABANOV, E., Upgrading of Confinement of NPP Kozloduy Unit 3 and 4, Energoproject, Sofia (Nov. 1993)

MISAK, J., Review of analytical work on bubbler condenser containment in Slovakia (Design Basis Accidents)

J. KUJAL, Review of experimental and analytical work on bubbler condenser containment in Czech Republic.

TECHY, Z., Review of experimental and analytical work on bubbler condenser in Hungary

KULIG, M., Containment related studies performed in Poland.

KARWAT, H., Report about the activities of an international working group on bubbler condenser containment research work

SIMON, U., Steam condensation in water pools

PREUSSER, G., Actual developments in hydrogen control

STRUPCZEWSKI, A., Comparison of design criteria for NPPs containments with bubbler condenser and for large dry containment type.
1. INTRODUCTION

The reactors WWER 440 model V-230 being operated in several countries of central and eastern Europe were designed in the 1960-ies assuming that the design basis accident can be limited to a break of a pipe of 100 mm diameter fitted with an orifice of 32 mm diameter. This assumption presently judged to be inadequate according to the international safety requirements, was used to determine the Emergency Core Cooling System. For this size of the break, the spray system of the reactor building was designed to prevent uncontrolled releases to the environment. For larger breaks, till full rupture of one of two pressurizer surge lines of 200 mm diameter each, large flaps were designed to open during the initial pressure peak after the accident and release to the environment large amounts of steam escaping from the broken reactor coolant system (RCS).

In view of this initial release of radioactive medium and due to its other unsatisfactory features, the building surrounding the WWER 440/230 reactor is not called a containment, but is said to fulfill a confining function, in short it is termed a confinement.

The shortcomings of the WWER 440/230 confinements have been long recognized and the newer model of WWER 440 units, called model V-213, has been provided with an improved building of higher leaktightness and higher strength, containing a complicated system of water trays and air traps designed to condense steam and remove a part of the air from the reactor compartments after large break loss of coolant accident (LB LOCA). For such case, the system provides fast pressure decrease in the containment to subatmospheric values and thus prevents any significant releases of radioactivity to the environment. As the main process is that of steam bubble condensation in water, the system is called bubbler condenser containment.

The bubbler condenser containment was the answer to the problem of providing the old WWER 440 model 230 units with a reliable containment without excessive changes in design of original hermetic compartments and without significantly increasing the maximum pressures and temperatures possible inside the containment, which would mean the necessity of exchanging a significant part of reactor equipment unable to stand high environmental demands typical e.g. for large dry containments. However, although the bubbler condenser containment could have been a good solution for the newly built units, it was rather difficult to adapt it to the old WWER 440 V-230 reactors already in operation. Therefore the WWER 440/230 units continued to be operated with previously built confinements, even though the contemporary safety rules clearly indicated inadequacy of such designs.

The IAEA has been studying the safety of WWER 440/230 reactors for more than 3 years. In February 1992 the ranking of safety issues identified in the Extrabudgetary Programme on WWER-440 model 230 NPPs was published [1.1], and in May 1992 the major findings of the Programme were summarized [1.2]. The issues related to radioactive materials confinement in case of LOCA were ranked as being of high safety concern, and those related to ECCS redundancy and physical separation - of highest safety concern. The main safety issue was connected with breaks larger than 32 mm, which in WWER 440 model 213 reactors were considered as being within DBA limits, but in WWER 440/230 units were equivalent to Beyond DBA events.
Recognizing the importance of improvement of the final barrier against fission product release in WWER 440/230 reactors and the necessity to upgrade it so that it could withstand breaks larger than 32 mm without uncontrolled releases to environment, the IAEA took the initiative of preparing a report on WWER 440/230 units confinement status and possible improvement, and obtained the assistance of the Swiss Government in financing the work which was eventually done by Elektrowatt Engineering Services Ltd. The report "Technical Basis for Improving the Confinement Function in WWER 440/230 NPPs" [1.3] provided a review of containment design requirements and containment designs in various countries and a detailed analysis of various measures possible to be implemented in WWER 440/230 confinements with the view to upgrade them for accident conditions. This report was provided to all participants of the present Consultants Meeting as the basis for further discussions.

In the framework of the Extrabudgetary Programme experts have also examined the proposed application of the concept of Leak Before Break and found it to be applicable to 500 mm pipes in the RCS of WWER 440/230 reactors [1.4]. In view of the unfeasibility of improving the confinement to cope with such large breaks and the reported results of the LBB application studies, it seems to be possible to exclude this size of break from the anticipated initiating events to be considered as the design basis for confinement improvement. The report on "Guidelines for the application of the leak before break concept" has been prepared by the IAEA [1.5] and is being circulated for comments.

The Agency has also investigated the performance of bubbler condenser containment of WWER 440/213 units, which should be regarded as reactors fulfilling all current international nuclear safety requirements. Within the framework of the Technical Cooperation Project RER/9/004 on WWER 440/213 Safety Aspects Evaluation a study of Bubbler Condenser Containment behaviour under DBA and BDBA conditions has been performed in Poland [1.7] and later provided for peer review by Ukrainian Energoprojekt Institute. The results of the Polish study generally confirmed large safety margins inherent in the bubbler condenser concept, but the evaluation of the mechanical strength under LB LOCA conditions revealed a number of weaknesses in the actual mechanical design of the bubbler condenser structure. The review of Ukrainian specialists showed that in many cases Polish approach was too conservative, but that the bubbler condenser structure was indeed too weak and had to be strengthened.

Basing on the original experimental work performed by the designer of the bubbler condenser and made available within the framework of the RER/9/004 project, and also on the numerous later publications on the subject, the IAEA secretariat has prepared a list of specific questions to the experts in general and to the Russian designers in particular so as to get answers to many concerns expressed over the years by various specialists. The topics include all aspects of aerodynamics, hydraulics and heat exchange after LB LOCA, as well as the problems of mechanical loads and bubbler condenser strength in various phases of its operation. The proceedings of this Consultants' Meeting provide the answers to these questions.

An additional matter of high interest is the problem of Beyond Design Basis Accidents, in particular the question of possible hydrogen hazards prevention. This field of
work has been studied in much detail within the framework of the RER/9/004 project and much progress has been achieved. During the meeting the questions of BDBA sequences and preventive measures were discussed separately and are presented under a separate heading.

The work of the experts was conducted in four working groups, namely the groups on:

- POSSIBLE IMPROVEMENTS OF WWER 440 MODEL 230 CONFINEMENT
- THERMAL HYDRAULIC BEHAVIOUR OF BUBBLER CONDENSER CONTAINMENT
- PROBLEMS OF MECHANICAL STRENGTH OF BUBBLER CONDENSER STRUCTURE
- ASSESSMENT OF THE WWER 440/213 CONTAINMENT FOLLOWING A SEVERE ACCIDENT

The meeting was started with the presentation of technical papers and discussions, after which the experts were divided into groups working mostly separately, although in many points interactions with other groups were necessary. Final conclusions were discussed and agreed upon in the general meeting.

The notes presenting the scope of discussion, findings and recommendations for each topic are given below. In addition, written answers provided after the meeting by Prof. Karwat and Prof. Bukrinski to the specific questions concerning bubbler condenser containment performance are given as annexes 3a and 3b. The references for the whole text are grouped together at the end of the discussions but before the technical papers.
2. POSSIBLE IMPROVEMENTS OF WWER 440 MODEL 230 CONFINEMENT

2.1 DETERMINATION OF THE DESIGN BASIS ACCIDENT FOR THE IMPROVEMENT OF WWER 440/230 CONFINEMENT

Scope of the Review: Determination of spectrum of accidents to be considered for confinement performance in the context of confinement upgrading

Documents Reviewed: [2.4, 2.9]

Note on terminology: The experts recommend against the use of the term "Design Basis Accident" in the context of plant upgrades, since this has caused confusion in the past. The discussion concerns which accidents or events should be considered for the design of specific system or safety function upgrades. A term such as "Upgrade Basis Event" is more suitable and will be used in the text for the discussion of WWER 440/230 confinement problems.

Summary of Discussions:

The discussions centered around the following areas:

• Which events should be considered in the design of confinement upgrades?
• Which events are the limiting ones for the different types of accidents and safety functions of confinement?
• How does the confinement upgrade basis event interface with the ECCS upgrade basis?
• The availability of the necessary accident analyses (especially confinement pressure for LOCAs and secondary side breaks)
• The consideration of events which fall outside the selected "Upgrade Basis Events"
• The methodology for performing the necessary accident analysis (i.e. best estimate vs. licensing grade analysis)
• The specialists views concerning the recommendations of the recent IAEA specialists meetings on WWER 440/230 upgrades [2.4 & 2.9]

Findings:

The experts believe that the recommendations from the two recent IAEA specialist meetings [2.4 & 2.9] in the area of confinement upgrade are consistent with each other, and they are in general agreement with them.

During the meeting, the experts had an opportunity to compare various existing analyses of V 230 confinement response to different loss of coolant accidents. These analyses were performed by Energoproject Sofia (using RELAP) and Westinghouse (using MAAP4/VVER).

Inevitably a number of accident sequences had been analyzed by more than one organization (e.g. 200 mm and 500 mm LOCAs), and so a comparison of the results was
possible. Due to the lack of time such comparison was not performed in detail. However, the comparisons that were made showed in general very much good agreement. The specialists regard such agreements as very encouraging, and indicative of a maturity in the capabilities available to analyze and understand confinement response. They also agreed that significant progress has been recently made in this area, and therefore recommend, the continuation or extension of such efforts in a number of areas listed further below.

**Plant Specific Status:**

Most of the available pressure transient analyses for large size pipe breaks were made for double ended 500 mm pipe break. Several pressure transient analyses for the 200 mm break size and secondary side breaks have also been made by various organizations for the Bohunice and the Kozloduy plant. Systematic pressure transient calculations for these accidents are still needed.

**Recommendations:**

The specialists recommend that the following approach be considered for the choice of the upgrading basis for the WWER 440/230 confinement:

1. The confinement upgrade should be realized such that, using standard (i.e. conservative) licensing basis safety analysis assumptions, compliance with the confinement design criteria (structural response and capability to perform its function as barrier to the release of radioactive material) can be demonstrated for all of the following events:
   (i) double ended break of a 200 mm diameter surge line in the reactor coolant system (RCS)
   (ii) single ended break of a 200 mm diameter line in the cold leg in the RCS
   (iii) all postulated secondary side breaks inside the confinement (considering steam and feedwater systems)

   A double ended blowdown from the reactor coolant system hot leg must be considered for the surge line break since the WWER-440/230 RCS has two parallel surge lines. In contrast, there is no 200 mm line connected to the cold leg and the given value is an equivalent diameter of postulated partial break which may occur on the cold leg. It is noted that, for confinement performance, the 2 x 200 mm surge line break is likely to be more limiting than the 1 x 200 cold leg break. However, the 1 x 200 mm cold leg break may be more limiting for ECCS (core integrity) analysis. Breaks in the secondary system (main steam and feedwater lines) have also to be analyzed in terms of their dynamic effects (pipe whip and jet impingement) affecting portions of RCS pressure boundary and confinement structure integrity as well as in terms of the resulting pressure and temperature transients affecting the confinement structure and retention function.

2. That leak-before-break (LBB) concept is applied to support the exclusion of LOCAs between 200 mm and 500 mm break sizes from the upgrade design basis. Such LBB investigations should also be performed for the secondary system piping inside the confinement, whose breaks could lead to unacceptable damage
to the RCS pressure boundary and to the confinement structure integrity (pipe whip, jet impingement, and pressure and temperature transients).

3. Confinement upgrades should be designed such that it can be demonstrated, using best estimate methods and computer models, that even LOCA break sizes larger than 200 mm (double ended) and the pressure transients resulting from those secondary system breaks not covered by the LBB concept, do not lead to loss of confinement integrity or excessive radiological releases.

The overpressurization challenge to containment from such events should be assessed against the structural capability based on best estimate analysis.

2.2 CONFINEMENT IMPROVEMENT FOR UPGRADE BASIS EVENTS

Scope of the review: Evaluation of pressure suppression devices with condensing function which can be used for confinement improvement for upgrade basis events, of filtered venting options presented by various organization, of confinement spray system, post LOCA instrumentation and other engineered safety features from the standpoint of their technical characteristics and effectiveness in reducing radiological impact after Upgrade Basis Events.

Documents reviewed: [2.1,2.2,2.3,2.4,2.5,2.6,2.7,2.8,2.9,2.10,2.11,2.12,2.13,2.14,2.15].

2.2.1 Pressure Suppression Devices with Condensing Function

Seven pressure suppression devices with condensing function have been evaluated in detail, taking into account their hydraulic characteristics, condensation effectiveness, hydraulic stability, the status of experimental verification, assessment of features important for confinement integrity and the status of implementation. The results of the comparison are given in table 2.2.1.
### Pressure Suppression Devices with Condensing Function

<table>
<thead>
<tr>
<th>Device</th>
<th>Characteristics, features, definitions</th>
<th>Condensation Effectiveness</th>
<th>Hydraulic Characteristics</th>
<th>Hydraulic Stability</th>
<th>Experimental Verification, Application, Recommendation</th>
<th>Assessment of Device from thermal-hydr. point of view</th>
<th>Application or Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet condenser with direct flow (VNIAES, Moscow)</td>
<td>Direct (mostly vertical) flow of air-steam mixture into condensing /mixing chamber, using for condensation full water volume of cond. pool by Submergence of the chamber only about 30% of the pool depth</td>
<td>High, channeling negligible</td>
<td>Small hydraulic resistance (“direct flow”)</td>
<td>Pressure oscillations are expected</td>
<td>Relatively large scope of experimental programme performed confirming assessments (on one condenser) Additional experimental program recommended to determine impact of common operation of neighboring jet condenser (4-5) on their condensing effectiveness and impact of pressure oscillations</td>
<td>Possible problems with pressure oscillations can be avoided by installing a filtered venting system (will take over at low flow rates)</td>
<td>NPP Ignalina [2.3]</td>
</tr>
<tr>
<td>Jet condenser with reversed flow (combined with barbotage function (VTI, Moscow, now NTC RB Moscow)</td>
<td>Air-steam mixture entering device mostly vertically is reversed before entering condensing / mixing chamber. Maximum submergence given by location of reflecting plate (1m)</td>
<td>High</td>
<td>Requires higher overpressure for the same mode of operation as compared with the above (“reversed flow”)</td>
<td>as above, but no impact on pool structure expected</td>
<td>Good performance proven by a relatively large scope of experimental program</td>
<td>Can operate at lower air-steam flows than barbotage condenser with natural circulation w/o creating dangerous pressure oscillations</td>
<td>Ignalina, Juragua NPP [2.7]</td>
</tr>
<tr>
<td>Horizontal ejector (NTC, Moscow now NTC RB Moscow)</td>
<td>Air-steam mixture enters device horizontally, other functions same as above. Submergence generally lower (15-20 %)</td>
<td>Sufficient</td>
<td>Expected to have lower resistance</td>
<td>Higher unstability performance (at lower steam flow rates) resulting in press. oscillations</td>
<td>First version experimentally verified indicated the aforementioned points</td>
<td>Advantage if can be installed inside leak-tight compartments</td>
<td>Will be installed in NPP Sosnowyi Bor (St. Petersburg)</td>
</tr>
<tr>
<td>Device</td>
<td>Characteristics, features, definitions</td>
<td>Condensation Effectiveness</td>
<td>Hydraulic Characteristics</td>
<td>Hydraulic Stability</td>
<td>Experimental Verification, Application, Recommendation</td>
<td>Assessment of Device from thermal-hyd. point of view</td>
<td>Application or Reference</td>
</tr>
<tr>
<td>--------</td>
<td>---------------------------------------</td>
<td>---------------------------</td>
<td>---------------------------</td>
<td>---------------------</td>
<td>---------------------------------------------------------</td>
<td>---------------------------------------------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>Vortex-type jet condenser (NIKJET, Ekaterinburg and VNIAES Moscow)</td>
<td>Vertical condensing chamber w. tangentially arranged jet condensers creating a vortex flow, enhancing filtration capability of device</td>
<td>Volume of cond. pool restricted by space if installed inside confinement resulting in not full condensation, saturation temp. of water may be reached</td>
<td>Higher hydraulic resistance may be expected</td>
<td>High stability expected</td>
<td>Filtration efficiency tested during ACE tests (Hanford), Experimental verification of condensing function performed</td>
<td>Rather complicated design, good filtration function</td>
<td>Not available</td>
</tr>
<tr>
<td>Combination of High-Flow Filter and Low Flow Filter (Sulzer)</td>
<td>Reversed flow of air-steam mixture thru nozzles located in lower, water-filled plenum of filter vessel</td>
<td>Good</td>
<td>Relatively high hydraulic resistance expected (High flow filter)</td>
<td>Good</td>
<td></td>
<td>Good filtration capability because of installation of industrially proven mixing elements</td>
<td>High flow filter not applied yet [2.10]</td>
</tr>
<tr>
<td>2. condensation stage of proposed pressure suppression (Siemens)</td>
<td>Reversed flow thru venturi nozzles of rectangular shape located in lower plenum of cond. pool</td>
<td>Good</td>
<td>Results from Siemens/ACE tests show Δp&lt;sub&gt;150&lt;/sub&gt;mbar Modified devices (JAVA-Tests) have been tested with lower hydraulic resistance</td>
<td>Good</td>
<td>Very good filtration efficiency verified, by tests at the PSI (Switzerland)</td>
<td>Not available</td>
<td>[2.11]</td>
</tr>
<tr>
<td>Bubble condenser of VTI concept, modified proposal of Westinghouse and ENERGoproject, Prague</td>
<td>Well known 'cap-gap' system</td>
<td>Good</td>
<td>very good, low hydraulic resistance</td>
<td>negligible oscillations expected, swaying of water level of cond. pool could have negative impact on operational function</td>
<td>see recommendations in Chapter 3</td>
<td>see recommendations in Chapter 3</td>
<td>At least 14 VVER 440/213 with this device in operation</td>
</tr>
</tbody>
</table>
2.2.2 Filtered Confinement Venting

Scope of the review: Three options were reviewed, namely:
- Sulzer/EWI Filtered Venting System (FVS) with Sulzer filters proposed for Kozloduy NPP and described in [2.10, 2.2],
- Siemens-KWU proposal for upgrading Bohunice NPP, described in [2.11])
- Accident Localization System Upgrading in Bohunice, with either water jet condensers or bubbler condenser tower, described in [2.1, 2.3, 2.5, 2.7 and 2.8].

The proposals were assessed under the following criteria:

a) Decontamination effectiveness
b) Hydraulic characteristics, especially the capability of operation at lower overpressures in the confinement
c) Interaction of FVS (filtered venting system) and PSS (pressure suppression system)
d) Other features
e) Experimental verification

Findings:

The Sulzer-EWI concept proposed for Kozloduy involves installation of two filters, one for the initial flow rates during the blowdown phase of the Upgrade Basis Event, another for the next phase, when the flow rate is low, but the contamination of the air steam mixture may be high. The high flow filter has to be designed so as to allow for high rate flows (up to 900 kg/s) of steam-air mixtures within pressure difference of about 0.4 bar, ensure good condensation of steam released from the confinement during LB LOCA and provide decontamination factor of 200 for aerosols and 100 for elemental iodine carried by non condensable gases. The low flow filter must provide low hydraulic resistance (about 0.2 bar) at low flow rates (about 17 kg/s), but will be designed to ensure high decontamination factor of at least 1000 for both aerosols and iodine.

Both filters will operate in parallel in the high confinement pressure range, however, in the lower confinement pressure range only the low flow filter will be required and will thus operate. This transfer will occur in a completely passive manner. The filtered gases would be released to the atmosphere. The filtered gases from the low filter could be directed to the stack.

Moreover, in view of the high leak rates measured in the WWER 440/230 confinements, it is proposed to install an additional line with two fans in parallel, which would draw the atmosphere from the confinement in the late stage after an accident and direct it to the low flow filter and then to the atmosphere. Thus, the pressure inside the confinement could be lowered below atmospheric and the releases could be filtered before getting out to the environment.

The high flow filter would be designed such that the peak accident pressure is below 80 kPa overpressure for the upgrade basis event and below the rupture pressure of the confinement for the double ended 500 mm pipe break. Thus the structural integrity of the confinement would be guaranteed.
The conceptual phase of the project has been completed and the feasibility of the proposed solutions confirmed.

The systems proposed to Bohunice included a number of concepts, of which two were chosen for the detailed analysis, namely the bubbler condenser concept and the installation of internal jet condensers [2.1]. The latter concept was chosen as offering more advantages. It consists in installation of a condensation pool of water (volume of about 190 m³ and the height of 3.5 m) in the space at the corner of the confinement made free by removal of the valves flap. 30 to 40 jet condensers of equivalent diameter of 400 mm would be then installed in the pool with their inlets connected to the confinement volume.

The space above water level would be connected through the existing openings with the atmosphere. The jet condenser and the condensation pool together provide a filter function by the mixing and condensation action of the entering steam and the pool water. For the later stage of the accident management a filtered venting system with forced ventilation would be installed. A suction fan would provide slight subatmospheric pressure in the confinement and direct the mixture of non-condensable gases and steam to a filter of scrubber type and then to the stack.

The proposals from Siemens KWU [2.11] and Westinghouse Nuclear Europe [2.12] are proprietary and were not fully discussed.

The two proposals described above were assessed. The following features of the proposals were determined:

**Advantages**

- Original design concept of dry containment, with 1 bar overpressure retained
- Designed to have the capability to cope with upgrade accident events (2 x 200 mm break size)
- Extension of confinement volume and addition of pressure-suppression system has the potential to guarantee the structural integrity for larger LOCAs (up to 2 x 500 mm break size)
- Upgraded to mitigate severe accident consequences using filtered venting
- Fully passive mode of operation possible
- Easy maintenance
- Suction mode of system operation during normal and post-DBA conditions (fan mode of operation)
- Limited modifications of present confinement structure
- Possibility of finding less costly and more easily implemented upgrading systems for upgrading basis event assumed to be a double ended 200 mm pipe break (Bohunice).

**Disadvantages**

- Possibility of release of uncondensed steam to the atmosphere from the Hi-flow filter at the end of blowdown phase for breaks > 2 x 200 mm (Kozloduy)
• Construction of large new buildings will be necessary to avoid large releases to the atmosphere if double ended 500 mm break is taken as the DBA (Bohunice).

**Influence of each scheme on NPP confinement**

• No major differences on pressure trend during accidents
• Limited impact on structural strength
• Minor impact on present confinement structures
• Full modernization of flap valve compartment necessary including:
  - removal of existing back pressure valves,
  - enlargement of flap valve opening,
  - installation of rupture discs.
• Uncontrolled leakage in suction/fan mode of operation avoided (Kozloduy only)

**Existing and required experimental and theoretical basis for proposed solutions**

**Existing basis**

• Full theoretical and experimental basis for low flow filter
• Model tests for optimization of vent and duct geometry
• Condensation effectiveness and water syphon function on 1:1 scaled model of jet condenser (Bohunice only)
• Small 1: $10^3$ scaled model of the entire system function (Bohunice only)

**Required investigations**

• Proof of filtration and condensation efficiency of high-flow filter under high flow conditions (Kozloduy only)
• Hydrogen distribution and control during severe accidents
• Theoretical and experimental investigation of structural integrity under full design overpressure.

**Recommendations**

An additional experimental program should be implemented in order to determine:

• hydraulic characteristics at confinement pressures of 80 to 150 kPa (abs)
• blower selection for forced flow operation through the filter
• feasibility of proposed solutions

**2.2.3. Improvements of confinement spray system**

**Findings**

To guarantee the performance of hermetic zone, modifications of the spray system are needed.
The present system does not comply with single failure criterion and common cause failure concept.

Recommendations

The capability of the improved confinement spray system shall be consistent with its expected function in reducing confinement pressure following high energy line tracks recommended to be analyzed in Section 2.1.

In order to assure the compliance of the spray system with actual safety criteria it is recommended:

- to divide the present system into two fully redundant trains (mechanical equipment and actuation logic);
- to separate them physically with possible means;
- to increase effectiveness of spray system by:
  * modernization and relocation of nozzles;
  * decreasing the starting time of the spray system within reasonable means;
  * protecting the water sump inlet against clogging;
- to analyze the possibilities of installation of passive spray system.

2.2.4 Post LOCA Instrumentation

Summary of Discussions

The specialists could not provide positive evidence that instrumentation provided to record important containment parameters is quantified to stand environmental conditions during a pipe medium size break inside the confinement.

Findings:

The instrumentation necessary for the measurement and recording of essential confinement parameters (such as global pressure and temperature of the confinement atmosphere and the radiation level at selected spots) during the upgrade basis event should be provided. Requirements and design guidelines for such instrumentation are contained e.g. in NRC Reg. Guide 1.97 and KTA Standard 3502. Application of these requirements and criteria for such instrumentation (extent, separation, environmental qualifications, etc.) for WWER-440 plants are given in an IAEA report to be issued soon [2.13].

Recommendation

Instrumentation for measuring and recording essential confinement parameters during an upgrade basis event should be installed in accordance with the recommendations of IAEA report [2.13].
2.2.5 Radiological Hazards

Recommendations

The radiological consequences to the public following the upgrade basis accident should be calculated. The calculated doses at the exclusion area boundary should be compared to the applicable safety criteria defined in national regulations.

The source terms should be based on a mechanistic calculation of the fission product releases following the upgrade basis accident. This requires combining the ECCS, containment, and offsite dose calculations. The number of fuel rods calculated to experience cladding rupture can be used to determine the gap fission product releases. The confinement pressure analysis can be used to calculate the releases to the environment through all possible release pathways. These releases are used as the basis for the exclusion area boundary doses based on site-specific parameters.

2.2.6 Reduction of Leakage from Confinement

Findings

One of the important safety concerns of WWER-440/230 confinement is the design and the actual leakrate.

The leakrate in the originally built WWER 440/230 confinements were very high, exceeding several thousands of volumetric percent per 24 hours at full design basis accident pressure. Such high leakages make it very difficult to retain radioactivity inside the confinement. However, the efforts of the operational crews have already made it possible to improve significantly confinement leaktightness. E.g. in Bohunice V-1 the leaks have been reduced more than by an order of a magnitude. Similar work should be conducted on all NPPs with WWER 440/230 reactors.

Recommendations

To improve the leaktightness of the confinement it is recommended:

1. To establish and apply systematically:
   - periodical local tests for all kinds of penetrations,
   - periodical integral over- and underpressure tests of the entire confinement,
   - use of the latest sealing materials approved for NPPs,
   - use of special sealing techniques.

2. To modify and, if necessary, replace certain confinement penetrations (e.g. ventilation penetrations, flap valves)

   The final goal should be to reduce the current leakrate as far as practically achievable.
2.2.7 Other Options

Findings

Ice Condenser

One concept that has been considered for an upgrade to the WWER 440/230 confinement involves the use of an ice condenser. This employs stored ice to provide a means to condense the steam releases from the core. Preliminary studies performed by Westinghouse have shown that the post LOCA confinement pressure can be maintained below 1 bar overpressure even for the 200-500 mm break [2.15]. The required volumes on the other side are very large.

Large additional volumes with sprays

At least two solutions have been proposed consisting in adding volumes, in which the steam fraction of the escaping air-steam mixture would be condensed by either a passive or an active spray system [2.4].

Vacuum building

Another solution that may improve the present confinement retaining capability consists in connecting to it a vacuum building including an automated spray system similar to the design for the multi-unit CANDU plants. As in those plants one building could serve both units of a WWER-440/230 power station [2.4].

Recommendations

None of these issues has been addressed due to the time limitation and lack of the necessary detailed information.

2.2.8 Regulatory Requirements for Upgrading

Recommendations

It is recommended to the Regulatory Bodies to consider the approach positively evaluated before, namely the assumption that the upgrading basis event for the confinement should be chosen with the consideration of Leak Before Break principles as a double ended break of a 200 mm pipe in the RCS. This event could be treated as equivalent to the DBA in other PWRs, so that full retention of gases after the accident would be required. The double ended 500 mm pipe break could then be assumed as the Beyond Design Basis Accident, for which it might be required:
- to maintain confinement integrity throughout the accident,
- filtrate the vented air-steam mixture so as to fulfill the regulations limiting the admissible radiological hazards at the exclusion area boundary.
2.3 CONFINEMENT IMPROVEMENT FOR SEVERE ACCIDENTS
(ACCIDENTS BEYOND AN UPGRADE BASIS EVENT)

2.3.1 Prevention of Hydrogen Combustion/Detonation

References: [2.3, 2.14]

Summary of discussion:

The specialists were not able at this time to provide recommendations regarding the most appropriate hydrogen control measures. They believe that it is too early to make such recommendations, but believes that it is very important that further analysis be performed in order to develop a better understanding of the phenomena and issues, and to serve as the basis for sound recommendations on hydrogen control.

The hydrogen generation rates and the amounts of released hydrogen determined in BDBA analyses of WWER 440/213 reactors can be in some extent used as starting points for hydrogen hazards evaluation in WWER 440/230 units because of similarities in reactor cores and reactor cavity performance of both these NPPs.

Systems or measures to prevent a hydrogen hazards during severe accidents have been proposed, developed and implemented or installed in various LWR plants. Technical solutions mostly consist of inerting the containment atmosphere with nitrogen and installation of thermal recombiners or a combination of ignitors and catalytic recombiners (dual system).

Investigations of the hydrogen hazards under severe accident conditions, taking into account accident management and confinement upgrade measures have not been made.

Findings:

Applications of presently available solutions for hydrogen hazards prevention in WWER-440 confinements have been reviewed from a technical point of view, however, no proposal has been made by industry up to this date. The group believes that for the 230 model confinement a suitable technical solution can only be determined based on a systematic analysis of the hydrogen hazards for BDBA event and taking into account the particular features of the confinement. Therefore no definite technical solution is available today to cope with a hydrogen hazards in a WWER-440/230 plant.

Recommendation:

Systematic analyses using conservative assumptions are recommended to be done to investigate the hydrogen hazards in the confinement under severe accident conditions to provide a basis for hydrogen control systems to be installed in the WWER-440/230 plants in the following areas:

a) Hydrogen generation rates and amounts, both in-vessel and ex-vessel. Sensitivity
to accident sequence, system pressure, core reflooding, and other parameters known to be important should be investigated.

b) Distribution and mixing of hydrogen in confinement: The nature of mixing of hydrogen in WWER confinements may be different than in other LWR containments since they are compartmentalized. It is recommended that detailed mixing analyses be performed for various accident sequences and these calculations be verified by experimental data where possible.

c) Gas compositions and consequences of hydrogen combustion: The likelihood of deflagration, detonation and transition to detonation should be assessed under actual confinement geometry and event specific conditions. The consequences of deflagration should be compared with best estimate structural capability evaluations.

For these investigations the measures for plant upgrade events such as those affecting the leakrate and accident management measures should be considered.

2.3.2 Assuring negative or at least reduced pressure to prevent large release of radioactivity materials

Findings

The actual high leakrate even after confinement upgrading can cause considerably high radioactivity release during severe accidents. To mitigate consequences of these releases it is recommended to reduce the post-accident confinement pressure or/and to bring it slightly below atmospheric pressure. This will provide the control of the discharges to the environment.

Recommendations

The proposed passively acting filter system should be upgraded using actively operating suction elements. In the latter phases the system should operate in a differential pressure that is defined by minimum allowable confinement negative pressure and maximum resistance of venting filters.

2.3.3 Severe Accident Instrumentation

Summary of Discussions

The specialists could not find evidence that instrumentation is provided to record important containment parameters after a beyond an upgrade basis event inside the confinement.

Findings:

There should be instrumentation to permit essential confinement parameters (such as global pressure and temperature of the confinement atmosphere and the radiation level at selected spots) be measured and recorded during an event beyond the upgrade
basis event for a later assessment of the accident in accordance with the international practice. Requirements and design guidelines for such instrumentation is contained e.g. in NRC Reg. Guide 1.97 and KTA Standard 3502. Application of these requirements and criteria for such instrumentation (extent, separation, environmental qualifications, etc.) for WWER-440 plants is given in a IAEA report soon to be issued [2.13].

Recommendation

Instrumentation that measure and record essential confinement parameters during an event beyond the upgrade basis event should be installed in accordance with the recommendations of IAEA report [2.13].

2.3.4. Radiological hazards

Recommendations

As mentioned above, the confinement upgrading should be realized in such a way as to assure confinement integrity for BDBA events such as 500 mm pipe break. The air steam mixture released from the confinement should be filtered before release to the environment.

It is recommended that best estimate analytical techniques be used for the evaluation of radiological hazards under BDBA conditions.
3. THERMAL - HYDRAULIC BEHAVIOUR OF BUBBLER CONDENSER CONTAINMENT

3.1. DETERMINATION OF THE DESIGN BASIS FOR BUBBLER CONDENSER CONTAINMENT DESIGN

Scope of the review

Basing on US General Design Criteria given in App. A to 10 CFR50 and on German design criteria for large dry containments to review the design basis criteria taken in the design of bubbler condenser containment and evaluate their adequacy in the light of international practices.

Documents reviewed: [3.7], [3.8]

Summary of discussions

The discussion was based on a working document presented at the meeting: "Comparison of design criteria for NPPs containments of bubbler condenser and large dry containment type" [3.8].

Concerning the accidents to be taken into account as possible DBAs, the approaches vary in the different countries with one common feature: LBLOCA (double ended instantaneous break of the largest pipe in the RCS) is taken into account everywhere. Main steam line break (MSLB) is another DBA for containment calculations (Belgium, Hungary), whereas MSLB and a spectrum of different size LOCAs are analyzed in Slovakia.

Basic assumptions for global containment maximum pressure prediction are essentially in agreement with the existing US or German requirements. The blowdown mass and energy is the RCS mass and energy derived from the transient blowdown calculations.

Safety margins in terms of percents above calculated values, which are also different in the US or German case, have not been required in the WWER countries, the issue is up to the national regulations.

Design temperatures are more important for steel shell containments; for a concrete structure like the WWER-440/213, it does not seem limiting.

From the specific requirements, the nodalization issue was mentioned to be important: the bubbler condenser function must be modelled. It means that at least a three node subdivision of the containment should be used to obtain qualitatively realistic results. Besides the consideration of the design criteria for large PWR containments, the same criteria for BWR containments with pressure suppression systems should be carefully evaluated, as the bubbler condenser fulfills an essentially pressure separation system (PSS) function. Section "5.4 Design conditions and material requirements" of the "General design criteria..." is mainly related to the materials of steel shells. This part should be replaced by requirements
for concrete containments.

For the time being, there are no formal regulatory requirements related to the behaviour of the bubbler condenser containments in severe accident situations. However, there are research and assessment activities going on in many countries to address the impact of severe accidents. Some of the activities are coordinated in the IAEA Regional Programme "The VVER-440/213 Safety Assessment" RER/9/004. There are also national efforts in this field for identification of possible challenges and ways of preventions or mitigation.

Recommendations

The design criteria adopted in the design of bubbler condenser containment are equivalent to the US General Design Criteria and generally address similar points as the design criteria in force in the Germany, but without specific requirements of safety margins characteristic for German rules. Thus bubbler condenser containment should be treated as a containment equivalent to other internationally recognized containment types. In view of its specific pressure suppression system it is recommended to compare design criteria for pressure suppression pools in BWR containments.

3. 2 FAILURES TO BE CONSIDERED IN BUBBLER CONDENSER CONTAINMENT ANALYSIS ACCORDING TO SINGLE FAILURE CRITERION

Scope of the review: In view of the complexity of sequences which can occur in bubbler condenser containments after DBA and the importance of single failure criterion in the deterministic approach to reactor safety it is desirable to determine the list of failures which should be considered in bubbler condenser analysis.

Documents reviewed: [3.9, 3.12, 3.13].

Summary of discussions

Owing to large safety margins, the consequences of single failures in bubbler condenser are not very severe, but qualitatively they influence either maximum pressure (in some cases even in negative direction) or the long-term pressure decrease.

The following single failures should be considered for the bubble condenser system:

1. Failure to open of 1 out of 12 check valves (between the air trap and the water shelf outlet plenums).

2. Loss of water inventory in one shelf level; this type of failure is extremely improbable due to redundant measurements of water level and the alarms which would be activated in case of reduced level. In spite of this, such an event was considered also in the design of the bubbler condenser.

3. Failure to open of 1 out of 2 relief valves φ 250 (between tower inlet shaft and water shelf outlet plenum)
4. Loss of leaktightness of the air trap compartment
   a. manhole left open
   b. ventilation line (normally used during refuelling period in case of inspection or maintenance work) not isolated
   c. let down line from the air trap not isolated

5. Loss of leaktightness of the water shelf upper plenum
   a. manhole left open
   b. relief valve φ 250 failed in open position

Likelihood of individual failures has been also discussed.

Failures (1), (2), (3), (5b) are typical failures of equipment. Failures (4b), (4c) may result from equipment failures or human errors; the latter cause seems to be the dominant. The most likely causes of failures (4a) and (5a) are human errors (manhole left open after use). Training of maintenance personal and appropriate test procedures should decrease the likelihood of these events. According to the information available there is a possibility that ventilation line and let-down line may be affected due to steam-air impact following DBA since these lines are partially located inside the leaktight compartments and may not be properly protected against physical damage. If this information is correct, an appropriate measure should be undertaken. Failure to isolate these two lines may be the result of human error (isolating valve left open). Personal training and appropriate procedures are important measures to minimize likelihood of these events.

Possibility of common cause failures should be evaluated with respect to identical redundant elements (check valves/relief valves φ 250 mm and shelves). These elements may be vulnerable to CCFs due to identical operational conditions and location (possible coupling factors - vibrations, temperatures, humidity, etc.). Probability of such events shall be reduced by e.g. appropriate testing.

As already mentioned, effect of various failures are different. Failures (1) and (2) result in the increase of maximum pressure peak during DBA conditions. They should be taken into account in the assessment of containment pressurization and strength analysis, but the impact is expected to be relatively small.

Failure (3) results in the possibility of losing shelf water inventory under small LOCA conditions. Should the small LOCA develop later on and become a large LOCA, the full efficiency of the condenser will be lost when it is needed. The valves φ 250 mm are redundant, therefore single failure is probably not a serious concern.

Failures (4) and (5) affect time to reach underpressure in the system (quantitative analyses should be performed for long-term period; the existing results are not sufficient to assess the consequences).

Recommendations

The failures listed above should be taken into account in the evaluation of bubbler condenser containment behaviour. Both the initial analyses performed by the authors of the
bubbler condenser containment design [3.13] and the later analyses [3.9] show that the bubbler condenser containment can be expected to fulfill its functions with this assumption of single failure criterion.

3.3 MAXIMUM PRESSURE DIFFERENCE ACROSS WATER TRAYS DURING INITIAL PERIOD FOLLOWING LB LOCA

Scope of the review

The determination of the maximum pressure difference on this internal structures inside the bubbler condenser containment including the walls of the bubbler condenser shelves is an important task, deciding about the maximum loads which must be taken as the basis of mechanical strength calculations. The scope of the review includes analysis of aerodynamic processes in the containment after LB LOCA, pressure wave propagation in the reactor compartments, connecting corridors and the bubbler condenser tower, the rate of pressure increase in various points of the bubbler condenser structure, the delay in water lock opening and the resulting pressure differences on the walls.

Documents reviewed: [3.1, 3.2, 3.4, 3.8, 3.11, 3.13].

Summary of discussions

Value of the pressure difference is of prime importance for assessment of integrity of the bubble condenser structure in case of LB LOCA. Maximum pressure difference of 30 kPa has been taken as the design value for water trays. There are several indications, both theoretical and experimental, that the above mentioned value represents a reasonable estimation, although some weak points were identified in all available sources of information.

The process is governed on one hand by the pressure wave (not shock wave) propagation and transport time from the break to water trays, on the other hand by energy transfer, which is determining the pressure increase rate at the front of the wave. For realistic estimation these two processes shall be modelled sufficiently in detail.

According to different sources of information, both experimental and calculational, transport time from the break to the trays may vary from 0.1 to 0.3 seconds and then the pressure increase rate may be within a range of 30 - 100 kPa/s. Increase of the pressure difference across trays is terminated, when water seal in the tray is open. Opening of the seal itself may take about 0.25 - 0.4 s and corresponding maximum pressure difference may be in the range of 12/30 kPa.

The values of 25-30 kPa are predicted in German calculations by means of DRASYS code and in Slovak calculations by TRACO V code. (In case of TRACO V, 25 kPa are predicted by fine nodalization with considerations of flow inertia, while with rough nodalization only 12 kPa overpressure was predicted.)

The aerodynamic behaviour of the system was investigated through experiments performed in small scale facilities. The scaling up of the results to real plants remains
questionable mainly because of the transient character of the flow and of large scaling factor. Therefore, the use of validated computer codes with appropriate nodalization can provide a reliable answer to the problem.

Nevertheless, in order to achieve significant progress in the area it will be necessary to perform additional experiments in large scale facilities, with good similarity of geometric and time dependant characteristics to the natural NPP bubbler condenser containment system.

Recommendations

The maximum pressure difference acting on bubbler condenser walls should be taken equal to 30 kPa and for this value the mechanical strength analysis should be performed.

Experiments in large scale facilities can help in establishing what are the safety margins involved in the above recommended approach.

3.4 EFFECTIVENESS OF CONDENSATION IN WATER TRAYS DURING BLOW DOWN

Scope of the review

The geometry of bubbler condenser water trays is significantly different from the other systems in which steam condensation occurs, such as BWR water pools. In particular, shallow depth of the water layer and gap-cap arrangement with narrow space for steam flow at the bottom are the peculiar features of the considered system. Therefore the review should cover full range of possible steam flow and condensation parameters and provide answer to the question of completeness of steam condensation under the conditions which may be expected after LB LOCA or other accidents considered possible in WWER 440/213 reactors.

Documents reviewed: [3.1, 3.4, 3.6, 3.13, 3.14].

Summary of discussions

High effectiveness (about 100%) of steam condensation during blowdown was confirmed by all available experiments:

- Russian tests performed by VTI Institute in the seventies and eighties
- Hungarian condensation effectiveness tests performed by VEIKI Institute in 1978
- early experiments performed at the Warsaw Technical University
- Czech experiments performed by SVUSS Institute in 1992.

Some of the experiments predicted that effectiveness of condensation is significantly
reduced at water temperature approaching saturation (i.e. temperature higher than 90°C). In this case the effectiveness depends on the steam flow rate; some steam penetration can be expected only for high steam flows. The above discussed concern has, however, nearly no practical impact due to the fact that water temperature in trays never exceeded ~ 70°C neither in experiments nor in calculations.

It may be concluded that the effectiveness of steam condensation in water trays is sufficiently addressed in the available results and no additional separate effect tests are required concerning this specific issue.

Recommendations

It should be admitted that the actual bubbler condenser geometry is properly chosen and assures full condensation of steam in water trays under all accident conditions.

3. 5 THERMAL AND MECHANICAL LOADINGS OF BUBBLE CONDENSER AND THEIR UNIFORMITY

Scope of the review:

As the bubbler condenser structure is very complex, consisting of 12 floors and many water trays in every floor, the question of distribution of steam flow among the trays and the corresponding thermal and mechanical loads should be addressed. The review should cover the experiments with vertical and horizontal models of the bubbler condenser arrangement performed originally in the design phase and the later experiments and analyses addressing the issue of thermal and mechanical loadings and their uniformity.


Summary of discussions

Two different kinds of loadings are distinguished, i.e. thermal and mechanical loading.

All experiments as well as calculations performed till now were predominantly oriented to the examination of uniformity of thermal loading. Several factors may contribute to non-uniform loading, e.g. different hydraulic resistances in relatively narrow flow channels or changing compositions of steam-air mixture along the bubble tower height. Non-uniform loading of different water trays is partly eliminated by damping effect of the air traps.

On the basis of experiments performed on aerodynamic model (scale 1:40) in Russian Federation it was concluded that non-uniformity in horizontal direction (in water tray) is not substantial and the peak non-uniformity of flow in different floors was ~ 1.5. In the enlarged experimental facility with 3 floors of water trays water heat up in different floors varied under conditions corresponding to LB LOCA from 11 to 30 K. In the calculations performed by TRACO V code water heat-up in different floors was in the range of 12.6 -
21.6 K and the mixture flow rate to the lowest floor was 2 times higher than to the highest floor. In calculations performed in VTI, maximum difference in temperature increase for different floors was 15 K with its reduction after the end of blowdown. For initial water temperatures in trays equal to 35 - 40°C, the maximum temperatures never exceeded 70°C. Owing to a sufficient margin to saturation temperature, the above mentioned non-uniform thermal loading does not lead to any substantial changes in pressure behaviour.

Future experiments need to be oriented to the mechanical loads in different modes of operation (high flow, low flow). Two aspects must be studied in more details:

- Oscillations evoked by the steam condensation.
- Eigenfrequencies of the bubbler condenser structure.

The large scale experiments should correspond to a maximum extent to the real conditions, including all bindings of bubbler condenser structure.

Recommendations

In view of the importance of checking the uniformity of the flows in the bubbler condenser structure for establishing mechanical loads it is recommended to support the experimental work aimed at large scale testing of thermal and mechanical loads of bubbler condenser structure.

3.6 POTENTIAL FOR CONDENSATION OSCILLATIONS AND CHUGGING

Scope of the review

As steam condensation in water can lead to pressure oscillations and chugging, which present potential hazards to the integrity of mechanical structure of the bubbler condenser, the range of occurrence of both these processes and their parameters should be reviewed taking into account the actual flow conditions in WWER 440/213 bubbler condenser water trays.

Documents reviewed [3.1, 3.3, 3.4, 3.5, 3.6, 3.11, 3.13, 3.14, 3.15, 3.17].

Summary of discussions

Both processes are of concern due to their possible impact leading to additional loads on the bubble condenser structure. The nature of both processes is different.

Condensation of steam bubbles in water trays, even if pressure pulses are expected to be small, may evoke constant-frequency oscillations, which may represent a potential risk in case of resonance with the eigen frequency of the bubble condenser structure. The results obtained till now are not applicable due to considerable differences in size, geometry, material and technology of construction applied in the experimental facilities. Chugging involves a potential risk of the high peak loads; thermal stresses due to rapid cold water contact with steel structure may be an issue. Chugging may also lead to a rapid
depressurization of the inlet channel and a rapid suction of water out of the tray. Chugging has been identified as risky effect in Siemens experiments with open ended pipes, but that geometry was completely different from bubble condenser trays. Observations from relevant experiments are ambiguous. While no chugging was observed in Russian experiments, there were some changes of water level in experiments performed in Czech Republic, which are difficult to explain.

Chugging is typical for low flow rates of pure steam in cold water. For LB LOCA, chugging may occur only at the end of blowdown, when the efficiency of condensation as well as the integrity of construction is less crucial. High water temperature will also partly prevent chugging. The effect may be more important for small leaks, even if it was commonly agreed that due to dimensional factors of the bubble condenser system the conditions are less conducive for chugging than in other designs.

The effects discussed above can not be reliably predicted by available computer codes and large scale experimental verification is necessary.

For an appropriate simulation of the dynamic fluid-structure interaction (FSI) of the bubbler condenser, particular attention has to be paid to dimensions, material, manufacturing and connections between the elements.

**Recommendations**

Large scale experimental investigations of steam-air mixtures flow across bubbler condenser water trays in natural geometry, including natural dimensions, materials, manufacturing and connections of the elements are recommended to finally determine possible fluid structure interactions and obtain either an experimental proof of the design correctness or indications what changes are necessary. Since this part of experimental support is practically the only one missing and the outcome is of primary importance for long term safe operation and acceptance of WWER 440/213 units, the efforts towards realization of such experiments should be supported.

### 3.7 EXPULSION OF WATER FROM TRAYS

**Scope of the review**

As a mechanism of reverse flow of water in the gaps can lead to passive spraying of the inside of bubbler condenser tower shaft - which is a positive feature of the design - and to the loss water on the shelves - which can have negative effects - the review should cover the mechanisms of water expulsion and the measures foreseen for its limitation.

**Documents reviewed:** [3.1, 3.3, 3.4, 3.6, 3.11, 3.13, 3.14].

**Summary of discussions**

In principle, there are two different mechanisms of reverse flow for water expulsion from trays to condenser tower in the case of sufficient pressure decrease in the tower:
1. Syphon flow, which may occur if entrance gaps (channels) are filled by water; this effect is possible for rapid increase of a negative pressure difference then all water may be sucked out of the water tray.

2. Spill-over flow, caused by smaller pressure difference across the water tray. The mechanisms differ from each other by the amount of water expelled from the trays and by speed of this process. The syphon effect will lead to complete loss of water from trays, while in spill-over flow the water expulsion will usually be terminated by the opening of check-valves of 250 mm dia situated above the water level.

For the time being, the models for water expulsion are different in different codes. For example, BURST-LT code developed in Hungary uses syphon flow model, while CONTAIN 1.12 and TRACO V codes both rely on spill-over flow.

None of these mechanisms may be explicitly excluded before large scale experiments on integral facilities are performed.

Due to the fact that both those mechanisms may have negative safety impacts (i.e. lead to a total loss of water, which may be needed in the later stage of the accident or to too low flow rates and too short duration of passive spraying), it is reasonable to consider both of them in safety analyses. It is obvious that these considerations are relevant only for long-term part of accidents.

Recommendations

The mechanism of water expulsion from the water trays and the effectiveness of its limitation by opening the check-valves of 250 mm diameter should be checked in a full scale experimental facility mentioned in previous points.

3.8. EFFICIENCY OF ACTIVE AND PASSIVE SPRAYING

Scope of the review

Since the bubbler condenser containment design includes systems providing both passive and active spraying of the atmosphere inside the containment the efficiency of active and passive spraying should be evaluated.

Documents reviewed: [3.1, 3.3, 3.4, 3.6, 3.9, 3.11, 3.13, 3.14].

Summary of discussions

It should be stated that the efficiency of spraying has no impact on maximum pressure reached under LB LOCA conditions, but it may considerably influence long-term part of the accident, leading to the different radiological consequences or to the different course of the beyond DBAs.

For active spraying it was confirmed both theoretically (Russian Federation, Slovakia)
and experimentally (Russia and State Machinery Institute in Bechovice, Czech Republic) that the temperature of water droplet fallings from a spray nozzle will be equalized with that of the post-accident atmosphere within a distance of a few meters and thus efficiency of active spraying can be expected to be nearly 100%. A precondition for this statement is sufficiently homogenous droplet distribution and appropriate diameter of water droplets (less than 1 $\div 1.5$ mm), which shall be proven by testing.

Effect of passive spraying is generally very high due to the fact that its mass flow rate may be 10-15 times higher than the flow rate given by 1 spray pump, even if the duration of the spraying is limited to some 3-4 minutes. There is no direct experimental evidence on the realistic heat-up of passive spray water in post accident atmosphere. The calculations performed in Slovakia by SPRAY C.C. Code show that the efficiency of passive spraying varies considerably for different floors, from 18% for the first floor to $\sim 85\%$ for the highest floor. The average efficiency of spraying from all floors is in the range of $45 \pm 65\%$. The calculations, however, considerably underestimated the duration of thermal contact between droplets and the atmosphere and may be therefore considered to be very conservative.

Actually, all available indirect experiments (i.e. observation of pressure decrease) show that the efficiency of passive spray is very high and it leads to a very rapid and deep pressure decrease.

The overall effect of passive spraying depends also on the amount of water expelled from water trays and on the speed of its expulsion. This problem is discussed separately.

For an illustration of the effect we can use the available Russian data. According to a conservative calculation the pressure was reduced during passive spraying from 0.2 to 0.14 kPa. According to some experiments the reduction of pressure was from 0.17 to 0.1 kPa.

According to calculations performed in Slovakia with TRACO V Code, pressure reduction was about $\sim 63$ kPa for the case with more than 90% of water expelled from trays and, about $\sim 35$ kPa, for a more realistic case of less than 40% of water expelled from trays.

Very high efficiency of passive spraying is evident from all available experiments and there is no need for a direct detailed examination of the process. Large scale integral experiments, would confirm previous results and provide the data on the influence of the fall height. Passive spraying is an important part for the whole concept of the bubbler condenser containment and should be tested as a part of the entire process following LB LOCA.

Recommendations

As all available experiments confirm very high efficiency of spraying, it may be assumed that the presently taken assumptions as to its efficiency are acceptable. Nevertheless, the large scale experiments should be utilized to check the previous results and provide more exact data on complex full scale process characteristics, including the influence of steam condensation in the bubbler condenser tower shaft on steam flow into the shaft from the other compartments and the overall response of the integral system to load spraying.
Active spraying is well studied and further experiments are not considered necessary.

3.9 HEAT EXCHANGE BETWEEN ATMOSPHERE AND CONTAINMENT STRUCTURES

Scope of the review

Heat exchange of steam-air mixture with containment inner lining and internal structure during blow-down and in the later stages of the accident.

Documents reviewed: [3.4, 3.8, 3.13, 3.20].

Summary of discussions

Heat exchange with structures may influence the maximum system pressure by about 10 kPa, and it is also essential to provoke passive spraying which considerably influences the course of the accident in the long-term period. Of course, the modelling of heat exchange in complex geometry and flow conditions is a complicated task.

Heat exchange issue is not a specific one for the bubbler condenser design and all available correlations are applicable if used within the range of their validity. Utilization of Tagami and Uchida correlations may be recommended for practical purposes having in mind that these correlations have been derived from measurements in a single volume containment, if other appropriate, experimentally verified correlations are not available.

Hence, no additional separate effect tests are needed to improve heat exchange modelling in bubbler condensers.

Recommendations

The correlations of Tagami and Uchita can be used in calculations of maximum overpressure in the bubbler condenser containment.

3.10. RELIABILITY OF CHECK VALVES 500 mm INTO THE AIR TRAPS

Scope of the review

The reliability of check valves 500 mm leading from the gas space above water trays into the air traps under various conditions of flow composition and speed possible after accident.

Documents reviewed [3.1, 3.4, 3.6, 3.9, 3.11, 3.13, 3.14, 3.18].

Summary of discussions

Testing of check valves of slightly different dimensions (diameter 400 mm) was
performed in Russian VTI Institute under realistic conditions (i.e. rapid steam-air mixture dynamic outflow) in 1970s and 1980s. The hydraulic resistance of the valve was also measured during these tests. A damping element acting during valve's opening can be considered as the critical element of the construction.

The 500 mm valves implemented in the plants were only partially tested with air at steady-state conditions, but the data collected for the 400 mm valve tests are applicable also to the new ones.

Check valves play a determining role to control the maximum pressure in the containment and sufficient flow through these valves must be assured. The fulfillment of this condition may be doubtful if flow velocity approaches sound velocity. Such situations may practically occur at higher water contents in the flowing mixture, which leads to the considerable reduction of sound velocity to about 100 m/s. Therefore, water carry-over from trays to air locks should be avoided, what may be assured either by vertical distance from water level to check valves or by special protective devices. Effectiveness of such measures should be tested by large scale experiments.

**Recommendations**

The reliability of 500 mm check valves should be checked in large scale experiments taking into account the possible hazards of water carry-over from the trays.

### 3.11. HYDROGEN ISSUE FOR BUBBLER CONDENSER UNDER DBA CONDITIONS

**Scope of the review**

The bubbler condenser containment of WWER 440/213 is provided with a hydrogen recombination system situated outside the containment in off-gas cleaning recirculation system. The sufficiency of this system for DBA conditions should be reviewed.

**Documents reviewed** [3.4, 3.6, 3.9, 3.10, 3.11, 3.14, 3.15, 3.16].

**Summary of discussions**

For DBA conditions following LOCA, the main sources of hydrogen are radiolysis of water and chemical reactions between steam and various materials. In any case, hydrogen release is a long-term process with duration of several weeks until the average concentration reaches the flammability limits (~4 % of H₂).

The sources of hydrogen are located in the primary system compartments and the highest concentrations can be expected in these compartments. Transport of hydrogen through water trays may be expected only in very limited amount (under DBA conditions) due to the fact, that pressure in air traps is higher than in SG compartments and pressure differences across the water trays are eliminated early after the blowdown period.

To prevent non-acceptable consequences of hydrogen accumulation in primary circuit
compartments, mixing of internal atmosphere in geometrically complicated building and removal of hydrogen should be assured. Several means exist to remove hydrogen from the containment atmosphere among which catalytic recombiners represent an important advantage.

Recommendations

The system of hydrogen recombination is sufficient for DBA conditions. Further work is recommended to provide the bubbler-condenser containments with hydrogen control systems preventing hydrogen deflagration hazards for BDBA sequences.

3.12. APPLICABILITY OF THE AVAILABLE DATA FROM MODEL EXPERIMENTS TO THE REAL BUBBLE CONDENSER

Scope of the review

In many discussions held up to now on the subject of WWER 440/213 reactors safety the question of experimental support for the bubbler condenser containment has been repeatedly raised. In particular, the problem of the lack of full scale tests has been stressed. The review should cover the whole experimental work performed up to now for this containment concept and determine the adequacy of the available results to the needs of safety analyses needed in the light of current international practice.

Documents reviewed [3.1, 3.2, 3.3, 3.4, 3.6, 3.11, 3.13, 3.14, 3.17, 3.18, 3.19]

Summary of discussions

The following aims of testing were considered and compared to the published results:

1. condensation effectiveness  
2. code verification  
3. overall pressures and pressure differences  
4. dynamic pressure oscillations  
5. non-uniformity of steam flow and thermal loads

3.12.1 Condensation effectiveness

This item was covered by the Russian work. The test results demonstrated complete and effective steam condensation up to water temperatures of 75°C. There is sufficient evidence that also at higher water temperatures the condensation is effective and complete.

3.12.2 Code Verification

The Hungarian and the Czech test programmes were aimed to confirm and verify computer codes. No direct measurement of the steam flow to the lower plenum was made. In spite of the fact that the inner walls of the test facilities were coated and thus thermally
insulated, considerable condensation of steam on the cold walls probably took place and made an interpretation of experimental data very complicated.

The effects of area/volume ratio being much higher than in the reality and the steam condensation on the cold walls made code verification questionable.

### 3.12.3 Overall pressures

The Russian "enlarged model" tested a non-typical geometry of gap/cap units. Due to this non-typicality an application of the as-measured data to the real bubble condenser system is questionable.

The Russian "reduced model" tested a nearly prototype gap/cap unit in the geometry closely resembling the one actually used in NPPs. The published data show only the pressure in the upper plenum, no pressure differences.

Both the Hungarian VEIKI test set up and Czech SVUSS test set up suffer from the uncertainty of the real steam flow rate to the lower plenum. Therefore the application of these measured pressures and pressure differences to the real bubble condenser system is questionable.

### 3.12.4 Dynamic pressure oscillations

None of the test facilities with gap/cap units was instrumented to measure dynamic pressure loads on the wall of the water trays or at the gap/cap unit. There is a complete lack of data concerning this item.

### 3.12.5 Non-uniformity of steam flow and thermal loads

Russian model tests indicated a maximum non-uniformity of flow ranging from -30% to +50% of the average flow rate. The non-uniformities generated differences in the water heat-up of a 3 floor bubble condenser model, which amounted up to about 15K. The non-uniform heat-up does not seem to be an issue when compared to the condensation capacity of the water trays.

### 3.12.6 Recommendations

The data on condensation effectiveness obtained in experimental models can be applied to the real bubble condenser system; the data allow the statement that the steam condensation in the bubble condenser is complete and effective.

The application of the as-measured pressures and pressure differences to the real bubble condenser system is questionable due to several effects discussed above.

No data are available for dynamic pressure oscillations and dynamic pressure loads on the water trays and gap/cap units.

Additional testing at larger and better instrumented test setups seems necessary to
answer the remaining questions. Interaction fluid-construction in real dimensions and using real fabrication technology will be of prime importance. Testing could be divided into separate effects and larger scale test facilities.

1. Separate effects test can be performed in a test set up with at least one, better with two parallel gap/cap units of original size.

   The instrumentation must allow to measure:

   - wall dynamic pressure loads
   - steam flow to the lower plenum as to the simulated hermetic compartments
   - water carry over to the air trap
   - water level in bubbler trays

   and to observe visually the water level.

   Non blowdown tests with controlled steam supply are desirable.

2. It is desirable to built a test setup in a larger scale with at least one complete floor with 17 trays per floor and 9 gap-cap systems per tray, which would also allow for load and stress measurements on endangered structures.

3. The non-uniformity tests performed so far allow an estimation of local steam overloads. Overloads of 150 -- 200% should cover all uncertainties. These tests could be performed in the test setups referred to in points 1 and 2 and the data of the Russian "aerodynamical facility" tests should be made available in order to assess the necessity of a multi-floor test setup. A multi-floor test facility would also allow verification tests of the sprinkler system. A large multi-flow test facility would be an excellent tool for code verification.

3.13 COMPUTER CODES FOR PRESSURE-TEMPERATURE TRANSIENTS AND REQUIREMENTS FOR THEIR UTILIZATION

Scope of the review

The analyses of pressure-temperature transients within the containments with bubbler condenser have been performed with various codes, based on partial experimental evidence and only partially accounting for the features specific for bubbler condenser operation. The review should permit to determine the adequacy of these codes and indicate areas where further improvement is needed.

Documents reviewed [3.4, 3.6, 3.9, 3.11, 3.14, 3.15].

Summary of discussions

It was generally agreed that available computer code such as DRASYS, CONTAIN, RALOC and TRACO V are sufficiently suited for analysis of DBAs, with some exceptions related to bubble condenser itself, which needs additional verification by means of large scale
experiments. Successful development of 3-D codes for VVER 440 containment is not expected within reasonable time.

As far as pressure distribution within hermetic compartments is of concern, codes were successfully validated on relevant experimental data. Especially in the case of RALOC code, 30 experiments performed at Batelle Institute and 18 HDR experiments, both of them large scale experiments corresponding to subdivided containments, have been used. The experiments performed till now have sufficiently covered various cases of geometry as well as flow rates and no other particular tests on steam air mixture flows are needed.

Analysis of experiments makes it possible to improve the prediction of the overall pressure build-up and pressure differences across internal walls. Available codes can also sufficiently well predict steam-air-water mixture velocities in complicated geometries.

Uncertainties in prediction of pressures and pressure differences are caused mainly by the following factors:

- nodalization
- flow resistances (flow contraction coefficients)
- heat exchange with structures
- water carry-over

As a general rule for nodalization, one node should correspond to one compartment. More detailed nodalization is needed only for special purposes. In such case, it should be, however, taken into account that some correlations (e.g. for heat transfer) are not applicable for analysis of local effects.

For flow resistances, it may be recommended to use usual coefficients, taken from engineering handbooks for similar opening and channels. Flow velocities close to the speed of sound are not considered to occur in usual reactor containments.

Water carry over under complicated conditions can not be predicted realistically and it is not worthwhile to develop too sophisticated description of this process. For conservative predictions, bounding calculations using e.g. carry over coefficient should be used. For conservative calculation of pressure differences, homogenous mixture in compartments should be considered.

Heat exchange with structures is discussed in other Section of this report.

According to German regulatory rules, 15% uncertainty margin is adopted to cover all above mentioned effects. There is no similar rule in USA, nor for WWER units.

Recommendations

The models of bubbler condenser operation should be introduced into Western codes such DRASYS, which have been validated in large scale experiments. Special care should be paid to the development of models to predict hydrogen distribution among the containment compartments.
ANNEX 3(a)

Answers of Prof. Bukrinski to the questions referring to "The experimental and calculational investigations of processes in bubbler-condenser containment systems of NPPs with WWER-440 reactors after LOCA", prepared by VTI (before 1979) and published by Sojuz-glav-zagran-atom-energo, USSR.

3(a).1. Modelling the initial pressure distribution in bubbler condenser structure

In the experiments performed in the" enlarged model of the bubbler condenser" the transient was initiated by breaking a membrane, after which the steam would start flowing into the upper plenum of the bubbler condenser model.

- What were the parameters of steam arriving to the lower plenum?

The parameters of the steam getting into the model of the bubbler condenser correspond to the parameters of steam generated in the steam generator given in the report.

In the steam generator the steam is generated due to the flashing of high temperature water under the influence of sudden pressure drop. The steam going out of the steam generator is a saturated steam according to its actual pressure. The changes and values of the pressure are given in each drawing separately. At getting into the lower chamber of the model, where the pressure is lower than in the steam generator, the steam is throttled and becomes overheated at the pressure which exists in the lower chamber. However, its enthalpy remains the same.

- Can they be considered as modelling the parameters of steam-air mixture entering the water shelves in the real bubbler condenser?

Since the volumes of the model correspond to the volumes of the real plant, in the first approximations, taking into account the lack of full geometric similarity, the parameters of the air-steam mixture in the model on the average correspond to those expected in the real plant.

- The ratio of the delivery pipe cross section area to the lower plenum volume is several times smaller than the ratio of the inlet corridor cross section area to bubbler condenser tower shaft volume in the real WWER NPP. How does it influence the modelling of the pressure increase in the initial period after LB LOCA, i.e. within time interval below 0.3 seconds?

This has no influence, since we study only the processes in the bubbler condenser.

- How soon will the water lock open after LB LOCA? A hydraulic study indicated the delay of 0.3 second. Is it close to the Russian evaluation?

In the series of experiments on the fragmentary model the experiments no. 36-43
included direct studies of water lock opening. In relationship to the conditions of the
experiments, the delays in opening of the water lock were from 0.267 to 0.55 s. These
experiments have confirmed the correctness of the calculation methods used for the
process of opening of water lock.

- According to the Polish experimental study the maximum pressure difference between
the vertical shaft of bubbler condenser tower and the outlet volume above the water
level is about 35 kPa. According to GRS calculations with DRASYS a differential
pressure of 30 kPa can be expected. Similar number is given in Ukrainian evaluation, as
taken from Russian documentation. However, in the calculations presented at the time
of safety discussions for Zarnowiec NPP, the Russian experts maintained that the
pressure difference will be much less (18 kPa). What is the present position of the
Russian design organization?

In the design documentation of the bubbler condenser the calculational pressure
drop for strength analyses was assumed to be 30 kPa. Although the calculations of
transient processes showed that the changes of pressures in the containment after DBA
with 500 mm break the values of this pressure drop were significantly lower. Today there
are no reasons to change the value of pressure drop assumed in the strength analyses.

The value 35 kPa obtained in the Polish experiments studying the pressure drop
can not be confirmed since as was shown during the meeting the transfer of the results
of experiments to the natural values was not correct. In order to ensure the similarity
of pressure propagation in the compartments in the model and in the nature it is
necessary to conduct the experiments in the model at real velocities of movement of gas
and pressure. At this, the time scale in the model will be assumed equal to the linear
scale of the model. Taking this into account it may be stated, that the experiments made
on that model were performed with too low flow rate of the air provided into the model.
The rate of pressure increase at the entrance to the bubbler condenser after
recalculation on a real structure taking the approach shown above will be about 13
kPa/s. instead of 70 kPa/s in the real plant.

- In view of the differences in the geometry between the real plant and the "enlarged
model of the bubbler condenser"is it possible to use the results of the experiments to
show that there will be no shock wave in the real plant?

The shock waves were not studied in these models. Their absence in the tower
of the bubbler condenser is confirmed by calculations.

- Have there been any measurements of steam-air mixture velocity in the inlet corridor
and in the bubbler condenser tower shaft?

The velocity of movement of air-steam mixture was not measured.

3(a).2. Steam-air mixture flow across water shelves

- How does the pressure drop change in function of the steam flow across the water tray?
In an experimental work it was established, that this pressure drop decreases with flow
increase. If it is so, what are the mechanisms assuring approximately uniform steam flow to all bubbler condenser trays?

The mechanism of self-equilibration of thermal loads in various trays is connected with the reduction of pressure drop on those trays which have higher loads due to pushing of larger volumes of air into upper chambers and higher partial pressure of steam above the water mirror. This leads to the decrease of the air-steam mixture flow into those trays, while the flow rate through those trays which have been less loaded remains the same.

- With large pressure differences characteristic for the initial time interval there may be a strong water carry-over with air-steam mixture. In one of the experimental investigations it was shown that water is thrown up for a few meters. The Russian study says that "only insignificant water droplet content was blowing out of the orifice with water". Can this statement be supported with some experimental evidence?

The height of the space above the water level has been chosen according to the results of special studies of the process of water level swelling during bubbling process. The result of these studies have been published. The copies of the publications have been distributed during the meeting.

- In Fig. 2.2.2 of the Russian study the experimental results are compared with the pressure in the upper plenum "calculated with the assumption of an equilibrium process". Can you explain how such a calculation was done?

The equilibrium process is understood as one in which the partial pressure of steam in the upper chamber corresponds to the temperature of the upper water layer. The real process is not equilibrated.

- The similarity of pressures above water trays containing different quantities of water is taken as the proof that the condensation of steam is complete. However, the depth of water lock is small compared to other reactor containments with water pools. What was the accuracy of measurements of pressures above the water tray? Was it enough to prove 100% condensation? If not, e.g. a fraction of steam still goes through, how much can it be?

The accuracy of pressure measurements in the upper level is about 2%, which corresponds to the accuracy of + - 3 kPa. The completeness of condensation is proven by the independence of the pressure in the upper chamber from the quantity of water in the water tray and from the steam load of the tray.

Besides, special studies of the completeness of condensation, which were published and the information of which was distributed during the meeting, have made it possible to formulate a dimensionless relationship determining the conditions of losing full condensation.

These conditions are not reached in the conditions of operation of the bubbler condenser of WWER 440/213 units.
3(a).3. Decontamination factor in water

- What is the efficiency of stopping aerosols and iodine species in the water? Are any experimental results of measurements available? Are there any differences among the results for various aerosols? What is the influence of the air to steam ratio in the mixture?

The effectiveness of the decontamination of the air-steam-gas mixture in the water of the bubbler condenser from the radioactive substances has been assumed in the design on the basis of calculations, assuming that during the time of flow up of the bubble in the water layer, we obtain an equilibrium state of the radioactive species concentration in water and in the air contained in the bubble. This assumption has been based on the data given in the published world literature. No special studies of these processes were made in Russia.

3(a).4. Mechanical failures possible in the containment with bubbler condenser

- Are there any pressure oscillations connected with the condensation of steam bubbles in the water? Can they lead to stresses in the bubbler condenser structure, as indicated to be possible in GRS study? Is mechanical failure of bubbler condenser shelves possible due to those oscillations?

The studies conducted in Russia concerning the design of the bubbler condenser of WWER 440 213 have not shown any low frequency oscillations or pressure pulsation which could be dangerous to the bubbler condenser. Therefore no special studies of pulsating regimes were made for this structure.

- Why (according to the Russian study) is the opening time of the check valve D = 500 mm at the pressure increase rate of 0.7 kg/cm² s limited to 0.3 seconds? What would happen if it was longer?

The time of opening equal to 0.3 s is the calculation time adopted in the design of the valve of 500 mm diameter. The design of the valve provides the fulfillment of this requirement. However, as the calculations have shown, even full failure of the valve to open does not lead to pressure increases higher than admissible ones, due to the redistribution of the flow among the trays.

- In the tests performed in the Russian study the expulsion of the water seal was due to stopping the steam flow coming from a separate steam generator volume. Are there any evaluations as to when the pressure in reactor compartments would fall below that above the water shelves in the real plant? What models of heat conduction and steam condensation were used in such an evaluation?

In the program of calculations WSPLESK, which has been used in the designing process of the bubbler condenser of WWER 440/213, the condensation of steam on the walls of the water trays has been taken into account. The results of the calculations made with this program have been compared to the results of the experiments on the fragmentary and enlarged models. The coefficient of heat transfer in calculations of
steam condensation on the walls and of air-steam mixture was taken equal to 1000 - 1300W/m²K.

This provided good agreement between the results of the experiments and those of the calculations.

- In "Safety Assessment of Unit 5 of the Greifswald NPP" the authors state that even the failure of a small number of "hoods" (which probably means troughs over the weirs through which steam-air mixture enters the water trays) per pool during the blowdown will cause the design pressure to be exceeded. Polish evaluation leads to different conclusions, showing high safety margins in thermal hydraulic design of the bubbler condenser tower. What are the results of Russian calculations on this subject?

In the report there the results of the study of accident with full absence of water at one of the trays. This is the same as in the presence of water to break all caps. The results have shown that the increase of the pressure in the system remains within the admissible limits.

This is due to redistribution of the steam load among the other trays due to the self-regulating properties of the system which has been mentioned above.

- The GRS authors point out that increasing the size of the discharge area through the non-return valves into the air traps greatly reduces the peak pressure. Is it true in the light of Russian experiments?

This is true and already has been used to lower the pressure in one of the units in Kola NPP, where there were problems with the maximum pressure. The multiplication of the number of valves by 2 has provided a decrease of the maximum pressure to about 1.99 bar (absolute).

- Is it possible, that due to pool swelling and the fast pressure buildup the check valves of 250 mm dia situated in the water tray cover (between the outlet volume and the bubbler condenser tower vertical shaft) will get locked in the open position? What is the functional concept of interlocking mechanism of these valves?

The valve will close due to the pressure drop across the membrane which is designed as redundant. Nevertheless, the safety analysis includes the results of the calculation of this case with the valve failure. There have been no inadmissible effects of this failure.

- Are there any results of the periodical testing done in NPPs for the check valves 250 mm mentioned above?

The valves are periodically checked tested in the process of operation of the NPP and the results are reported to the regulatory authorities. There is no information about any problems with these valves.
- What is the minimum absolute pressure (or maximum negative pressure) at which the containment inner lining will remain in place?

0.8 bar - absolute pressure.
ANNEX 3(b)

Answers of Prof. Karwat to specific questions on thermal hydraulic behaviour of bubbler condenser containment

There are 6 detailed questions which are answered in sequence as follows:

3(b).1 What are the experimental bases for the determination of flow velocities?

Reflecting to the compartment structure of the hermetic part of the containment building several codes are available which have been validated on basis of a large number of relevant full pressure containment pressurization experiments. More than 30 experiments have been performed within the Battelle containment test facility in the seventies. Another 16 experiments have been performed within the large scale HDR containment test facility. Altogether, more than 46 relevant containment blowdown experiments performed in facilities volume-scaled 1:100 and 1:5 served as an experimental data base to validate relevant blowdown codes. Many of these experiments provided measured information about local flow velocities between interrelated compartments. In general, it has been shown that flow velocities are predictable within reasonable margins of uncertainties.

As far as the hermetic compartment system is concerned codes will provide sufficiently reliable local velocity predictions.

Velocity predictions within the bubbler condenser tower largely depend on the function of the bubble condenser and will be dependent on upstream conditions arriving from the hermetic compartment system.

3(b).2 What are the experimental results of measurements of pressure distributions in reactor compartments, bubble condenser tower, in the structures of the bubble condenser shelves?

The above mentioned experimental data base primarily served to validate codes with respect to pressure differences generated during blowdown. Particular attention was devoted to the pressure differences in the vicinity of the location of the rupture (compartment of rupture). Concerning pressure distributions in the vicinity of the compartment of rupture codes may be used in order to predict these parameters with well-known uncertainties. Existing uncertainties have been found as being influenced by the limited understanding of flow resistance coefficients of apertures between adjacent compartments and by the limited understanding of phase separation processes characteristic for two-phase flow jet disintegration inside the compartment of rupture. This experience is relevant and applicable to the conditions of the hermetic compartment system.

Pressure differences expected to occur inside the bubble condenser tower and in particular across structure of the bubble condenser shelves may be a priority subject of future bubble condenser research work. Existing knowledge about comparable processes expected to occur inside pressure suppression systems of Western boiling
water reactors cannot be transferred for estimating these parameters within the WWER bubble condenser tower. The difference in the design of the gap-cap systems and of the water trays and the overall arrangement of both inside the bubble condenser tower prohibit any extrapolation.

3(b).3 In view of the difference in the geometry between the real plant and the "enlarged model of bubble condenser" used in Russian experiments is it possible to use the results of the experiments to show that there will be no shock wave in the real plant?

Obviously, all bubble condenser related experiments performed in the former USSR have been oriented towards an understanding of the thermal efficiency of bubble condenser system. As far as integral experiments have been performed (blowdown into a simulator of the hermetic compartment system associated to a bubble condenser model) considerable uncertainties exist with respect to the determination of the applied blowdown rates and to the interpretation of the resulting pressurization waves.

However, due to the subcompartmented structure of the hermetic compartment system it is not expected that "shock waves" of meaningful magnitude will arrive at the bubble condenser structure even under BDBA conditions. Of main interest will be the magnitude of the pressurization transient arriving at the shelves and subsequently causing the clearing of the gap-cap system. This process should be one of the objectives of the large scale bubble condenser experiments presently under discussion.

3(b).4 Have there been any measurements of steam air mixture velocity in the inlet corridor and in the bubbler condenser tower shaft?

The safety relevance of this question is not at all clear. Of importance is the air/steam transport between the location of the rupture and the inlet into the bubble condenser system. Considerably different swell level processes inside the water trays at the moment of activation of the bubbler condenser system are expected in dependence of the air/steam ratio of the arriving mixture. Two bounding cases may be distinguished: the remote location of a rupture may result in a well-defined air/steam front which pushes most of the air content of the hermetic compartment system into the bubble condenser tower at the beginning of the accident. This may result in the most challenging swell level process with the potential of water droplet transfer via the check valves into the air trap. Later, this location of a rupture may also result in a considerable period of steam transfer with very low air content into the bubble condenser tower. The other extreme situation would be a rupture as close as possible to the condenser tower shaft. This situation would minimize the initial air transport into the bubble condenser tower and smoothing the air/steam ratio transient all over the blowdown period. For this case the transfer of air-free steam flow into the bubble condenser may be minimal.

A more or less correct prediction of the mixture velocity and its steam/air ratio when arriving at the bubble condenser tower should be expected from the application of validated codes like RALOC or CONTAIN if the chosen nodalization allows to properly simulate the location in space of the rupture (see also Sec. 1).
3(b).5 Are there any experiments (beyond those published in the Western literature) showing heat exchange with the containment walls, with internal structures and reactor systems?

The above mentioned integral containment experiments performed inside the Battelle and the HDR containments provided a large data base of measured heat transfer coefficients under relevant blowdown conditions. This data base was utilized within the frame of code validation activities. Experience has shown that locally measured heat transfer properties largely depend on local flow conditions. In contrast global heat transfer correlations like the Tagami - or the Ushida-correlation have been delivered on basis of an integral assessment of integral containment pressurization experiments. Such correlations can only be applied in an integral manner simulating the overall pressurization behaviour of an entire containment. This has to be taken into account by strongly simplified nodalization concepts. For a highly sophisticated nodalization concept the application of heat transfer correlations which are based on available local information (air content, local velocities, orientation of heat conducting structures) is recommended.

If a detailed knowledge of heat exchange with the structures of the bubble condenser is necessary existing or future experiments must be evaluated in this respect to provide relevant experience.

3(b).6 What should be the assumptions for calculational codes (number of compartments, homogeneity of air/steam mixtures, heat exchange with walls, steel liner concrete heating etc.)?

Depending on the technical parameters to be investigated the requirements for useful nodalization schemes applying containment codes may be different. Taking about the simulation of the hermetic compartment system with respect to the generation of local pressure differences during the blowdown process a minimum requirement is that each compartment involved into the distribution of released energy should at least be simulated by an individual computation node. Relevant information may be derived from a number of international standard problem activities as well as from numerous recalculations of individual experiments performed by various institutions. If the objective of the code application is the prediction of the global pressurization process of a containment the nodalization requirements may be somewhat different.

Concerning the homogeneity of the steam/air mixture a conservative approach may be to assume no phase separation to occur inside the compartment of rupture if the prediction of the local pressure difference to adjacent compartments is of interest. Here again, experience with former code application exercises to relevant experiments should be consulted (see 3(b).1 and 3(b).2).

Concerning heat exchange with walls including those which are protected by a steel liner no general recommendations can be given as long as the envisaged goal of code application is not specified.
Concerning the generation of pressure differences inside the bubble condenser tower it must be stated that hitherto an experimental evidence is not existing. Most experiments performed in the former USSR were essentially oriented towards an evaluation of the thermal efficiency. One of the main goals of forthcoming bubble condenser experiments is indeed the investigation into the local pressurization behaviour of the bubble condenser units and associated local pressure effects. For the time being no code is known which may have received adequate validation with respect to these phenomena. The same holds for the prediction of local pressure differences between the bubble condenser tower and the air trap, separated by the check valves. The check valve flow itself and the resulting local pressure difference may be influenced by water carry over from the trays into the air trap. If only pure air flow has to be handled the situation might be simple. Flow resistance coefficients of the applied circular check valves should be readily available from existing separate effects tests. Such experiments have been mentioned during the discussion in Vienna. Even if they were performed at somewhat different diameter it should be possible to extrapolate the specific resistance coefficients if the flow conditions were known.
4. PROBLEMS OF MECHANICAL STRENGTH OF BUBBLER CONDENSER STRUCTURE

4.1. SCOPE OF THE REVIEW

The thermal hydraulic properties of the bubbler condenser being generally well established, the effectiveness of the system could be proven under condition that the bubble condenser structure is strong enough to stand all possible loads under accident conditions.

Two main concerns have been expressed, namely

- the transient loads on bubbler condenser structure due to initial (pressure differences after LB LOCA are high. The calculations performed initially in Poland under an IAEA contract showed a number of weak points. If the bubbler condenser structure were to fail at the start of the accident, all later analyses of thermal hydraulic would have to be changed. Thus the problem of bubbler condenser strength is of high safety importance and required detailed peer review.

- the load due to possible oscillations in the system which could be possible due to steam bubbles condensation and/or chugging are not well known today due to the lack of full scale experiments. If these loads were excessively large or if there was a coincidence of frequencies of load changes and eigen-frequencies of the bubbler condenser structure, then the bubbler condenser elements could fail.

The review should cover the initial mechanical strength calculations of the bubbler condenser structures made in SverdNIKhimmarsh, the later analyses made in Poland by Polytechnic School of Warsaw and Military Academy of Technology under the IAEA contract and the mechanical strength analyses made by Ukrainian Energoprojekt Institute within the IAEA TC Project RER/9/004. The structural elements of insufficient strength should be identified and the feasibility of improvements established.

Documents reviewed [4.1, 4.2, 4.3, 4.4].

4.2 FINDINGS

Within the framework of the IAEA TC/RER/9/004 programme an analysis of mechanical strength of bubbler condenser structures was performed by Polish organizations specialized in mechanical strength problems [4.1] and subsequently evaluated by the Ukrainian Energoprojekt Institute [4.2] in charge of strength calculations of nuclear power plants of WWER type in Ukraine. Both sets of analyses including all pertinent calculations were sent to the Russian design institute SverdNNIKhimmarsh, which had initially designed the bubbler condenser structure and is still responsible for its design. Using the above mentioned materials and the initial analyses of SverdNNIKhimmarsh for Zarnowiec NPP in Poland [4.3] and for Rovno NPP [4.4] in Ukraine, after detailed discussion, the main doubts as to the assumptions, methods and results of calculations have been resolved.
4.2.1 The methods of calculations

Calculations of the bubbler condenser structure originally performed in the 80-ties were based on the USSR calculation methods of technological systems (Codes of calculations of strength for elements of reactors, steam generators, vessels and pipelines of nuclear power plants, experimental and research reactors and installations, Metalurgiya, Moskva, 1973), which since then have been replaced with newer regulations.

The verification of design made by Kiev Institute "Energoproekt" was based on building codes and regulations actually in force at Ukraine, namely "Design specifications. Steel constructions" (SNiP II-23-81) and "Codes of calculation of equipment and pipelines strength of Nuclear Power Plants" PiN AEG 7-002-86.

The sequence of calculations made for design verification was as follows:

- Verification of stresses according to building codes and regulations. The allowable stresses were chosen in the elastic deformation region and determined as indicated below.
- Calculation of mechanical strength of the structure taking into account possible plastic deformations of various elements according to the rules formulated in building codes.

If the above calculations showed that the structure strength is not sufficient, then further evaluation was performed according to the rules formulated in the code PiN AEG 7-002-86 assuming allowable deformations of the structure which do not lead to the loss of the function of the bubbler condenser.

In such a case it was taken into account that the Design Basis Accident will happen only once in the lifetime of many nuclear power plants. Therefore the structure of the bubbler condenser may lose its shape as long as it performs sufficiently to prevent the failure of the containment.

4.2.2 Initial data specified for the calculation of the elements

Under normal operating conditions the load carrying structures of the bubbler condenser have to stand the load of the water in bubbler condenser shelves with the layer depth of 50 cm and the dead load of the bubbler condenser structure itself.

During DBA, the pressure difference acting on the walls of the bubbler condenser shelves was assumed to be
- 0.30 bar in the calculations for Zarnowiec NPP,
- 0.30 bar in the calculations for Rovno NPP
- 0.35 bar in the calculations made in Poland
- 0.32 bar in control calculations made for Rovno NPP by Kiev Institute "Energoproekt".

The consultants meeting accepted the view of the Russian specialists, that there is no need to consider loads higher than 0.3 bar, as assumed in the original design of Rovno NPP.
Besides the load accompanying a LB LOCA, The Kiev Institute Energoproekt considered also the loads which may appear due to an earthquake. The intensity of the seismic event was assumed to be equal to 8 in MSK scale.

The loads during an earthquake would mostly act on beams, while the pressure loads after LB LOCA would in the first range act on large thin walls of the bubbler condenser shelves. Hence the calculation of walls and beams was repeated for both cases and the more limiting conditions of each case were chosen as the future design basis.

4.2.3 Limiting values of material strength taken in the calculations

The value of admissible stress \( R_{adm} \) was chosen differentially in the initial strength calculations [4.3] and in the later Polish and Ukrainian analyses [4.1, 4.2].

The initial admissible stress \( R_{adm} \) was defined in [4.3] as

\[
R_{adm} = \frac{\text{Yield Strength} \cdot \delta_{02}}{1.5} 
\]

where 1.5 - safety factor and 1.8 - coefficient of strength increase for momentary loads. In the case of stainless steel type 12 Cr 18 Ni 10T this gave

\[
R_{adm} = 2400 \cdot 1.8 / 1.5 = 2880 \text{ kg/cm}^2
\]

In the Polish study it was

\[
R_{adm} = \frac{K_m \cdot R_m}{2.48 \cdot \alpha_s} = \frac{K_m \cdot R_{02}}{\alpha_s}
\]

where \( K_m \) = coefficient of strength increase for momentary loads, \( K_m = 1.15 \)

\( R_m \) = immediate static strength or ultimate tensile strength

\( \alpha_s \) - reliability coefficient, for 12 C, 18N10T equal to 1.15.

\( R_{02} \) - yield strength or static yield point.

In Ukrainian study it was similarly

\[
R_{adm} = \frac{K_m \cdot R_{02}}{\alpha_s}
\]

and for 12 C, 18 Ni10T in both cases for DBA conditions was

\[
R_{adm} = 2100 \cdot 1.15/1.15 = 2100 \text{ KG/cm}^2
\]

Thus, the admissible stresses according to the actual regulations are significantly lower than they were at the time when the bubbler condenser design was originally prepared.
In Ukrainian study there was also the consideration of stresses in load carrying beams in the case of an earthquake. According to the building calculations code, the value of coefficient $K_m$ for Design Basis Earthquake is 1.4, so for the beams the value $R_{adm}$ is

$$R_{adm} = 1.4/1.15 \cdot 2100 = 2800 \text{ Kg/cm}^2.$$

4.2.4 **Assessment of the results of strength calculations**

The analysis of modes of operation, types of beam fastening, distribution of loads among membrane walls, wall strengthening ribs and load carrying beams, and finally the consequences of neglecting a part of ribs which are not necessary for the integrity of the bubbler condenser has shown that:

- The thin side walls of water trays, their bottom and cover plates and the walls of caps work as membranes and will not fail under DBA conditions provided the strengthening ribs and welded joints remain operable.

- The large size load carrying I beams are tied with tray bottom and cover plates on the upper and lower surface and thus are not subject to one-directional loads under DBA conditions. The pressure loads acting upwards on tray bottoms equalize each other. In this connection it will be necessary to verify that the lowest level of load carrying beams is well connected to the bottom of the bubbler condenser tower. The pressure loads acting on the side walls and thus on the side beams are significant but the lateral rigidity of the structure is high and does not fail.

Still, to provide better strength, the supports of the load carrying beams in the walls should be rigidly fixed to supports in the walls not only from one side (below) but from both sides (below and above the beam). This arrangement has been already introduced in Paks NPP.

- The vertical stiffening ribs on lateral walls of the water trays are rigidly kept by load carrying, beams and thus will not fail. There is no need to strengthen them.

- However, the vertical stiffening ribs on the front walls of the water trays are not fastened to any beams. They are connected with the thin front wall, working as a membrane. Their strength is insufficient. It is necessary to either:
  - increase the number of these ribs, approximately twice, or
  - to introduce additional horizontal beams across the front wall and tie them with tendons.

The increase of the number of ribs seems the easiest way of solving the difficulty.
- The welds joining horizontal stainless steel plates to the load carrying beams are not sufficient and would bend and break. The remedy is simple, the plates should be cut and welded not only to the edge, but also to the centre of the I beam.

- Stiffening ribs on cap walls are insufficient. The stresses under DBA conditions would be much higher than the admissible ones and the caps would significantly deform.

It is necessary to weld additional stiffening ribs.

Other elements in the bubbler condenser structure may remain without changes.

An evaluation of the feasibility of purposed improvements has shown that all above mentioned tasks are feasible, do not require any dismantling of the existing structure and can be fulfilled during normal planned NPP shutdown for yearly fuel loading and maintenance.

Upon execution of these tasks the structure of bubbler condenser will be able to stand load corresponding to the pressure difference on the tray walls equal to 30 kPa with a safety margin.

The Ukrainian analysis has also shown, that the load carrying beams in the bubbler condenser structure can stand an earthquake of 8 MSK intensity with a safety margin.

4.2.5 Possible periodical loads due to steam condensation

The results of the experiments conducted by Prof. Bukrinski [3.13] did not indicate any periodical loading oscillations. Generally, the operation of the bubbler condenser shelves under full flow conditions did not involve any noise, trembling of the walls or vibrations. Thus the problem of oscillating loads was not considered in strength calculations of the original bubbler condenser design.

Eigen-frequencies of bubbler condenser structures were evaluated in Polish analyses [4.1]. Their comparison with the frequencies of load oscillations determined in Prof. Bukrinski's experiments show that these two ranges of values are different. So no immediate hazards can be indicated. Nevertheless, the lack of full scale tests makes it impossible to give a final proof of bubble condenser structure stability.

4.3. RECOMMENDATIONS

As the peer review confirmed several mechanical weaknesses of the bubbler condenser structure, which not stand full loads corresponding to the DBA conditions adopted as the basis of the mechanical design, the weak elements pointed out in the previous section 4.1.2.4 should be strengthened. The analysis performed by Ukrainian Energoprojekt Institute and confirmed at the meeting by Russian designer organization shows that the necessary changes do not require any disassembly of the bubbler condenser and that they can be performed during regular shutdown for annual maintenance.
The regulatory bodies in the countries operating WWER 440/213 reactors with bubbler condenser containment should be informed of the problem and take appropriate decisions as to the time of implementation of mechanical improvements for strengthening the bubbler condenser structure.

In order to get the data necessary for the determination of bubbler condenser strength under conditions of oscillating loads due to steam condensation full scale tests in a large facility mentioned in section 3 are needed. The experiments should be made aware of the planned strengthening of the bubbler condenser structure and correct their experimental arrangement of bubbler condenser elements accordingly.
5. ASSESSMENT OF THE WWER-440/213 CONTAINMENT FOLLOWING A SEVERE ACCIDENT

5.1 ASSESSMENT OF THE DESIGN FEATURES OF WWER-440/213 NPPS FROM POINT OF VIEW BDBAS

Scope of the review: Review of geometric, thermal hydraulic and technological features of WWER 440/213 NPPs from the point of view of their influence on BDBAs.

Documents reviewed: [5.1, 5.2, 5.3].

Findings

5.1.1 Advantages of WWER-440/213 NPPs

- Relatively large free volume of the containment (50000 m³, hermetic boxes + corridor + pressure suppression system with air traps) with respect to the maximal thermal power
- Removal of a significant fraction of air from the compartments which may be subject to hydrogen release, which decreases chances of hydrogen ignition.
- Large amount of internal structures and walls with significant heat capacity for heat removal from the atmosphere
- Relatively large amount of water in the primary and secondary circuit (with respect to the maximum thermal power)
- Small density of the thermal power in the active core
- Isolation valves in each loop
- 6 primary loops
- Large amount of water in bubbler condenser shelves, available for passive spraying even under BDBA conditions.

5.1.2 Disadvantages of the containment of WWER-440/213 NPPs

Compared with advanced PWRs the following disadvantages can be observed:
- Low design pressure of the containment (2.5 bar, absolute)
- Hermetic door in the reactor shaft wall at the reactor cavity bottom level; early penetration of melted core into non-hermetic rooms
- Rectangular shape of pressure suppression tower
- High leakage rate from unfailed containment
- Large number of penetrations through the containment walls due to six primary loops and 3x100 % redundant ECCS
- Relatively narrow reactor cavity can hardly cope with high energetic events.

Recommendations

The codes used for the analysis of BDBAs in WWER-440/213 units should be adapted to the specific characteristics of those reactors.
The methods of BDBA management should take into account comparatively low containment strength and high leakage rates. All possible measures should be taken to decrease leakrates from WWER 440/213 containments.

5.2. POSSIBLE WAYS OF LOSS OF CONTAINMENT INTEGRITY OR INCREASING LEAKS UNDER BDBA CONDITIONS

Scope of the review: The studies of BDBA performed up to now for WWER 440/213 reactors are reviewed to determine the dominating sequences leading to the loss of containment integrity.

Documents reviewed: [5.1, 5.2, 5.3, 5.4, 5.5, 5.6]

Findings

- Long-term overpressurization of the containment by noncondensible gases generated during molten core-concrete interaction is dependent on concrete composition and leakage rate, i.e. it is plant specific. A considerable fraction of noncondensible gases are carbon oxides. That is why composition of reactor cavity concrete (content of limestone or any chemical compounds comprising CO\textsubscript{2}) plays the key role in determining long-term overpressurization. For some BDBA scenarios the containment pressure exceeds design pressure after 5 days. For other scenarios this effect does not appear, e.g. for Paks NPP there is no overpressurization if the leakage rate is 9% per day.

- Early containment overpressurization is probable in the case of hydrogen combustion. Pressure peaks at hydrogen burnings reach 5 bar, which is well above design pressure (calculations with STCP). In some scenarios the combustion of carbon monoxide occurs as well. Other highly energetic events (direct containment heating, steam explosion) were not considered.

- Meltthrough of the containment basemat slab or cavity walls threatens with basemat penetration in 5-7 days, with corium spreading out of the reactor cavity via melted cavity door. Corium penetration into non-hermetic rooms via ventilation tubes is plant specific; it can be excluded in some NPPs, e.g. in Paks.

- Low leaktightness of unfailed containment results in relatively high source term of radioactivity escaping to the environment, significantly higher than from unfailed containment of western PWRs.

- High temperatures of the containment atmosphere during combustion of inflammable gases can cause failures of sensors and cables of diagnostic and controlling devices.

- Direct containment heating (DCH): There are experiments for "open" type cavities like in NPP Zion. For "closed" type of cavity, as in a WWER, there are neither experiments nor analytical results assessing possibility of occurrence and consequences of DCH. From recent experimental studies in US national laboratories it follows that important characteristics influencing the course of DCH are the ratios of nominal thermal power and primary system volume resp. containment volume or cavity volume. These ratios are lower for WWER-440/213 than in western PWRs. Thus the hazards of DCH are correspondingly smaller.
- **Containment bypass**: No bypass sequence was analyzed until now. The importance of such sequences will be determined in probabilistic studies.

- **Containment failure due to earthquake**: The recent analytical studies performed in the Czech institutions (Energoprojekt Prague, State Machinery Research Institute Bechovice) show, that for both combined loads considered (nominal loads + maximal hypothetical earthquake) and (design earthquake + design basis accident conditions) the containment copes with the loads only if the strength of the liner is taken into account. Stresses in the piping system of pressure suppression system under dynamic load conditions may considerably exceed ultimate tensile strength.

**Recommendations**

The dominating process dangerous to the containment integrity is hydrogen burning. In the studies of BDBAs management the preferred approach should consist in preventing hydrogen burn.

Long-term overpressurization and containment basemat slab meltthrough are comparatively slow processes and can be mitigated with proper measures for BDBA management. Special attention should be paid to providing emergency electric power in such a way that no common cause failure can appear both in the Diesels dedicated to the safety systems of the plant and the additional reliable power source available in the case of a BDBA.

The problem of stresses in the piping system of pressure suppression system due to earthquake should be considered in mechanical strength analysis of the system.

**5.3. IDENTIFICATION OF DOMINATING OR ENVELOPING SEQUENCES**

**Scope of the review**

In order to approach the question of measures which would be preferable to cope with the hazards to containment integrity the dominating sequences (of the greatest risk) or the enveloping sequences (with the earliest hydrogen ignition, the highest pressures or the earliest ROV meltthrough etc.) should be identified.

**Documents reviewed**: [5.1, 5.2, 5.3, 5.4].

**Findings**

The question of dominating or enveloping sequences could not be answered in a proper way without probabilistic studies. Some sequences with severe consequences for the containment integrity might be highly improbable and so the risk (the product of the amount of damage and the probability of a sequence) is low. Some aspects for the ranking of sequences with regard to the containment integrity are the following:

- hydrogen release (total amount of hydrogen release and maximum of hydrogen release rate)
- time to reach failure pressure of containment
- time to reach basemat penetration.
5.3.1 Analyzed severe accident sequences

Below given evaluation was made by consultants based on analyses of the following sequences, which had been performed in the Nuclear Research Institute in Rez, Czech Republic.

- **S21B** Small LOCA (d=25 mm) in the cold leg of the primary loop with total blackout
- **S22B** Small LOCA (d=40 mm) in the cold leg of the primary loop with total blackout
- **S23B** Medium LOCA (d=100 mm) in the cold leg of the primary loop with total blackout
- **A200B** Large LOCA (d=200 mm) in the cold leg of the primary loop with total blackout
- **AB** Large LOCA (d=2x500 mm) in the cold leg of the primary loop with total blackout
- **TB** Transient with total blackout. Large heat losses from the primary system were used.
- **S21G** Small LOCA (d=25 mm) in the cold leg of the primary loop, failure of heat removal from the containment
- **S22H** Small LOCA (d=40 mm) in the cold leg of the primary loop, failure of HPI and LPI systems in recirculation phase
- **S22C** Small LOCA (d=40 mm) in the cold leg of the primary loop, failure of active spray system
- **AC** Large LOCA (d=2x500 mm) in the cold leg of the primary loop, failure of active spray system
- **S23I** Medium LOCA (d=100 mm) in the cold leg of the primary loop, only HPIS available
- **S23II** Medium LOCA (d=100 mm) in the cold leg of the primary loop, only HPIS available without heat exchanger

5.3.2 Identification of dominating BDBA sequences with significant hydrogen releases

The model used enables to include hydrogen generation by the zirconium steam reaction and in some extent by iron oxidation. The total amount of hydrogen produced by oxidizing all zirconium is 790 kg. Hydrogen is generated by the zirconium-steam reaction during the core melting, when steam, produced in the lower part of the core, comes into contact with the hot fuel rods in the upper part of the core. The longer the time between the start of core uncovering and core collapse (the slower sinking of water level in the core) the more hydrogen will be produced. The rate of hydrogen generation is not very high due to the long time period. If the produced hydrogen can leave the primary system continuously (for example by the leak) the concentration of hydrogen in the containment will increase slowly. If the hydrogen is stored in the primary circuit (for example in the high pressure case) and released instantaneously after bottom head failure, a very high pressure peak will occur, due to the release of large amounts of noncondensible gases of at high temperature and to possible violent deflagration).

Another source of hydrogen is the core-concrete-interaction. The main source of hydrogen in the ex-vessel phase is again zirconium (left from the in-vessel reactions) reacting with steam from decomposed concrete. This reaction (and the production of hydrogen) plays an important role at the start phase of core-concrete-interaction.
From the analysis of the above listed severe accident scenarios it follows, that about 25% to 40% of the total weight of zirconium reacts with steam in the RPV. This corresponds to a mass of 200 kg to 310 kg of hydrogen.

In Table 5.3.1 taken from [5.4] the above mentioned results are summarized. Violent deflagrations with pressures of 0.5 MPa after RPV-failure were analyzed for a small break LOCA-sequence and two transient-sequences.

Comparable pressure peaks are analyzed for a medium sized LOCA after loss of all water in bubbler condenser tower.

5.3.3 Identification of dominating BDBA sequences with early containment failure

From table 5.3.1 one can derive the most important parameters of flammable gases combustions that may occur during BDBA scenarios. It should be kept in mind that the results presented were obtained by running MARCH3M-code, with high degree of uncertainty due to the model of combustion used in this code. Anyway the results can serve as background at least for identification of relative contributions of some sequences analyzed for the threat of loss of containment integrity.

From these results it follows that the most dangerous combustion occurs for the small and medium break LOCA with station blackout and for high pressure transients. In these cases pressure peaks reach and exceed 5 bar, i.e. anticipated failure pressure of the bubble tower. No combustion occurs in the air traps. According to the calculations made with presently available codes, most of combustion occurs in the volumes above water trays where possible damage of structure is very probable.

Recommendations

In view of limited modelling possibilities of the codes available until now for WWER calculations it is recommended to perform analyses of the sequences with SB and medium break LOCA with station blackout by means of improved codes, modelling possibly well hydrogen distribution within containment. The results should be used for decisions as to the possible positioning of hydrogen recombiners in the containment. In particular, the possibility of hydrogen accumulation above the water trays and the effects of its possible burning should be investigated.
<table>
<thead>
<tr>
<th>Sequence</th>
<th>Core collapse (min.)</th>
<th>RVP failure (min.)</th>
<th>Start corium-concrete interaction (min.)</th>
<th>Hydrogen burning time (min)</th>
<th>Place of burning</th>
<th>Maximum temperature (K)</th>
<th>Maximum pressure (MPa)</th>
<th>Energy released (J)</th>
<th>Amount of H₂ burned (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S21B</td>
<td>419.73</td>
<td>506.72</td>
<td>523.38</td>
<td>506.78</td>
<td>2nd com.</td>
<td>1390</td>
<td>0.50</td>
<td>1E10</td>
<td>83</td>
</tr>
<tr>
<td>S22B</td>
<td>174.70</td>
<td>261.86</td>
<td>262.24</td>
<td>262.03</td>
<td>2nd com.</td>
<td>1383</td>
<td>0.513</td>
<td>1.02E10</td>
<td>84</td>
</tr>
<tr>
<td>S23B</td>
<td>78.92</td>
<td>241.40</td>
<td>242.44</td>
<td>142.02</td>
<td>1st com.</td>
<td>1420</td>
<td>0.215</td>
<td>2.2E10</td>
<td>174</td>
</tr>
<tr>
<td>AB</td>
<td>68.80</td>
<td>235.35</td>
<td>236.39</td>
<td>69.65</td>
<td>1st com.</td>
<td>930</td>
<td>0.191</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S21G</td>
<td>2242.00</td>
<td>2339.00</td>
<td>2412.00</td>
<td>2339.00</td>
<td>2nd com.</td>
<td>1392</td>
<td>0.55</td>
<td>1.E10</td>
<td>91</td>
</tr>
<tr>
<td>S22H</td>
<td>206.70</td>
<td>295.40</td>
<td>295.8</td>
<td>207.35</td>
<td>1st com.</td>
<td>1041</td>
<td>0.228</td>
<td>1.8E10</td>
<td>148</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>350.75</td>
<td>1st com.</td>
<td>1140</td>
<td>0.228</td>
<td>1.5E10</td>
<td>121</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>425.75</td>
<td>1st com.</td>
<td>1217</td>
<td>0.232</td>
<td>1.4E10</td>
<td>115</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>768.75</td>
<td>2nd com.</td>
<td>1442</td>
<td>0.413</td>
<td>0.91E10</td>
<td>52</td>
</tr>
<tr>
<td>TB</td>
<td>1078.00</td>
<td>1155.00</td>
<td>2303.00</td>
<td>1155.00</td>
<td>2nd com.</td>
<td>1250</td>
<td>0.49</td>
<td>1.E10</td>
<td>84</td>
</tr>
<tr>
<td>S22C</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AC</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S23I</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S23II</td>
<td>5867.8</td>
<td>6339.3</td>
<td>6340.3</td>
<td>no</td>
<td>no</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: S21B-dₑ=25 mm, S22B-dₑ=40 mm, S23B-dₑ=100 mm, S21G- loss of containment heat removal, S22H-ECC system failed in recirculating phase, TB - TMLB, S22C - spray system failure, AC-spray system failure, S23I- dₑ=100 mm, HPIS available, S23II dₑ = 100 mm HPIS available without heat exchanger.
5.4. ADVANTAGES AND DRAWBACKS OF HYDROGEN MITIGATION METHODS

Scope of the review: Assuming hydrogen release during BDBA sequences to review the methods preventing hydrogen deflagration, taking into account the advantages offered by bubbler condenser system and its limited mechanical strength.

Documents reviewed: [2.14, 5.3, 5.6, 3.10].

Findings

For the prevention of sudden pressure peaks threatening with the containment destruction, hydrogen and oxygen must not exceed the deflagration limits. In fact, if a flammable mixture remains in the containment for a long period, sooner or later ignition will take place. Therefore reactants must be eliminated by recombining or diluted by pre- or post-accident inerting to avoid deflagration.

5.4.1 Inerting

A pre-inertisation of the entire containment is not feasible.

Post-inerting involves injecting an inert gas at the beginning of the accident. The best inert gas for this proposal is carbon dioxide; a CO$_2$/air molar ratio of 62/38 is necessary to inert any containment atmosphere. For the volume of about 50 000 m$^3$ an amount of 160 000 kg of carbon dioxide is needed. One advantage of the pressure suppression system used in the WWER-440/213 NPPs is the under-pressure reached in the containment after the blowdown. This under-pressure is a good measure against the leakage of fission products to the environment due to the low leak tightness of the containment. However, in the case of post inerting this underpressure is used for the inert gas supply. In the long term phase of the accident the pressure would be significantly higher as a consequence of post inerting and the leakage of fission products to the environment would be higher.

5.4.2 Recombining

A thermal recombiner is a device that combines the hydrogen and the oxygen of a nonflammable mixture to form water in a combustion chamber at high temperatures (900 to 1000 K). A current type of thermal recombiner can be installed outside the containment. This location prevents mechanical damage as the result of LOCA and allows the combustion heat to be discharged outside the containment without affecting temperature and pressure inside. A disadvantage of this location is the need of penetrations through the containment wall. The thermal recombiner is an active system, it needs power for its operation and so it is not usable in the case of station blackout.

Catalytic recombiners recombine hydrogen and oxygen by passive catalytic devices providing large surfaces and being effective before hydrogen reaches its flammability limits. The catalytic effectiveness depends on temperature, hydrogen and steam concentrations, and on the flow rate reached in the result of natural convection. Passive catalytic recombiners can be installed inside the containment. They present advantages of passive operation and prevention of sudden pressure peaks due to hydrogen burning.
5.4.3 Igniters

Igniters deliberately start a combustion. They can assure that the combustion of hydrogen starts early, as soon as the atmosphere reaches flammable conditions.

The most common types of igniters used are glow and spark plug igniters. These igniters need an electric power supply, either an accumulator or external electric power. The use of the latter would be problematic in the event of a blackout accident. Recently, catalytic igniters have been put on the market. These igniters work automatically without an electric power supply.

The ignition of hydrogen will provoke sudden pressure increase inside the containment. This may be especially hazardous if the hydrogen burning takes place within bubbler condenser structure.

Recommendations

The development of passive catalytic recombiners is recommended as a measure of free hydrogen removal without threats to the containment structure. Recombiners could solve the hydrogen problem in most of the BDBA-scenarios. Catalytic recombiners have the advantage that they are passive systems (they need no power and can work also in blackout sequences). Igniters can be helpful in the sequences which produce a high rate of hydrogen released into the containment. In this case they will assure an early and gentle combustion of the hydrogen which cannot be converted by the recombiners.

Post-inertisation of the containment is one of the possible ways to avoid a deflagration.

Overall more detailed analyses about hydrogen production and hydrogen distribution in the containment are necessary to decide which measures will be adequate for each plant. Only the catalytic recombiner seems to cause no hazard.

5.5. MELTING THROUGH OF THE REACTOR CAVITY WALL AND BOTTOM

Scope of the review: The hazards to containment integrity due to melt through should be reviewed taking into account specific structural features of WWER 440/213 containment.

Documents reviewed: [5.3, 5.4, 5.6].

Findings

The meltthrough of cavity concrete threatens the integrity of WWER-440/213 containment. Basemat slab or cavity walls are relatively thin and significant penetrations affect the concrete (door, ventilation ducts).

At the very beginning of core-concrete interaction the rest of zirconium oxidized in the molten pool produces additional heat that exceeds in some cases twice the fission product decay heat. That is why at the initial phase of the interaction the concrete ablation rate is
several times higher than long-term average value. The average value of the concrete decomposition rate in all analyzed cases is higher in the vertical direction. The average value for five days of the interaction (calculated or extrapolated from shorter scenarios) is approximately 40 cm per day or more in the vertical direction and about 30 cm per day in the radial direction.

The thickness of the basemat is 3 m and the thickness of the cavity wall is 2.4 m. So we can assess the time needed for meltthrough of reactor cavity concrete in both horizontal and vertical directions to be about 7.5 to 8 days after the moment when core-concrete interaction starts. These values are not conservative, since containment overpressure can speed up the failure of the partially ablated concrete walls.

A specific problem of WWER-440/213 NPPs is the meltthrough of reactor cavity hermetic door. The thickness of the concrete cover of the door is 50 cm, which means that the meltthrough will occur during one day or probably less due to above mentioned higher ablation rate in the beginning of interaction. In view of the fact that the core-concrete interaction phenomena are not known at present time in a sufficient degree the values presented above have more qualitative than quantitative character.

Recommendations

The possibility of the meltthrough of reactor cavity hermetic door should be further analyzed and the measures increasing its resistance under BDBA sequences should be proposed, so as to reach the meltthrough delay times similar as for the basemat (one week after accident).

5.6. INFLUENCE OF HIGH LEAKAGE RATE IN WWER-440/213 CONTAINMENTS ON RADIOLOGICAL HAZARDS UNDER SEVERE ACCIDENT CONDITIONS

Scope of the review: In view of the wide variety of leakrates occurring in the operating WWER 440/213 containment, the influence of high leak rates on fission product leakage under severe accident conditions should be evaluated.

Documents reviewed: [5.4, 5.6]

Findings

Leaks from containment contributing to radiological hazards consist mostly of fission products in the form of:
- noble gases,
- volatile forms of chemical compounds or elements,
- aerosols.

Leaks are controlled by overpressure in the containment volumes and by the amount of airborne fission products present actually in the containment. The amount of radioactive materials escaping from containment is almost a linear function of leakage rate.
For characteristic BDBAs such as total blackout or LBLOCA and SBLOCA with active sprays available and a leakage rate of 16% of total volume per day, the relative leaks (related to inventory of fission products in the core) are of following orders of magnitude for most important elements or groups of elements:

<table>
<thead>
<tr>
<th>Fission Product</th>
<th>Range (Fraction of Inventory)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>$10^{-2} \div 10^{-4}$</td>
</tr>
<tr>
<td>Cs</td>
<td>$10^{-2} \div 10^{-3}$</td>
</tr>
<tr>
<td>Ng</td>
<td>$0.3 \div 0.5$</td>
</tr>
<tr>
<td>Te</td>
<td>$10^{-3} \div 10^{-4}$</td>
</tr>
<tr>
<td>Sr</td>
<td>$10^{-2} \div 10^{-4}$</td>
</tr>
<tr>
<td>Ru</td>
<td>$10^{-6} \div 10^{-7}$</td>
</tr>
<tr>
<td>La</td>
<td>$10^{-4} \div 10^{-6}$</td>
</tr>
<tr>
<td>Ce</td>
<td>$10^{-4} \div 10^{-6}$</td>
</tr>
<tr>
<td>Ba</td>
<td>$10^{-3} \div 10^{-4}$</td>
</tr>
</tbody>
</table>

These cumulative values have been calculated for 4 days of severe accident scenario [5.5, 5.6]. The average fraction of gases leaking from the containment is several percent of the total amount.

**Recommendations**

In view of the possibility of significant releases of fission products under some BDBA sequences all technically reasonable measures should be taken to improve leaktightness of WWER 440/213 containments.

Other measures, which would assure long term decrease of overpressure in the containment are also to be considered.

**5.7. POSSIBLE EFFECTIVENESS OF CONTAINMENT VENTING FOR WWER-440/213 UNITS**

**Scope of the review:** A filtered venting system proposal for WWER 440/213 containment should be reviewed, its potential advantages assessed and the problems connected with its installation identified.

**Documents reviewed:** [5.7]

**Findings**

Taking into account the unique design features of WWER-440/213 and the results of a preliminary assessment of containment filtered venting system (CFVS) we can state:

- CFVS brings solution of the two serious drawbacks of the design arising under BDBA conditions:
- It eliminates completely the risk of containment failure due to long-term overpressurization. With the exception of pressure peaks during combustion of inflammmable gases, the containment keeps stable pressure slightly above the atmospheric pressure.

- Uncontrolled leakage of fission products to surrounding environment is substantially reduced even for containments of poor leaktightness (by factor 10 for leakage rate 18% per day).

New problems of the CFVS design described in [5.7] are related to hydrogen combustions:
- Due to high pressure peaks during hydrogen combustions in volumes above water trays the destruction of operational part of pressure suppression system is much more probable.
- Another hazard can be caused by much higher frequency of inflammmable gas combustion in air traps (above all for the leak-tight containment) and subsequent underpressurization well below minimal pressure.

Above mentioned problems can be solved by proper technical measures within hydrogen risk mitigation concept and hazardous drops of pressure in air traps can be prevented by installation of fast-acting check-valves at outer side wall of air traps. However, no detailed design has been proposed yet.

Conclusions

- Installation of the CFVS may contribute to solving significant safety issues connected with BDBAs.
- The results of BDBA analysis show that for some compositions of concrete (no limestone in the concrete used in Czech NPPs) and leakrates long-term overpressurization does not reach the anticipated failure pressure. The main reason for the CFVS installation would be reduction of uncontrolled leakage of radioactive materials from containment to environment.
- The proposed CFVS has yet to be designed and its influence on the design functions of the containment under normal operation and DBA conditions should be assessed.

Recommendations

When the actual concept of CFVS has been brought to the design stage it can be considered in more detail.

5.8. OPEN ISSUES

5.8.1. BDBA modelling

- Very important are the input data and results of PSA level 1. Two probabilistic safety analysis studies for WWER-440/213 units are being conducted, but have not been completed.
More advanced integral codes for assessing BDBA sequences are necessary like MELCOR, RELAP/SCDAP, CONTAIN. They should be adapted to the conditions typical for WWER-440/213.

Some models are missing even in advanced codes used for PWR analysis: core melt progression, natural convection and heat transfer in the pool of melted materials inside RPV-bottom head, steam explosions, direct containment heating etc.

Many existing models of physical phenomena used significantly in the BDBA analysis should be further improved.

Integral experiments and separate effects experiments are needed to verify:
- existing models of important physical phenomena
- new models for new phenomena arising mostly from demands on accident management
- separate experiments for verification of WWER-440/213 specific features.

### 5.8.2. Hydrogen deflagration prevention

The development of an efficient passive catalytic recombiner would provide the tool for safe hydrogen deflagration prevention.

### 5.8.3. Hydrogen distribution

The development of a code for realistic modelling of hydrogen distribution in complicated WWER 440/213 bubbler condenser containment conditions is needed for successful implementation of measures for hydrogen deflagration prevention.

### 5.8.4 CFVS

The possibility of CFVS installation inside the existing air locks remains an unresolved question.

### 5.9. CONCLUSIONS AND RECOMMENDATIONS

The containment (or hermetic rooms) are, according to "the defence in depth" concept, the third and the last barrier which can retain fission products inside nuclear power plant and protect environment from massive release of radioactive materials.

The containment of the WWER-440/213 was not designed to cope with "beyond design basis accident (BDBA)" conditions and consequences. If a severe accident occurred it would present a real hazard to NPP operation but a quantitative estimation of the core damage frequency will be available only after finishing complete PSA level 1 studies.

According to the preliminary results of BDBA analysis there are two most important threats to containment integrity:
hydrogen combustion in the pressure suppression system, producing high pressure peaks;
melt through of reactor cavity concrete during molten core-concrete interaction.

There are other possible modes of containment integrity failure as well e.g. direct containment heating, steam explosions, containment bypass but their probability is much smaller. Some of them cannot be assessed at present time because of the lack of analytical models and experimental verification. Containment isolation problems can be solved by operational or emergency procedures in the plant.

High leakage rate of unfailed containment could create hazards for the environment under BDBA conditions. It follows from the analyses performed, that accident management strategies should be focused on measures preventing development and progression of accidents beyond DBA. The most effective measures that can be applied are prevention of total blackout situations in NPPs and wise application of the bleed and feed procedures. Monitoring of containment atmosphere composition can play an important role for any hydrogen mitigation measures.

For hydrogen mitigation we can use several possibilities: catalytic recombiners, igniters, post-inerting and some combination of them. Decision on choosing proper measures needs more detailed analysis keeping in mind possibility of formation of local areas with high hydrogen concentration. The development of passive catalytic recombiners may bring a safe solution to this problem.

According to the present knowledge it is very difficult to stop the progression of molten core-concrete interaction in the reactor cavity when it has already started. Accident management strategy should be concentrated on measures preventing RPV-failure, i.e. on retention of the melted core inside the vessel. This can be achieved by flooding of reactor cavity. The WWER-440/213 has one promising feature for such measure: relatively low decay heat output of the core in relation to pressure vessel dimensions.

Containment filtered venting system, if installed, could substantially decrease uncontrolled leaks of radioactive materials outside containment. However, at present this proposal has not been yet thoroughly worked-out, there are no design solutions proposed and no peer review has been made.

Conclusions and recommendations written above reflect our limited knowledge and experience in the field of BDBAs and can serve only as a very preliminary guidance.
6. GENERAL CONCLUSIONS AND RECOMMENDATIONS

1. The specialists recognize the value of the meeting and the preparatory work done under the IAEA guidance, which has helped to elucidate difficult problems connected with WWER 440/230 confinements and WWER 440/213 containments. The Elektrowatt report prepared for the IAEA provided a broad review of the available and proposed means for WWER 440/230 confinement upgrading. Similarly, the work done in the project RER/9/004 on bubbler condenser has served as the starting point for the proposals of strengthening the mechanical structure of the bubbler condenser. The review of the status of confinements for WWER 440/230 reactors and of bubbler condenser containment for WWER 440/213 performed during the meeting provided valuable material which can serve as the basis for the further safety analyses and decisions concerning implementation of proposed improvements.

Concerning WWER 440/230 Confinement

2. In the case of WWER 440/230 reactors there are several proposals for confinement upgrading. In filtered venting systems it is possible to use mechanical filters or water filters of various designs developed by Western companies, or jet condensers developed and tested in Russia. The presented conceptual designs offer the possibility of filtering the released gases throughout the accident without losing the integrity of the confinement.

3. It is also possible to provide a forced ventilation system having filtered discharge. This would assure in a long term an underpressure within the confinement after BDBAs in spite of high leakage rates.

4. The improvement of leaktightness of WWER 440/230 confinements is very important and should be treated as an urgent task.

All the countries operating WWER 440/230 units are strongly recommended to intensify work for the improvement of leaktightness of the existing confinements. The example of Bohunice V-1 NPP, where the leakage rates have been decrease by more than an order of magnitude, shows that this task is feasible and can bring important safety improvements in comparatively short time.

5. The specialists support the opinion that a LOCA with a break size equivalent to 200 mm should be considered when defining the DBA for the purpose of designing the upgraded confinement, provided adequate in-service inspection is performed and LBB concept can be applied to 500 mm pipes in the RCS.

6. The 500 mm pipe break should be considered along with other BDBAs when designing the upgraded confinement system. The integrity of confinement should not be lost after 500 mm pipe break or after pressure transients resulting from secondary system breaks if no other failures occur exceeding single failure criterion.
7. The proposals of WWER 440/230 confinement upgrading presented at the meeting show that the filtered venting concept both with filters or with jet condensers are feasible and allow to limit radioactivity releases to admissible values for the accidents initiated by breaks of RCS pipes of 200 mm or less. Further design studies of filtered venting and experimental verification of the key elements needed for this concept should be pursued so as to provide the possibility of practical implementation of the systems.

8. As in the short time available it was not possible to review all problems related to WWER 440/230 confinement and upgrading in detail, it is recommended to continue the work on the subject on the international level. New proposals of upgrading of accident localization systems for WWER 440/230 units, unavailable at the time of this meeting, should be compiled for further discussion and clarification.

Concerning WWER 440/213 bubbler condenser containment

9. The aerodynamic, hydraulic and thermal characteristics of bubbler condenser containment have been extensively studied in small scale and partial modelling experimental stands. All results reached up to now have shown that the thermal hydraulic parameters found experimentally correspond to those assumed in design calculations with a significant safety margin. The logic of the bubbler condenser operation under conditions of LB LOCA or of SB LOCA developing later into LB LOCA has also been confirmed. However, there have been no large scale tests which could provide final evaluation of safety margins inherent in the bubbler condenser design and to provide indications of possible loads due to vibrations provoked by steam condensation and in general by steam-air mixture interaction with solid structures of the bubbler condenser.

10. It is recommended to support the proposals of large scale testing of the bubbler condenser operation, preferably in a facility which permits to test at least three levels of water trays in real geometry, made under normal technological conditions. Such tests would provide valuable data on

- the maximum pressure difference possible on the walls of water trays after LB LOCA,
- oscillations provoked by the steam condensation
- eigenfrequencies of the bubbler condenser structure
- mechanism of reverse water flow from the trays and the reliability of its stopping by means of 250 mm check valves,
- influence of drops fall height on the efficiency of passive spraying,
- possible effects of water carry-over from the trays on the efficiency of work of both types of valves above the water level.

11. The mechanical strength of the existing bubbler condenser structures is insufficient to withstand the loads assumed to appear in the case of a LB LOCA. The pressure difference on the walls of the bubbler condenser water trays in the initial transient after large break was taken in the bubbler condenser design initial data as equal to 30kPa, which may include some safety margin. However, this safety margin would
be impossible to specify without large scale tests. Since under such a pressure difference several elements of key importance for the integrity of the bubbler condenser can fail, a strengthening of the bubbler condenser structure is recommended. The feasibility of such strengthening has been confirmed by the experts. It is proposed that the IAEA compiles information on the subject and provides it to the regulatory bodies in the interested countries.

12. An initial comparison of the general design criteria used for containments in Germany and in the USA with the criteria used for bubbler condenser design has shown their general similarity. However, a more precise judgement is not possible until the design criteria for bubbler condenser containments are formulated and approved by the regulatory bodies in the countries involved. It is recommended to take up this work with the possible assistance of the IAEA. The existing design criteria used in the US, Germany and other countries for containments, in particular for partition walls of ice condensers and for pool condensers of BWR containments could be helpful in this work.

Concerning both types of WWER confinement/containment

13. The problems of management of beyond design basis accidents with severe core damage remain unsolved. In particular, the question of prevention of hydrogen deflagration hazards requires further studies, both through calculations of hydrogen distributions and burning effects and through technological development of devices for hydrogen control. The most promising seems to be the development of passive hydrogen recombiners which can control hydrogen concentration without precipitating its burning with the accompanying temperature and pressure increases.
REFERENCES


[1.5] Guidelines for the application of the leak before break concept - draft of a TECDOC of the IAEA


[2.1] BALAZ, P., V-1 Accident Localization System Upgrading to Cope with Large LOCA Scenarios, VUEZ, Tlmace (Nov. 1993)

[2.2] BALABANOV, E., Upgrading of Confinement of NPP Kozloduy Unit 3 and 4, Energoproject, Sofia (Nov. 1993)


[2.5] CSEKEY, CESNAK, Hermetic Compartment Leak Tightness Enhancement, VUEZ, Tlmace (Nov. 1993)


[2.10] The Sulzer-EWI Containment Filtered Venting Concept for Upgrading the WWER 440/230 Confinement, Sulzer-EWI, Winterthur, Switzerland

[2.11] Proposal to Bohunice NPP (Proprietary), Siemens-KWU, Erlangen

[2.12] Proposal to Bohunice NPP (Proprietary), Westinghouse Nuclear Europe, Brussels


[2.15] Proposal for Upgrades to the Greifswald NPP units, Westinghouse (Sept. 1990)

[3.1] The summary of experimental and calculational investigations of processes in the bubbler condenser containment system of NPPs with WWER-440 reactors after LOCAs performed by VTI (Russian Federation), Working Material, IAEA Project TC/RER/9/004


[3.8] STRUPCZEWSKI, A., Comparison of design criteria for NPPs containments with bubbler condenser and for large dry containment type, Proceedings of the Consultants Meeting on Containment and Confinement Performance in NPPs with WWER 440/213 and 440/230 Reactors, IAEA, Vienna, Austria (29 Nov.- 3 Dec. 1993)

[3.9] KULIG, M., Analysis of containment pressure changes inside WWER-440/213 Zarnowiec NPP (Poland) TC/RER/9/004-A008


[3.13] BUKRINSKI, A.M., Eksperimentalnye i raschetnye issledovaniya processov v barbotazhnoy sisteme AES s WWER pri avarii s poterei teplonositela, Sojuzglavzgrag-atomenergo, USSR.


[4.1] Strength analyses of bubble-condenser structures under dynamic load conditions in the VVER-440/213 Zarnowiec NPP (Poland), Working material, IAEA Research Contract No. 4782 RB, IAEA TC project RER/9/004.

[4.2] SHENDEEROVICH, V., Estimation of results of test strength calculation of system of bubble devices for Rovenskaya NPP (units 1, 2) Kiev Institute "Energoproekt", Vienna (6-8 October 1993).

[4.3] Sistema barbotazhnyh ustoroistv, Raschot na prochnost A.07.071.000 PP, SverdNIKhimmash.


[5.1] KUJAL, J., Severe Accident Analysis of VVER-440/213 Nuclear Power Plant, Part 1, Nuclear Research Institute, Rez, Czechoslovakia (June 1992)

[5.2] KUJAL, J., DUSPIVA, J., Severe Accident Analysis of VVER-440/213 Nuclear Power Plant, Part 2, Nuclear Research Institute, Rez, Czechoslovakia (October 1992)

[5.3] KUJAL, B., KUJAL, B., Assessment of the Ways of Containment Integrity Loss for Accident Conditions Beyond Design Basis, Nuclear Research Institute, Rez, Czechoslovakia (November 1992)

[5.4] KUJAL, J., DUSPIVA, J., Review and Summary of Severe Accident Sequences analyzed, Nuclear Research Institute, Rez, Czechoslovakia IAEA, VVER-440/213 Safety Assessment Project RER/9/004 (October 1993)


CONSULTANTS’ MEETING ON THE CONTAINMENT AND CONFINEMENT PERFORMANCE IN NPPS WITH WWER-440/213 AND 440/230 REACTORS

LIST OF PARTICIPANTS

Belgium

Mr. R. Prior
Westinghouse Energy Systems Europe
Boulevard Paepsem 20
B-1070, Brussels
Tel: (32) 2 556 8965, Fax: 32 2556 8926

Mr. J. Snoeck
Tractebel
Av. Ariane 7
B-1200 Brussels
Tel: 322 773 8355, Fax: 322 773 8900

Bulgaria

Mr. E. Balabanov
Nuclear Safety and Automation Division
Institute Energoproekt
51 J, Baucher Bulevard
Sofia
Tel: (3592) 66 5325, Fax: (3592) 66 8951

Czech Republic

Mr. J. Kujal
Nuclear Research Institute plc.
Power and Safety Division
25068 Rez nr. Prague
Tel: & Fax: (422) 6641 2029

Germany

Mr. H. Karwat
Technische Universität München
Forschungsgelände
85747 Garching
Tel. 32004/128, Fax: (89) 32004299
Mrs. G. Preusser  
Siemens AG, Energieerzeugung KWU  
Berliner Strasse 295-303  
63067 Offenbach  
Tel: 69 807 4792, Fax: 69 807 4567

Mr. U. Simon  
Siemens AG, Energieerzeugung KWU  
Section NT 34  
Seligentädter Str.  
63791 Karlstein  
Tel: 6188/780 331, Fax: 6188/780 309

Hungary

Mr. Z. Techy  
Institute for Electrical Power Research VEIKI  
P.O. Box 233, Zrinyi 1  
H - 1368 Budapest, Hungary  
Tel: 1183-233, Fax: (36) 1 1179956

Russia

Mr. A.M. Bukrinski  
Scientific and Engineering Centre  
for Nuclear and Radiation Safety  
14/23 Autozavodskaya str.  
109280 Moscow, Russia  
Tel: 275 3756, Fax: (095) 2788090

Mr. A.N. Kudriashov  
SverdNIIKhimmash  
Griboedov str., 32  
6202010 Ekaterinburg  
Tel: 275 765, Fax: (3432) 275505

Slovak Republic

Mr. P. Balaz  
Power Equipment Research Institute ((VUEZ)  
935 28 Tlmače  
Tel. 42 813 9263140, Fax: 42 813 921617

Mr. J. Misak  
Nuclear Regulatory Authority of Slovak Republic  
P. O. Box 24, Bajkalska 27  
82 007 Bratislava  
Tel: 42 7221531, Fax: 42 7 293 603
Switzerland

Mr. A. Wanner
Electrowatt Engineering Services Ltd.
Bellerive strasse 36
P.O. Box
CH-8034 Zurich
Tel: 01/ 3852211, Fax: (41) 1/38524252

Ukraine

Mr. A.I. Muchnik
Energoproject
252135 Kiev
4 Pobeda Av.
Tel: 274 3994, Fax: (044) 274 6091

USA

Mr. Jim Gresham
Manager
Containment and Radiological Analysis
Nuclear and Advanced Technology Division
Westinghouse Electric Corporation
P. O. Box 355
Pittsburgh PA 15230-0355
Tel: 412 374 4643, Fax: 412 374 5099

IAEA

Mr. M. Jankowski, Division of Nuclear Safety
Mr. M. Kulig, Division of Nuclear Safety
Mr. A. Granda, Division of Nuclear Safety
Mr. A. Strupczewski, Division of Nuclear Safety
Consultants' Meeting on the Containment and Confinement Performance in NPPs with WWER 440/213 and 440/230 Reactors

29 November - 3 December 1993
Vienna International Center, Meeting Room B 0742

PROVISIONAL AGENDA

Monday, 29 November 1993

09:30 Opening of the Meeting.
Overview of the program of the week. Mr. Strupczewski

10:00 Review of new developments in the experimental and analytical justification of bubbler condenser design Mr. Bukrinski

11:00 Coffee break

11:15 Technical basis for improving the confinement function in WWER 440/230 NPPs. Mr. Wanner

11:45 Upgrading of confinement of NPP Kozloduy, Units 3 and 4 Mr. Balabanov

12:15 Experimental work on jet condenser and other elements of improved confinement concept for NPPs with WWER 440/V-230 Reactors Mr. Balaz

12:45 Lunch break

14:00 Review of experimental and analytical work on bubbler condenser containment in Czech Republic Mr. Kujal

14:45 Review of Polish studies on pressure changes in the bubbler condenser containment in the early and later phases of LB LOCA accident with possible failures in the bubbler condenser system Mr. Kulig

15:15 Review of experimental and analytical work on bubbler condenser containment in Hungary Mr. Techy

15:45 Coffee Break

16:00 Report about the activities of an international working group on bubbler condenser containment research work Mr. Karwat

17:00 Steam condensation in water pools Mr. Simon
A - for WWER 440/V-230 confinement improvement,
B - for hydrogen problems and other BDBA threats to containment integrity,
C - for WWER 440/V-213 bubbler condenser containment problems connected with pressure changes, thermal hydraulic phenomena in water shelves, steam-air mixture condensation and fission product removal in water shelves,
D - for loads and stresses in bubbler condenser and containment structures.

Tuesday, 30 November 1993

Joint meeting of all groups, Room B 0742

09:30 Review of experimental and analytical work on bubbler condenser containment in Slovak Republic Mr. Misak
10:15 Review of bubbler condenser containment design in the light of German standard requirements for PWR containments Mr. Strupczewski
10:45 Coffee break
11:00 Discussion of the main design criteria for WWER 440 containments, proposed improvements General
12:00 Lunch break

Work in teams:

A: Room C0737
Issues to be addressed listed in attachment

B: Room C 0741
Issues to be addressed listed in attachment

C and D, Room B 0742
14:00 Discussion of pressure loads to be taken as the basis for strength calculations of the bubbler condenser General

14:30 Mechanical stresses in bubbler condenser elements Mr. Strupczewski
Mr. Muchnik
Mr. Kujal
Mr. Kudriashov
15:30 Coffee break

15:45 Discussion of admissible assumptions for bubbler condenser strength calculations

16:15 Discussions and preparation of technical notes in Working Groups, separately,

List of issues to be addressed in attachment

A - room C0737
B - room C0741
C - room B0742
D - room B0837

Wednesday, 1 December 1993

Thursday, 2 December 1993

09:00 till 17:30 Preparation of technical notes in Working Groups.

Friday, 3 December 1993

09:00 Preparation of technical notes in Working Groups

12:00 Lunch break

14:00 Presentation of the reports of Working Groups and plenary discussion:

For Working Group A: Mr Balaz
For Working Group B: Mr Kujal
For Working Group C: Mr Misak
For Working Group D: Mr Kudriashov

16:00 Summary of the conclusions of the meeting Mr Strupczewski

16:30 Adjourn
BUKRINSKI, A.M. Review of experimental work for thermal hydraulics of the bubbler condenser system.

BALASZ, P., V-1 Accident Localization System Upgrading to Cope with Large LOCA Scenarios, VUEZ, Tlmace (Nov. 1993)

BALABANOV, E., Upgrading of Confinement of NPP Kozloduy Unit 3 and 4, Energoproject, Sofia (Nov. 1993)


MISAK, J., Review of analytical work on bubbler condenser containment in Slovakia (Design Basis Accidents)

J. KUJAL, Review of experimental and analytical work on bubbler condenser containment in Czech Republic.

TECHY, Z., Review of experimental and analytical work on bubbler condenser in Hungary

KULIG, M., Containment related studies performed in Poland.

KARWAT, H., Report about the activities of an international working group on bubbler condenser containment research work

SIMON, U., Steam condensation in water pools

PREUSSER, G., Actual developments in hydrogen control

STRUPCZEWSKI, A., Comparison of design criteria for NPPs containments with bubbler condenser and for large dry containment type.
REVIEW OF EXPERIMENTAL WORK FOR THERMAL HYDRAULICS OF THE BUBBLER CONDENSER CONTAINMENT

A. M. Bukrinski
Scientific and Engineering Centre for Nuclear and Radiation Safety
Moscow, Russian Federation

VIENNA, AUSTRIA
29 NOVEMBER - 3 DECEMBER 1993
The presentation of the latest developments in bubbler condenser containment systems will be based on the work done for WWER 440 containment in Juragua NPP, presently under construction in Cuba. Many considerations will be applicable to the older, but also quite reliable bubbler condenser systems installed in NPPs in Russia, Ukraine, Hungary, Czech and Slovak Republic.

Schematic diagram of a cylindrical containment system with bubbler condenser vacuum system limiting the consequences of accidents is presented in Fig. 1. The bubbler condenser is a fully passive device used for the condensation of steam released from the Reactor Coolant System (RCS) during Loss of Coolant Accident (LOCA). In order to improve the reduction of pressure after the accident a fast acting passive sprinkler system is also applied.

The containment volume is divided into two compartments: lower and upper. In the lower compartment the reactor primary cooling system including horizontal steam generators is located. In the upper compartment there is technological equipment for reactor servicing, refuelling, transport, spent fuel pool etc. The lower and upper compartments are divided with a wall, made in the shape of an annular sector type box, where the bubbler condenser is located. The passive sprinkler device tanks are located here too. The air space of the well before the bubbler condenser communicates with the reactor rooms by a corridor. The space above the water level of the condenser tank is connected to the upper compartment through a special passage, where a gas seal is provided.

The upper compartment of the containment is separated from the lower one by a relatively leak-tight floor made of reinforced concrete. This partition wall includes a metal cap, situated over the reactor shaft, and water layers in the bubbler condenser tanks. Every containment compartment has its own independent ventilation system. As a result, possible coolant leaks from the reactor facilities under normal operation conditions make no contribution to the radiological hazards in the upper compartment, where the personnel of the reactor may stay.

In the case of LOCA pressure increases in the lower containment compartment, and the air-steam mixture, which is created in the result of coolant release from the RCS, goes into the bubbler condenser, bubbling through the water tanks. During bubbling, the steam is being totally condensed, while the air and non-condensible gases go to the volume above the water layer and further on to the upper compartment volume.

The maximum pressure excess in the lower compartment (reactor rooms) does not exceed approximately 0.12 MPa, while the pressure in the upper containment compartment is not higher than 0.03 MPa.

In about 2 minutes after the accident starts, due to the passive sprinkler operation the pressure falls down below atmospheric and the releases of radioactivity from the reactor rooms into the environment are stopped.
In the upper compartment the overpressure remains for a longer time, but its value is very small. At the same time, the level of radioactivity in the upper compartment is very low, because the air from the reactor rooms goes into the upper compartment only for the first 25 seconds after the accident. Moreover, the radioactive products contained in the air-steam mixture are in a large degree captured in the water layer in the process of bubbling.

Thus the containment with a bubbler condenser provides good protection of the environment from the radioactive contamination. Even if the core were to be damaged, no fuel melting can occur after LOCA earlier than after 5 minutes since the beginning of the accident. i.e. when the rarefaction is already achieved in the reactor rooms.

This creation of rarefaction and its maintenance during a long period after the accident is of principal importance for the improvement of NPP accident localization system concept. Such an approach removes a paradox, which is characteristic for many other types of reactor containments. The paradox consists in the following contradiction: during normal operation, when the level of contamination with radioactive products in the reactor rooms atmosphere is very small, negative pressure is maintained in these rooms, preventing any direct radioactivity releases into the environment. On the other hand, during an emergency and after the accident, when the radioactive contamination levels increase many times, overpressure exists in the reactor rooms, thus giving rise to radioactivity leaks into the environment.

The main element of the depressurization system in the bubbler condenser containment is the bubbling system. The design of this system is comparatively simple. It includes water tanks and bubbler pipes through which the air-steam mixture or steam is brought under the water layer. At the same time the processes which take place in such devices are rather complicated and may be characterized by instability and pressure pulsations or even water hammer occurrence.

This can result in additional dynamic loads acting on the structure of the bubbler condenser, in particular on water pipes and on the walls of the water tanks. The last is very hazardous, because a damage to the tank can lead to water loss and non-fulfillement of the important safety functions of the bubbler condenser. Therefore good knowledge of possible dynamic loads during bubbler condenser operation and an appropriate choice of its mechanical structure are extremely important for its reliability.

Unstable regimes of bubbler condenser operation are well known and they have received the title of "chugging". In the former Soviet Union and in some other countries much attention has been given to their studies. In one of our papers [5] the occurrence of chugging during bubbling condensation of steam or air-steam mixture was studied in connection with the specific features of bubbler condenser devices.

Fig. 2 shows the characteristics of the performance of the simplest bubbler condenser device with a cylindrical steam supply pipe dipped under water for the case when the steam or steam air mixture with low air content is supplied. The line presents the relationship of the pressure drop to the flow rate through the water layer.
It is seen that the curve has a characteristic break, due to the sharp increase of steam condensation intensity at the moment when the water column is pushed out of the boundaries of steam supply pipe. In the region of the so called 'jet of condensation' the heat and mass transfer is much intensified.

The part of the curve 0-a corresponds to the phase of pushing the water column from the steam supply pipe. This part of the curve is stable. Steam condensation in this region is carried out due to heat removal through the walls of the steam supply pipe and to the surface of the water. Part c-d is also stable. It corresponds to steam condensation in the jet beyond the boundaries of the steam supply pipe.

Unstable regimes occur when the steam flow rate coming into the steam supply pipe is in the break area, i.e. G1 Gb G2. In this case, after the water column is pushed out to the point "a", the steam flow rate immediately increases up to the value which corresponds to the point "b".

Since such a flow rate exceeds that supplied to the tank, the pressure in the steam supply pipe decreases and the steam flow rate falls down, approaching G2 in the point c. After reaching this flow rate, further pressure reduction will lead to an interruption of bubbling process and the pipe will begin to fill up with water. Then the pressure will start to build up and the cycle will be repeated again.

The mechanism described above was used for qualitative analysis of the influence of various design factors in bubbler condenser structure on possible pressure changes. It was also used [6] for developing of a semi-empirical model, which allows to determine by calculation the boundaries of instabilities and average pulsation frequencies.

During chugging, when water comes into the steam supply pipe, water hammers can occur at the inlet of the pipe due to collapse of steam space, as a result of steam condensation. Such water hammers additionally load the steam supply pipe, which must be resistant to pressure increases and vibrations. Owing to cylindrical form of the pipes the problem is comparatively easily solved. On the other hand, water hammers which might occur in the pond after water heating are much more dangerous. Their intensity increases with water heating. Pressure impulses from such water hammers directly influence pond walls, which must be correspondingly resistant.

In the bubbler condenser containment such hazards can be excluded by using bubbler circulating condensing devices, developed in the Soviet Union. The design of such a unit as used in NPP Juragua is shown in Fig.3.

In this device the steam supply pipe 1, dipped under water for 1 m depth, has at the outlet a conical device for flow direction deflection and is surrounded with a circular pipe 3, situated under the water level at some distance from the bottom of the pool. Cold water is taken from the pool bottom and brought into the condensation zone in the outlet area of the circulating pipe. Water hammers which may occur in this zone at the occurrence of the condensation jet instability are not transferred to the pond walls but remain enclosed within sufficiently strong shell of the circulating pipe.
The bubbler circulating device presented in Fig. 3 has other advantages too. With its usage the depth of the pond is practically unlimited. The device operates in a very calm manner, has a comparatively low resistance and assures a stable condensation of the steam. Its injection factor does not depend on the steam flow rate, neither theoretically nor in practice. Fig. 3 shows the main technical characteristics of the condensation module used in Juragua NPP. The diameter of the steam supply pipe in this module is 400 mm. This diameter was chosen due to the specific design requirements, but it can be increased, as it has been shown by the experimental work done in the former USSR.

In order to compete the considerations of a containment with bubbler condenser, one more important problem should be discussed, namely the question of hydrogen removal from the containment in the case of its release into the reactor compartments during the accident. The concentrations of hydrogen potentially possible in a bubbler condenser containment are 3 times higher than in a large dry containment, because the available free volume of the bubbler condenser containment is threefold smaller. Therefore it might seem that the explosive concentration of hydrogen can be reached faster.

In reality it is not so. In the bubbler condenser containment a considerable part of the air (about 60%) is forced from the reactor rooms into the upper compartment and remains there, while the volume in the reactor rooms is filled up with steam. For such a situation the explosive concentration of hydrogen is much higher (up to 17%, according to the available data [7]). Due to this, the safety margin before explosive concentration is reached is the same as in a large dry containment.

In practice, local high concentrations of hydrogen may be the main-source of danger. In order to prevent concentration non-uniformities it is necessary to provide good hydrogen mixing in the volume used for the localization of the accident. It is obvious that the smaller this volume, the easier it is to provide good air mixing.

A schematic diagram of the mixing system used in Juragua NPP is shown in Fig. 4. It includes two circuits for medium circulation in the lower compartment of the containment: mixing circuit and cold hydrogen burn out circuit. In order to assure good circulation in these circuits special water steam ejectors were developed. They work with water supplied by sprinkler system pumps. In this way a high degree of reliability of the system is assured, because all other elements are passive.

The contact device used for hydrogen burning is situated outside the hermetic volume because it needs servicing. The medium being returned into the containment after passing the burning device should be cooled.

The depressurization containment with bubbling condensation used in Juragua NPP is the modification of the containment based on the same concept and realized in a number of WWER-440 units in former Soviet Union and in some countries of Eastern Europe. These units can be classified as belonging to the second generation of WWER-440 reactors.

The main distinction between these units and the Juragua NPP is the usage of traditional rectangular structures for creating the containment volume for accident localization purposes. This determines also the main deficiency of those systems. A
schematic drawing of a NPP with rectangular bubbler condenser containment is shown in Fig. 5. Its central reactor servicing hall, similarly as in the first generation of WWER-440 units, is not included into the zone of accident localization system, while the air traps are located in a separate building built especially for this purpose next to the reactor building. The air is enclosed and kept in the air traps by means of double check valves, not by means of a water seal as is done in Juragua NPP. In a rectangular bubbler condenser system twelve bubble tiers are used, the water level in each of them being 0.5 m, while in Juragua a pond of 4 m depth has been applied.

Thus Juragua NPP containment can be treated as a further step in the development of depressurization containment with bubbling-vacuum system, which provides improvements in the field of reliability, economics and environment and public protection.

It would be premature to describe possible further developments of the bubbler condenser systems or similar systems providing containments with fast depressurization possibilities, because the reactors of the third generation are now just at the stage of initial development.

REFERENCES


<table>
<thead>
<tr>
<th>Containment type</th>
<th>Full pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design pressure</td>
<td>5 MPa</td>
</tr>
<tr>
<td>Inside diameter</td>
<td>45 m</td>
</tr>
<tr>
<td>Height</td>
<td>67 m</td>
</tr>
<tr>
<td>Thickness</td>
<td></td>
</tr>
<tr>
<td>dome</td>
<td>1.1 m</td>
</tr>
<tr>
<td>cylindrical part</td>
<td>1.2 m</td>
</tr>
<tr>
<td>Free volume</td>
<td>66 000 m³</td>
</tr>
<tr>
<td>Construction</td>
<td>Prestressed reinforced concrete</td>
</tr>
<tr>
<td>Number of penetrations</td>
<td></td>
</tr>
<tr>
<td>pipes</td>
<td>196</td>
</tr>
<tr>
<td>cables</td>
<td>660</td>
</tr>
<tr>
<td>Design rate leakage</td>
<td>0.3% per day</td>
</tr>
<tr>
<td>Sprinkler system</td>
<td></td>
</tr>
<tr>
<td>number of trains</td>
<td>3</td>
</tr>
<tr>
<td>supply capacity per train</td>
<td>750 m³/h</td>
</tr>
<tr>
<td>number of nozzles</td>
<td>25</td>
</tr>
</tbody>
</table>
### Table 2 MAIN TECHNICAL CHARACTERISTICS
**OF THE CONTAINMENT OF JURAGUA NPP WITH WWER 440**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Containment type</td>
<td>Depressurization</td>
</tr>
<tr>
<td><strong>Design pressure</strong></td>
<td>2.5 MPa</td>
</tr>
<tr>
<td><strong>Inside diameter</strong></td>
<td>45 m</td>
</tr>
<tr>
<td><strong>Height</strong></td>
<td>60 m</td>
</tr>
<tr>
<td><strong>Thickness</strong></td>
<td></td>
</tr>
<tr>
<td>- dome</td>
<td>1.5</td>
</tr>
<tr>
<td>- cylindrical part</td>
<td>1.5</td>
</tr>
<tr>
<td><strong>Free volume</strong></td>
<td></td>
</tr>
<tr>
<td>- lower compartment</td>
<td>17 700 m³</td>
</tr>
<tr>
<td>- upper compartment</td>
<td>44 200 m³</td>
</tr>
<tr>
<td><strong>Construction</strong></td>
<td>reinforced concrete</td>
</tr>
<tr>
<td><strong>Number of penetrations</strong></td>
<td></td>
</tr>
<tr>
<td>- pipes</td>
<td>152</td>
</tr>
<tr>
<td>- cables</td>
<td>790</td>
</tr>
<tr>
<td><strong>Design leakage rate</strong></td>
<td>1 % per day</td>
</tr>
<tr>
<td><strong>Sprinkler system</strong></td>
<td></td>
</tr>
<tr>
<td>- number of trains</td>
<td>3</td>
</tr>
<tr>
<td>- flow capacity per train</td>
<td>240 m³/h</td>
</tr>
<tr>
<td>- number of nozzles</td>
<td>40</td>
</tr>
<tr>
<td><strong>Bubbler condenser</strong></td>
<td></td>
</tr>
<tr>
<td>- number of tanks</td>
<td>4</td>
</tr>
<tr>
<td>- total water storage</td>
<td>110 m³</td>
</tr>
<tr>
<td><strong>Hydrogen burning out system</strong></td>
<td></td>
</tr>
<tr>
<td>- number of exchanges per hour</td>
<td>0.7</td>
</tr>
<tr>
<td>- extraction flow rate</td>
<td>60 m³/h</td>
</tr>
<tr>
<td>- for burning out device</td>
<td></td>
</tr>
</tbody>
</table>
LIST OF FIGURES

1. Cylindrical containment with bubbler condenser vacuum system
   a) Schematic principle of operation
   b) Elevation view of Juragua NPP containment
   c) Plan view of Juragua NPP containment
2. Hydraulic characteristics of bubbling condensing device performance
3. Circulating bubbling device developed for Juragua NPP
4. Hydrogen removal system used at Juragua NPP
5. WWER 440 containment with rectangular bubbler condenser system
6. Hydrogen removal system proposed for WWER 440 containment with rectangular
   bubbler condenser system
7. Experimental stand for accident localization system studies in Zugros
8. Water preparing tank in Zugros installation
9. Containment simulator in Zugros installation
10. Air trap simulators in Zugros installation
11. Simulator of the bubbler condenser tower in Zugros installation
1. Cylindrical containment with bubbler condenser vacuum system

   a) Schematic principle of operation
b) Elevation view of Juragua NPP containment

1-steel-lined reinforced concrete shell; 2-reactor vessel; 3-ventilation equipment; 4-annular shield building; 5-electrical equipment compartment; 6-borated water storage tank compartment; 7-emergency core cooling system components; 8-diesel generators

1. Cylindrical containment with bubbler condenser vacuum system
2. Hydraulic characteristics of bubbling condensing device performance
3. Circulating bubbling device developed for Juragua NPP

Technical characteristics of the module of "Huragua" NPP circulating bubbling device:

- Maximum flow rate through module: 50–65 t/h
- Flow rate factor: 0.85
- Injection factor: 20–30
- Pressure difference on circulating bubbling device at pressure increase rate:
  - 1.4 bar/s: 0.7 bar
  - Pressure pulsations value on the tank walls: -0 bar
  - Pressure pulsations value in the shell: 3 bar
  - Pressure pulsations value in the rotary tube: 4.5 bar
  - Pressure pulsations value in the pipe: 5 bar
4. Hydrogen removal system used at Juragua NPP

1 - sprinkler system pumps; 2 - valve with electrodrive; 3 - sprinkler system header with nozzle; 4 - return valve; 5 - flowmeter; 6 - ejector for medium mixture in hermetic zone; 7 - excess pressure valve; 8 - blowdown; 9 - heater; 10 - recombinater; 11 - heatexchanger.
5. WWER 440 containment with rectangular bubbler condenser system

1-reinforced concrete walls and floors; 2-steam generator; 3-primary coolant pump;
4-reactor vessel; 5-protective shielding cap; 6-sprays; 7-spray system pump;
8-heat exchanger cooler for water drawn from sump; 9-tunnel connecting steam
generator compartment with bubbler-condenser tower; 10-reinforced concrete walls;
11- suppression pool system at each level; 12-air trap volume; 13-check valve;
14-shaft convecting steam and air to tray levels; 15-tray; 16-steam channels;
17-deflector cover tray; 18-plenum region cover; 19-overflow discharge; \( V_1 \)-steam generator compartment; \( V_2 \)-pump compartment; \( V_3 \)-shaft inside bubbler condenser tower; \( V_5 \)-air trap volume
6. Hydrogen removal system proposed for WWER 440 containment with rectangular bubbler condenser system
7. Experimental stand for accident localization system studies in Zugros
8. Water preparing tank in Zugros installation
9. Containment simulator in Zugros installation
Air trap simulators in Zugros installation
11. Simulator of the bubbler condenser tower in Zugros installation
V-1 ACCIDENT LOCALIZATION SYSTEM
UPGRADING TO COPE WITH LARGE
LOCA SCENARIOS

P. Baláž
Power Equipment Research Institute
Tlmače, Slovak Republic

VIENNA, AUSTRIA
29 NOVEMBER - 3 DECEMBER 1993
Requirements for ALS upgrading

Nuclear Regulatory Authority (ČSKAE) Decision No 5/91:

"V1 operation after 1995 only in case of its nuclear safety enhancement to a level comparable to European standards which should be achieved via a reconstruction"

Further conditions for ALS

1) To cope with large LOCA 2 x DN 500 (as no LBB approach existed in '91)

2) No unfiltered atmospheric venting

3) To make V1 ALS parameters close to those of V2
First bids for ALS upgrading

1) ŠKODA: Connection of the existing hermetic zone to an external steel pressure tank containing passive sprinklers

2) ENERGOPROJEKT and WESTINGHOUSE: Connection of the existing hermetic zones (of both Units) to one VBS (Vacuum Bargotage System) of the same type as at V 213 model Units

3) Bohunice NPP: External pressure tanks with non-qualified condensers and water siphon ideas

4) VÚEZ 1: Atmospheric venting of the first pressure maximum combined with FVS

5) VÚEZ 2: Internal jet condensers

6) Westinghouse: Ice-condensers

7) SIEMENS: Venturi scrubber in 2 stages combined with unfiltered discharge to the outside atmosphere
Recommendation of Assessing Commission (chaired by VÚJE)

The focus should be on the alternative No 3 combined with some ideas of the VÚEZ proposals (FVS, jet condensers), and on the alternative No 2. As a back-up the alternative No 2 is considered.

Choice of the ultimate alternative

Localization of jet condensers inside the hermetic zone: after seismic upgrading (installation of "gerb" viscodampers) there is not enough space left.

Both of the two remaining alternatives were assessed by an experts' audit.

1st alternative: JCS (Jet Condenser System) with FVS (Filtered Venting System)

2nd alternative: VBS (Vacuum Barbotage System)

Comparison of 104 items with the following result:
- the same for both systems 70
- advantages of JCS 29
- advantages of VBS 5
The most important advantages of JCS:

- JCS is an innovation of VBS (no VBS design for newer VVER NPPs, e.g. the Juragua NPP, Cuba, is equipped with JCS)

- the idea of 2 air traps in JCS with water siphon is more reliable than 1 barbotage tower with separation of both Units by large area folding flaps with rupture membranes

- cylindrical structures of JCS opposed to rectangular ones of VBS

- condenser pool only on the ground floor (seismic events)

- absence of sophisticated valves (VBS: 24 back valves DN 500 + 24 special valves DN 250 versus JCS: none)

- higher flexibility in accident management

- no condenser pool by-pass scenarios

Advantages of VBS:

- single element failure with lower sequences

- lower swelling ("relative" advantage)

- lower chugging effects expected

Result: Future work is to be concentrated only on JCS with FVS.
Pre-design study was completed
Calculational and experimental data:

a) **Accident analysis** (Δp and T transients)
done by VÚJE Trnava, TRACO code
Maximum Δp 75 kPa in HZ (Fig 1)
                 45 kPa in air traps (Fig 2)

b) **Experiment with JC, scale 1:1**
done by VÚEZ Tlmače + VNIIAES Moscow (subsidiary Kashira)
JC with D_{exv} 400 mm
Test rig - Fig 3
Installed measurements - Fig 4
Test scenarios:
- long-term 1.5-3.5 kg/s
- short-term (simulation of LOCA) 30-40 kg/s
  (in maximum region)

Results:
- pressure oscillations (caused by chugging) max ±10 kPa
  without impact on structures (Fig 5)
- no pulsations with risk of piping damages
- simulation of large-LOCA-caused pool heating  + 20 K
- no channelling observed
- swelling much lower than calculated

Conclusion (in the presence of NRA representative):
JC is a pertinent equipment for condensation function in ALS.
c) **Verification of water siphon function**
done by VÜEZ, JC scale 1:1
Test rig and measurement scheme - Fig 6
Condition: no channelling (water seal opening) at the most conservative pressure dynamic increase upon the water level (50 kPa/2s)
Result: max \( h \sim 0.5 \text{ m} \) (a large reserve to 1.0 m) 
(see Figs 7, 8)

d) **Simulation testing on the whole ALS model**
done by VÜEZ Tlmače
System scale 1:50\(^3\) (\( \approx 1:10^5 \))
based on the HZ model tested at the Slovak Technical University, Bratislava, Engineering Faculty (another paper)
Model scheme - Figs 9, 10
Measurement scheme - Fig 11
First results (experiments are going on):
- measured pressure transients in good correspondence with the those calculated, see Figs 12, 13
- main goals of modelling: demonstration, qualitative confirmation of the proposed ALS function, assessment of ALS response to various component parameter changes

**ALS able to cope with 2 x Ø 500 LOCA as DBA**

All the above results of calculational and experimental work have led to and confirmed the following proposal for the existing V-1 confinement upgrading and backfitting:
Confinement upgrading and backfitting purposes:

a) substantial increase in hermetic zone volume (up to a value comparable to that of V 213)

b) steam-air mixture condensation with the purpose of hermetic zone pressure reduction below 100 kPa(g)

c) entrapment of non-condensables in air traps with subsequent filtered venting, and

d) hermetic zone leaktightness enhancement up to a level required by the SR Nuclear Regulatory Authority.

ALS fulfills all items mentioned above.

ALS comprises 2 main systems (combining condensation and filtration functions):

- JCS
- FVS

and many other additional systems (water treatment, normal ventilation, drainage, power supply, I & C etc.) not being the subject of this presentation.
JCS - Jet Condenser System

Description of the most important parts:
(see Figs 14, 15, 16, 17)

- HZ: removal of relief flaps and ceiling of their corner location making thus an opening with a cross section of about 40 m² (Fig 15)

- interconnecting piping between HZ and an air trap is a slight difusor DN 6-8 m with suitable compensators (Fig 16)

- in the air trap, the piping is connected to an expansion "bell" directing the accidental air-steam mixture to the orifices of JCs, located in the plate

- the plate standing on the circular wall creating thus with the base a condensation pool and connecting through its openings the volume under the pool water level with the air trap free volume

- air trap: 40 m high cylindrical vessel Ø 27 with hemispherical cap, reinforced, lined

- condensation pool: 3 m high, volume of 1350 m³
-JC (Fig 17): 200 pieces, condensation function see Fig 16; condensation takes place in MC (Mixing Chamber) where this together with the expansion effect creates an underpressure causing water suction from the pool bottom

- air traps connection: common free volume of 26000 m³

(Note: Civil structure elements and problems in detail – see another presentation)

- water treatment: in addition to its "normal" tasks it enables by means of connecting lines (not shown in the figs) filling the 800 m³ tank (in case of a BDBA) with water from condensation pool (one of possible measures against strainer clogging)

- water siphon: divides the damaged and the intact Units by means of water column in the JC inlet piping in the air trap of the intact Unit (8 m - 80 kPa)
Main features of FVS (Figs 18, 19, 20, 21)

- connection to HZ through a ventilation system SV-2 (DN 600)

- almost all piping on FVS DN 600

- filter: scrubber qualified type, cca 5-6 kg/s, operation at lower $\Delta p$ possible

- blower: to enable a forced ventilation through the filter to keep HZ at atmospheric (slight subatmospheric) pressures, independent power source, pressure ratio 1.4, 20000 m$^3$/h
Modes of ALS operation (Fig 18 as an example only for HZ1)

at DBA:

HZ - air traps
HZ - filter - HZ, recirculation
air traps - filter - air traps, recirculation (both if needed)
air traps - stack (active)
HZ - stack (active) (both at the end of liquidation)

at various BDBA:

HZ - (air traps) - filter - stack (passive)
HZ - (air traps) - filter - stack (active)
other options as at DBA

New concept for ALS

Application of LBB approach to V-1 NSSS enables to reduce the strength of NRA requirements:
If the LBB approach is approved then it will be possible to redefine the DBA (instead of 2 x DN 500 LOCA 1 x DN 200 (equiv.) LOCA; then 2 x DN 500 will be a BDBA scenario.
This new philosophy of ALS has a furtherance of IAEA mission, July '93, Piešťany.
There are two main approaches available:

1. re-scaling the ALS able to cope with 2 x DN 500 DBA to that for 1 x DN 200 (this option is relatively very expensive)

2. to design a new ALS with functioning qualitatively different from that of the proposed one

This option is more interesting and a few variants are being analysed now:

- re-evaluation of some older ideas

* Sulzer offer with the so called "high flow" filter

* Siemens offer with 2-stage condensation and filtration

* Westinghouse offer with vacuum barbotage tower
All these options need for BDBA (now 2 x DN 500) mitigation a new opening in the hermetic boundary. In order to eliminate disadvantage VÜEZ proposes an ALS for DN 200 DBA (and 2x DN 500 BDBA) as follows:

- to remove flap valves together with their burden parts
- in the established new free volume to install a condensation pool with about 200 m³ water inventory
- to install "horizontal ejector" type condenser (Fig 22) into this pool
- to connect the flap valve openings (left after valve removal) to the outer air trap keeping hermetization at DBA and venting at BDBA
- to combine this concept with PSS (Passive Sprinkler System) inside the HZ and FVS of the same design as for 2 x DN 500 ALS

Horizontal ejector type condenser is a proposal of an expert group of NTC Moscow (Scientific Centre of Russian Nuclear Regulatory Authority).

First experiments were conducted at the experimental basis in Zugres, Ukraine. If this variant is chosen further programme will be planned based on pre-design analysis.
Further V-1 HZ leaktightness enhancement

Two main objectives:

a) To keep the (after the small reconstruction) obtained leaktightness level:
   * regular maintenance of elements on the hermetic boundary
   * during each outage - search for leaks, hermetization, integrated leak rate test

b) To apply new procedures to hermetize detected leaks with the aim to reduce leak rate even further (to a half of that existing):
   * installation of new or additional hermetic coverings (by welding) on liner and penetrations (Fig 23)
   * improvement of rubber sealings (a new one is being developed)
   * application of new hermetization procedures to some elements (shaft penetrations, bearing structures on the floor, locking mechanisms on the doors and air locks, special drainage etc.) original design of which is not satisfactory with regard to reliability of sealing
   * doubling of relevant valves on the hermetic boundary (Fig 24)
   * application of new and reliable sealing coatings
   * supporting work, e.g. making all locations on hermetic boundary easily accessible from inside of the HZ
Conclusion

* Proposed V-1 ALS can cope with 2 x DN 500 DBA.

* Work on V-1 ALS able to cope with DN 200 DBA and to mitigate DN 500 BDBA will have been finished by April 1994.

* Further leaktightness improvements are going on on the V-1 HZ boundary during outages with the aim to reduce the existing leak rate by 50%.
Fig. 1

HZ overpressure (kPa)

HZ temperature (°C)
Fig. 2

Air trap overpressure (kPa)

Air trap temperature (°C)

Fig. 2
1 High pressure vessel (20 MPa; 365°C; 0.91 m³)
2 Mixing chamber
3 Rupture discs
4 HZ mock-up (25 m³)
5 JC (see fig. 17)
6 Condensation pool (water level 3.1 m, water volume 6 m³)
7 Pressurized air station
8 Steam network, 24 MPa, 545°C
9 Feedwater network, 32 MPa, 270°C
10 Interconnecting lines and valves (not all valves provided)

Fig. 3. VNIIAES Moscow (Kashira) test rig scheme for JC testing
Fig. 4 JC test rig thermo-hydraulic measurements
Fig. 5  Pressure oscillation spectra in JC pool in various times (small break)
Fig. 6 Measurement of the water siphon function on test rig in VUEZ Tlmače.
Fig. 7 Pressure oscillations of water level in JC pool during its lock function.
Fig. 8 Water level swaying in the JC inlet pipe during its lock function.
Fig. 9 High pressure part of ALS mockup in VÚEZ Tlmače
1 Bearing frame
2 Air trap II
3 Connecting piping
4 Air trap I
5 JC model
6 Piping
7 Inlet to JC
8 Outlet from HZ
9 HZ model

Volumes: \((2+3+4)=200 \, \text{dm}^3\), Pool in 5 = 10 \, \text{dm}^3,
\((7+8+9)=64 \, \text{dm}^3\)

Fig. 10 Low pressure part of ALS mock-up in VÖEZ Tlmače
Fig. 11  ALS mock-up measurement scheme
Fig. 12  ALS mock-up pressure transient at the JC inlet and in the primary circuit model vessel
Fig. 13 ALS mock-up pressure transient in various locations of the HZ model
1,2 HZ of Unit 1, 2
3,4 Air traps
5,6 Condensing pools
7,8 800 m³ tanks (for SS and ECCS)

9,10 SS-Sprinkler systems
11,12 Vacuum breakers
13,14 Existing leakages
15,16 Jet condensers
17 New water treatment systems
18 Existing water treatment systems
19 Blower
20 Filtered venting system

Fig. 14 ALS scheme
Fig. 15: New opening in the HZ boundary for ALS

Part of existing opening to be removed
Fig. 16 Air trap - main dimensions
Fig. 17  Jet condenser for ALS

Mixing Chamber

WATER

STEAM-AIR MIXTURE

3000

9000

1020

1000

Φ26.7

Φ800.6

Φ902.4
Fig 18 FVS simplified function scheme
Linking pipings of FVS:
- from HZ 1,2 to FVS (FT) header
- from air trap 1,2 (SLH 1,2) to FVS header
- from FVS header to filter through active and passive (by-pass with rupture disc) train
- from filter to HZ 1,2 (recirculation train)
- from filter to air trap 2 (recirculation train)
- from filter to stack (VK)

Fig. 19 FVS linking to SLH, HZ and stack
Fig. 20 Possible solution of FVS connection to HZ through ventilation system SV-2
Fig. 21 Axonometric view of FVS and JCS main elements and piping location
Fig. 22  Possible application of horizontal condensators inside the HZ of V-1
Fig. 23 Installing new hermetic coverings on V-1 penetrations.

1... liner
2... new covering
3... hermetic collar
4... penetration (stable part)
Fig. 24 Doubling of ventilation system hermetic valve
UPGRADING OF CONFINEMENT
OF NPP KOZLODUY - UNIT 3 AND 4

E. Balabanov
Nuclear Safety and Automation Division
Energoproekt
Sofia, Bulgaria

VIENNA, AUSTRIA
29 NOVEMBER - 3 DECEMBER 1993
I. INTRODUCTION

KOZLODUY NPP COMPRISSES 6 NUCLEAR POWER UNITS EQUIPPED WITH PRESSURIZED WATER REACTORS - TYPE WWER.


DURING THE LAST FEW YEARS MANY SAFETY IMPROVEMENTS HAVE BEEN IMPLEMENTED IN KOZLODUY. THE NEW APPROACH OF NUCLEAR ENERGY MANAGEMENT IN BULGARIA IS THE IMPROVEMENT OF SAFETY TO BE CONTINUOUS. ONE OF THE FURTHER SAFETY MODIFICATIONS COULD BE THE IMPROVEMENT OF THE CONFINEMENT CAPABILITY OF THE V230 MODEL.


TO UPGRADE THE SAFETY OF WWER 440/V 230, A VENTING SYSTEM IS PROPOSED WHICH ALLOWS A FILTERED PRESSURE RELIEF IN EVERY PHASE OF A DESIGN BASIS OR SEVERE ACCIDENT. THE SULZER-EWI CONCEPT FORESEES THE INSTALLATION OF TWO FILTERS;
ONE FOR THE HIGH INITIAL FLOW RATES DURING THE BLOWDOWN PHASE AND ANOTHER FILTER - BASED ON THE SULZER-EWI CONTAINMENT FILTERED VENTING SYSTEM - FOR THE PHASE AFTER THE BLOWDOWN, WHEN THE FLOW RATE IS LOW.

II. DESCRIPTION OF THE WWER-440/V 230 CONFINEMENT

The hermetic zone of WWER-440/V 230 is a dry confinement with 22 interconnected steel lined compartments. The total free volume of the confinement is approx. 12000 m³ (Fig.1, 2).

The design pressure of the V230 confinement is 1 bar internal overpressure. Protection of the confinement is performed by activation of a spray system and 9 counterweight type flap valves, called back pressure valves, located in the steam generator section of the confinement. The flap valves are open respectively one at 0.6 bar and 8 at 0.8 bar internal overpressure. They are venting directly to the atmosphere.

The considered maximum design basis accident (MDBA) is the break of a pipe of 100 mm diameter fitted with an orifice of Ø 32mm. The accident can be grouped to the class of small loss of coolant accidents (LOCA). Assuming that the spray system is operable, the flap valves are not required to open in case of small LOCA (Fig.3). If the spray system is not operable, the back pressure valve will open during small LOCA (Fig.4).
III. UPGRADING OF CONFINEMENT (PROBLEMS TO BE SOLVED)

The design status is of "high safety concern" [2] as there is insufficient defence in depth and violation of the last physical barrier under certain circumstances.

The V230 confinement is not designed for a large break (LB) LOCA defined as double ended guillotine break of a main circulation pipe (Fig. 5, 6, 7, 8).

In these cases the confinement integrity is not guaranteed.

Another problem is the ability of the confinement to handle conditions resulting from severe reactor accidents. Significant amounts of hydrogen would be generated under severe accidents with core damage and these would be released to the relatively small confinement volume. Although the confinement has a very high leak rate, it is judged to be insufficient to prevent the accumulation of explosive concentrations of hydrogen in the building. A major hydrogen explosion could cause the failure of the confinement structure, increasing accident severity and the release of radioactivity to the environment. Even if the confinement structure would maintain its integrity, the high confinement leak rate would result in significant radioactive release to the environment under severe accident conditions. The requirement towards the containment to prevent large releases following severe accidents is not met. A modernization aimed at solving these problems for a reasonable spectrum of events will greatly reduce the risk.

Possible solutions of hydrogen control should be investigated, such as hydrogen igniters and/or recombiners.
AS WELL AS THE POTENTIAL OF FILTERED VENTING TO REDUCE THE RADIOACTIVE LEAKS.

THE IMPLEMENTATION OF PRACTICAL MEANS OF CONTROLLING RADIOACTIVE RELEASES FOLLOWING SEVERE ACCIDENTS WILL MITIGATE THE CONSEQUENCES OF THIS KIND OF ACCIDENTS. FOR ACHIEVEMENT OF THIS THE FOLLOWING ACTIONS SHOULD BE ADDRESSED:

- DETERMINE THE ABILITY OF STRUCTURE TO WITHSTAND LARGE BLOWDOWN FORCES.

- EVALUATE AND UPGRADE AS NECESSARY AND PRACTICAL THE RELIEF VALVES.

- DETERMINE THE POTENTIAL FOR IGNITERS TO SIGNIFICANTLY REDUCE HYDROGEN EXPLOSION PROBLEM.

- BASED ON RESULTS OF THE ABOVE LISTED ANALYSES, DETERMINE THE PRACTICALITY OF INSTALLING A SEVERE ACCIDENT FILTER WITH FORCED VENTILATION OF THE CONFINEMENT TO MAINTAIN SLIGHT VACUUM AFTER INITIAL BLOWDOWN.

- DETERMINE OVERALL PRACTICALITY, COST EFFECTIVENESS FOR SPECIFIC PLANT, IMPLEMENT AS WARRANTED.

IV. CONCEPTUAL DESIGN OF THE V 230 CONFINEMENT UPGRADING WITH THE SULZER-EWI SYSTEM

IV.1 GENERAL DESIGN CRITERIA

THE CONCEPT OF THE DRY CONFINEMENT DESIGNED FOR 1 BAR INTERNAL OVERPRESSURE IS ADHERED TO. DURING A LARGE LOCA OR A SEVERE ACCIDENT, THAT IS, WITHIN THE NEW DESIGN BASIS LOSS OF
COOLANT ACCIDENT (DBA-LOCA) AND BEYOND THE NEW DESIGN BASIS ACCIDENT, THE INTEGRITY OF THE EXISTING CONFINEMENT IS PROTECTED BY FILTERED VENTING. AS THERE IS NO DIRECT VENTING TO THE ATMOSPHERE, THE RELEASE OF ACTIVITY TO THE ATMOSPHERE IS CONTROLLED.

THE SEQUENCE OF EVENTS OF A LARGE LOCA CAN BE DIVIDED INTO FOUR PHASES:

- **Blowdown**, characterized by rapid depressurization and intense break flow, initially high, but then rapidly decreasing.

- **Refill**, which occurs when the break flow stagnates and the supplied water begins to refill the vessel. During this phase the core is filled with steam and cooling deteriorates, causing fuel cladding temperature to rise rapidly.

- **Reflood**, which is defined as starting when the water level reaches the lower edge of the core. The maximum fuel cladding temperature is reached during this phase.

- **Long-term cooling** which starts when the cladding temperature has dropped to normal values.

During the blowdown phase the fuel elements and their claddings are still cooled by the water-steam mixture escaping from the reactor pressure vessel. Therefore, only minor activity releases are to be expected during the blowdown phase. The fuel cladding temperature starts to increase at the beginning of the refill phase. Therefore, a higher probability release is to be expected after the blowdown phase.

Considering the high steam flow rate of the blowdown with minor activity release, SULZER-EWI propose the following configuration of the V 230 confinement filtered venting system:
A) A high flow filter for the blowdown phase of a large LOCA. With respect to the very high initial steam flow, the high flow filter has to be designed to allow the condensation of nearly all steam released from the confinement during a DBA-LOCA. Most of the active aerosols carried by steam will condense, will be retained by the water inventory and in this case the decontamination factor is very high. Due to the low activity of the blowdown, a decontamination factor for aerosols and elemental iodine carried by non-condensible gases of 200 resp. 100 shall be sufficient.

B) A low flow filter for the post-blowdown phases of a large LOCA. In view of the high activity releases, a minimum decontamination factor of 1000 for aerosols and of 1000 for elemental iodine are required.

IV.2. The LOCA from DY 200 mm break in the WWER-440.

In order to estimate the general design data of the high and low flow filters, it is important to assess the characteristics of a larger LOCA for a WWER-440 type of reactor. In the WWER-440 the large LOCA is defined as a double ended guillotine break (DEGB) of a pipe with a diameter of 200 mm connected to the primary coolant loop pipe with a diameter of 500 mm. As a result of the LBB-study (Leak Before Break), SULZER-EWI is postulating only the break of the largest (200mm) pipe, but not the primary coolant pipe. The justification for this assumption is to be found in the LBB-study. The primary coolant pressure is 122.6 bar. The total water content of the primary system is estimated to be approx. 200 tons.

Considering the 200 mm pipe diameter and pressure of the WWER-440, estimation of a large LOCA based on a simplified model of the WWER-440 is:
BLOWDOWN PHASE: DURATION 300 SECONDS, INITIAL STEAM FLOW APPROX. 1000 KG/S, STEAM TEMPERATURE APPROX. 325°C, REFILL AND REFLOOD PHASE: THE DURATION OF THESE PHASES ARE NOT RELEVANT FOR THE SIZING OF THE HIGH FLOW AND LOW FLOW FILTERS.

THE ESTIMATION OF 300 SECONDS FOR THE BLOWDOWN TIME IS ALSO CONSISTENT WITH THE DATA FOR WESTERN PWRS, (LB LOCA) WHERE THE BLOWDOWN PHASE CEASES AFTER ABOUT 15 SECONDS, WHEN THE Pressures IN THE PRIMARY SYSTEM AND THE REACTOR CONTAINMENT ARE EQUALIZED AT ABOUT 4-5 BAR AND THE BREAK FLOW CEASES. IN THE WESTERN PWRS A BREAK FLOW AREA CORRESPONDING TO A DIAMETER OF 80 UP TO 250 MM IS CALLED MEDIUM LOCA.

THE POSITIVE SAFETY CHARACTERISTICS OF THE WWER IMPOSE LESS STRINGENT REQUIREMENTS ON THE REFILL AND REFLOOD PHASES, SINCE AFTER 300 SECONDS THE THERMAL POWER RELEASED BY THE FISSION PRODUCTS HAS DECREASED FROM 4.9% (AFTER 15 SECONDS) TO 2.81% OF THE REACTOR NOMINAL POWER. THE BLOWDOWN WILL CONTRIBUTE TO THE REMOVAL OF THE DECAY HEAT. WHEN THE BLOWDOWN PHASE ENDS, THE RESIDUAL THERMAL POWER TO BE EVACUATED IS 37 MW. ASSUMING A DBA-LOCA, THE EXISTING SAFETY INJECTION PUMPS WILL PROVIDE MORE THAN ENOUGH WATER TO COMPENSATE THE WATER BOIL-OFF FROM THE CORE DUE TO THE DECAY HEAT. THE STEAM RESULTING FROM THE WATER BOIL-OFF WILL HAVE TO BE RELEASED FROM THE CONFINEMENT.

ASSUMING A BEYOND DESIGN BASIS ACCIDENT, WHERE NO ACTIVE SAFETY SYSTEMS ARE AVAILABLE, THE CORE WILL START TO MELT DOWN AND NO STEAM WILL REACH THE FILTER.
IV.3. Design data for the high flow filter (HF filter)

The HF filter is designed to cope with the blowdown phase of a 200 mm LOCA and shall operate during the first 5 to 6 minutes. Considering the volume of the hermetic zone of the confinement of approx. 12000m³ only, the blowdown causes a rapid pressure increase in the confinement. 6-7 seconds after a 200 mm LOCA, the pressure in the confinement reaches 2 bar(abs). At this stage, the leak flow rate is approx. 900 kg of steam per second. The temperature of the air/steam mixture entering the filter is estimated to be approx. 200°C. The initial air/steam volumetric flow rate is approx. 1000 m³/s. Since the blowdown will last for a relatively long time and the receiving volume is relatively small (approx. 1/4 compared to Western style pressure containments), it is advisable to allow for the discharge of the full initial steam flow, provided that this is calculated according to a best-estimate method.

Therefore, the design data for the high flow filter are:

<table>
<thead>
<tr>
<th>MEDIUM</th>
<th>AIR/STEAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRESSURE</td>
<td>1.6 - 2 bar(abs)</td>
</tr>
<tr>
<td>TEMPERATURE</td>
<td>200 °C</td>
</tr>
<tr>
<td>MASS FLOW</td>
<td>900 kg/s</td>
</tr>
<tr>
<td>VOLUMETRIC FLOW</td>
<td>1000 m³/s</td>
</tr>
</tbody>
</table>

VI.4. Design data for the low flow filter (LF filter)

The LF filter is designed to protect the confinement after the blowdown phase and is sized to remove the decay heat after 300 seconds, that is, for 37 MW. At a pressure of 1.8 bar, with a specific heat of evaporation of 2210.8 kJ/kg this results in a steam flow of 16.8 kg/s.
INITIALLY THE CONFINEMENT OF THE WWER-440 IS FILLED WITH AIR. HOWEVER, 300 SECONDS AFTER A 200 MM LOCA, ONLY MINOR QUANTITIES OF AIR ARE TO BE EXPECTED IN THE HERMETIC ZONE. THEREFORE, THE HERMETIC ZONE IS ASSUMED TO BE FILLED WITH SATURATED STEAM AT 2 BAR (ABS) OR LESS. THE TEMPERATURE IS EXPECTED TO BE THE SATURATION TEMPERATURE, APPROX. 120°C. WITH THE SPECIFIC VOLUME OF THE STEAM, 0.885 M³/KG, IT FOLLOWS THAT THE LOW FLOW FILTER HAS TO BE DESIGNED FOR 15 M³/S.

POSTULATING A BEYOND DESIGN BASIS ACCIDENT, OTHER GASES MAY BE RELEASED SUCH AS HYDROGEN, CO, CO₂. THE LOWEST OPERATING PRESSURE OF THE LF FILTER IS GIVEN BY ITS TOTAL PRESSURE DROP AND COULD BE 1.2 BAR (ABS).

**DESIGN DATA FOR THE LOW FLOW FILTER:**

<table>
<thead>
<tr>
<th>MEDIUM</th>
<th>SATURATED STEAM, NONCONDENSIBLE GASES</th>
</tr>
</thead>
<tbody>
<tr>
<td>DESIGN FLOW</td>
<td>17 KG/S</td>
</tr>
<tr>
<td>MAX. PRESSURE</td>
<td>2 BAR</td>
</tr>
<tr>
<td>MAX. TEMPERATURE</td>
<td>120 °C</td>
</tr>
<tr>
<td>MAX. VOLUMETRIC INLET FLOW</td>
<td>15 M³/S</td>
</tr>
</tbody>
</table>

**V. DESCRIPTION OF THE PROPOSED SULZER-EWI CONCEPT**

THE SYSTEM INCLUDES (FIG.9) A HIGH FLOW FILTER (HF FILTER) FOR THE FILTERED BLOWDOWN VENTING WITH A DECONTAMINATION FACTOR OR 200 FOR AEROSOLS AND A LOW FLOW FILTER (LF FILTER) FOR THE FILTERED POST-BLOWDOWN VENTING WITH A MINIMUM DECONTAMINATION FACTOR OF 1000 (FOR AEROSOLS).

THE EXISTING BACK PRESSURE VALVES OF THE WWER-440/V 230 CONFINEMENT ARE REMOVED AND THE CROSS SECTION OF THE BACK
PRESSURE VALVES OPENING IN THE CONFINEMENT IS ENLARGED FROM PRESENTLY APPROX. 8 m² TO APPROX. 17 m². THEN, RUPTURE DISCS ARE INSTALLED INSTEAD OF THE BACK PRESSURE VALVES.

A CONNECTING DUCT OF APPROX. 17 m² CROSS SECTION LINKS THE LOW PRESSURE SIDE OF THE RUPTURE DISCS TO THE VERTICAL INLET DUCT (WITH THE SAME CROSS SECTION) OF THE HIGH FLOW FILTER. A VACUUM BREAKING SYSTEM MAY BE THE CONNECTING DUCT.


THE INITIAL WATER INVENTORY OF THE HF FILTER IS APPROX. 360 M³.

THE LF FILTER VESSEL HAS A WATER VOLUME OF APPROX. 80 M³. IT IS EQUIPPED WITH NOZZLES, STATIC MIXING ELEMENTS AND WITH A THIRD STAGE.

THE LF FILTER IS LOCATED NEAR THE HF FILTER AND IS CONNECTED BY MEANS OF A PIPE WITH 2 ISOLATION VALVES TO THE DUCT AND DISCHARGE TO THE STACK.
THE OPERATION OF BOTH FILTERS IS AS FOLLOWS:

THE OPERATION OF THE HF FILTER IS COMPLETELY PASSIVE. AT A CONFINEMENT PRESSURE TO 1.5 TO 1.8 BAR (ABS) THE RUPTURE DISCS OPEN AND RELEASE THE AIR/STEAM MIXTURE TO THE HF FILTER. THE WATER HAS TO BE EXPELLED FROM THE VERTICAL INLET DUCT AND THE LOWER PLENUM, BEFORE THE STEAM STARTS TO CONDENSE. INITIALLY, THE WATER LEVEL IS AT 4.0 M AND AFTER BLOWDOWN THIS LEVEL INCREASES. AFTER THE BLOWDOWN PHASE THE PRESSURE IN THE CONFINEMENT AND IN THE HF FILTER ARE EQUALIZED AT A VALUE OF 1.2 BAR AND THE WEIGHT OF THE WATER COLUMN IN THE HF FILTER STOPS AUTOMATICALLY THE DISCHARGE TO THE HF FILTER. ONCE THE OPERATION OF THE HF FILTER HAS ENDED, AND ASSUMING THAT THE PRESSURE INSIDE THE CONFINEMENT STARTS TO INCREASE, THEN THE VALVES TO THE LF FILTER START TO OPERATE. THE LF FILTER OPERATES AT A LOWER PRESSURE COMPARED TO THE HF FILTER. INITIALLY, IT IS FORESEEN TO HAVE 1.8 M OF WATER COLUMN IN THE LF FILTER. SINCE THE PRESSURE DROP IN THE INLET AND OUTLET PIPES IS VERY LOW, THE TOTAL PRESSURE DROP OF THE LF FILTER COULD BE IN THE RANGE OF 0.20 BAR. DURING THIS PHASE ALL THE FLOW WILL BE AUTOMATICALLY DIRECTED TO THE LF FILTER, SINCE THE HF FILTER IS ISOLATED BY A WATER COLUMN. IF REQUIRED, ADDITIONAL MEASURES COULD BE ENVISAGED, E.G. MAKE-UP WATER DIRECTED TO THE HF FILTER, TO STOP ITS OPERATION.

THEORETICALLY, IT SHOULD BE POSSIBLE TO HAVE BOTH FILTERS IN PARALLEL WITHOUT VALVES AND HAVE AN AUTOMATIC SWITCH FROM THE HF FILTER TO THE LF FILTER. THIS POSSIBILITY WILL BE EVALUATED AT A LATER STAGE, WHEN THE SYSTEM CHARACTERISTICS AND DETAILED DESIGN WILL BE KNOWN. IN SUCH A CASE THE OPERATION OF THE LF FILTER COULD ALSO BE COMPLETELY PASSIVE.
THE OTHER SAFETY ISSUE IS RELATED TO THE HIGH LEAK RATE OF THE CONFINEMENT. THEREFORE, IT WOULD BE ADVISABLE TO FILTER THE DISCHARGED FLOW FROM THE CONFINEMENT: THIS IS POSSIBLE BY DIRECTING THE LEAKAGES INTO THE CONFINEMENT BY SUCTION. FOR THIS PURPOSE A SPECIAL FAN AND A DUCT WOULD CONNECT THE CONFINEMENT WITH THE LF FILTER. DUE TO THE LOW DISCHARGE HEAD REQUIRED AS WELL AS THE LOW SUCTION HEAD (-5 KPA) IT WOULD BE POSSIBLE TO SELECT A CENTRIFUGAL FAN. DUE TO THE SINGLE FAILURE CRITERIA, WE RECOMMEND TO INSTALL 2 FANS. SUCH A SYSTEM COULD ALSO BE USED DURING A SMALL ACTIVITY RELEASE INSIDE THE CONFINEMENT WHEN THE HEATING AND VENTILATION SYSTEMS ARE NOT WORKING PROPERLY.

VI. DEVELOPMENT OF THE PROJECT

THE DEVELOPMENT OF THE PROJECT IS PLANNED TO BE SPLIT INTO FOUR MAJOR PHASES AS FOLLOWS:

- CONCEPT PHASE (COMPLETED)

- PROJECT PHASE P1 (ANALYSES, QUALIFICATION TESTS AND PSAR)

- PROJECT PHASE P2 (ENGINEERING)

- PROJECT PHASE P3 (CONSTRUCTION AND IMPLEMENTATION).

ACTIVITIES IN PROJECT PHASE P1:

- BLOW DOWN ANALYSES AND CONFINEMENT PRESSURE RESPONSE WITH THE TWO VENTING FILTER UNITS
- QUALIFICATION TESTS FOR HIGH FLOW FILTERS
- ADAPTATION OF FILTER TECHNOLOGY TO WWER REACTORS
- BASIC DEFINITION OF SYSTEMS
VII. CONCLUSIONS

The proposed concept fulfills all the requirements expressed in the TECDOC-640 in relation to the confinement capability.

The hydrogen hazard is mitigated by the forced filtered venting system but its analysis is not considered in this concept.

The next phase would be a feasibility study with a cost evaluation for Kozloduy NPP, Units 3 and 4.

VIII. REFERENCES


IX. **List of Figures**

1. Plan of the Hermetic Zone at Levels 5.4 m and 6.3 m
2. Cross Section of the Reactor Building
3. Pressure Trend in the Hermetic Zone during LOCA: 100 mm Pipe Rupture with an Orifice with De=32 mm. Total Free Volume of Hermetic Zone 9300 m³, Confinement Spray in Operation
4. Pressure Trend in the Hermetic Zone during LOCA with De = 32 mm, No Confinement Spray
5. Pressure Trend in the Hermetic Zone during LOCA with De = 200 mm, No Confinement Spray
6. Pressure Trend in the Hermetic Zone during LOCA 2x100% DE 200 mm, No Confinement Spray
7. Pressure Trend in the Hermetic Zone during CL LOCA 1x100% DE 500 mm, No Confinement Spray
8. Pressure Trend in the Hermetic Zone during CL LOCA 2x100% DE 500 mm, No Confinement Spray
9. Proposal of Sulzer-EWI for the Confinement Upgrading

A1. Containment Filtered Venting System (Sulzer-EWI)
APPENDIX 1.

GENERAL DESCRIPTION OF
THE SULZER-EWI CONFINEMENT
FILTERED VENTING SYSTEM
The SULZER-EWI containment filtered venting system uses a fully wet scrubber equipped with nozzles of a special design and industrially proven SULZER static mixing elements.

A typical flow sheet is shown in FIG.A1. The filter is connected to the containment via two distinct paths:

- A passive path with rupture disc;
- An active path consisting of motor and manually operated throttling valves.

An isolation valve is installed before the rupture discs to allow controlled venting via the throttling valves after break of the rupture disc. This isolation valve is normally open.

The aerosols and the dust are retained in the filter vessel. The elemental iodine and - partially - the organic iodine are also retained. After passing through the filter, the cleaned gas is directed either to an existing stack or directly to the atmosphere.

A recirculation system allows the homogenization on the water inventory in the vessel. This system is not required for filter operation after a severe accident.

Water supply to the filter vessel (initial filling, refill after inspection, make-up during operation after a severe accident) can be accomplished through the make-up water line. Demineralized water is used for make-up. Other sources of water can be used during a severe accident.
Sodium thiosulphate, stored in a separate vessel, is added to the filter water in order to enhance the retention of iodine in the filter. During the initial operation phase the sodium thiosulphate is transferred automatically to the filter by means of the pressure of the incoming gas mixture, no pump being required for that purpose.

During containment venting a gas mixture (steam, air, hydrogen, carbon monoxide, carbon dioxide and noble gases) is released from the containment, in order to limit the pressure inside the containment. The gas mixture expands in the nozzles and the mixing elements of the filter to almost atmospheric pressure. At the beginning of the venting, the filter water is cold and the steam in the gas mixture condenses rapidly in the filter. Later on, at elevated filter water temperature, the steam passes the filter without condensation.

To achieve a relief of the pressure in the containment, the pressure has to be higher than the pressure corresponding to the water column of the wet scrubber. This water column is also acting as a containment isolation means.

In the filter three separation mechanisms are predominant:

Separation in the nozzles:

The expansion of the gas mixture in the nozzles produces a large number of water droplets. The highly turbulent flow conditions create an intensive contact between the water droplets and the aerosols, resulting in the separation of the aerosols. The nozzles have a convergent profile. Baffle plates are arranged above the nozzles to break up the water and form a fast-moving foam leading to an
EFFECTIVE MASS TRANSFER. THE DECONTAMINATION FACTOR OF THE NOZZLES INCREASES WITH INCREASING FLOW RATE.

SEPARATION IN THE SUBMERGED MIXING ELEMENTS:

THE BUBBLES FORMED IN THE NOZZLES MUST BE CONTINUOUSLY RENEWED AND THEIR DIRECTION CHANGED FOR MAXIMUM CONTACT EFFICIENCY TO THE SURROUNDING WATER. THIS IS ACHIEVED BY THE SULZER MIXING ELEMENTS WITH THEIR ZIGZAG COURSE. THE DECONTAMINATION FACTOR OF THE MIXING ELEMENTS DECREASES WITH INCREASED FLOW, COMPENSATING THE OPPOSITE BEHAVIOUR OF THE NOZZLES.

SEPARATION IN THE DRY MIXING ELEMENTS:

THE DRY MIXING ELEMENTS ARE MOUNTED IN THE UPPER PART OF THE VESSEL ABOVE WATER LEVEL. IT PROVIDES AN ADDITIONAL FILTRATION LAYER FOR SMALL DIAMETER AEROSOLS AS WELL AS DROPLETS SEPARATION.

THE UPWARD MOTION OF THE BUBBLES IN THE MIXING ELEMENTS CREATES A RECIRCULATION OF THE WATER IN THE VESSEL.

THE REMARKABLE FEATURES OF THE SULZER-EWI CONTAINMENT FILTERED VENTING SYSTEM ARE:

- LOW MAINTENANCE

- THE SYSTEM IS PASSIVE, REQUIRING NO PUMPS TO START OR VALVES TO OPEN DURING THE CONTAINMENT VENTING AFTER A SEVERE ACCIDENT

- SUITABILITY FOR LOW PRESSURE CONTAINMENTS; OVERPRESSURE IN THE CONTAINMENT AS LOW AS 0.15 BAR IS SUFFICIENT TO OPERATE THE SYSTEM AND REACH THE
REQUIRED HIGH DECONTAMINATION FACTOR. THIS IS DUE TO THE LOW PRESSURE DROP IN THE SULZER MIXING ELEMENTS AND TO THE FACT THAT A GOOD SEPARATION EFFICIENCY IS OBTAINED WITH LOW PRESSURE DROP NOZZLES. IMPORTANT WITH RESPECT TO THE MINIMUM OVERPRESSURE IS THE HEIGHT OF THE WATER COLUMN (OR WATER SUBMERGENCE), WHICH CAN BE ADAPTED TO ANY SPECIFIC FILTERED VENTING APPLICATION.

A SULZER-EWI FILTERED VENTING SYSTEM IS INSTALLED IN EACH OF THE TWO HIGH-PRESSURE CONTAINMENTS OF THE TWIN REACTORS OF THE BEZNAU NUCLEAR POWER STATION IN SWITZERLAND. ANOTHER SULZER-EWI FILTERED VENTING SYSTEM WILL BE ADDED TO THE LOW-PRESSURE CONTAINMENT OF THE LEIBSTADT NUCLEAR POWER PLANT, ALSO IN SWITZERLAND.
fig. 1. Plan of the hermetic zone at level 5.4 m
fig. 3. Pressure trend in the hermetic zone during LOCA: 100 mm pipe rupture with an orifice with De=32 mm. Total free volume of hermetic zone 9300 m3, Confinement spray in operation.
fig. 4. Pressure trend in the hermetic zone during LOCA with De = 32 mm, no confinement spray.

fig. 5. Pressure trend in the hermetic zone during LOCA with De = 200 mm, no confinement spray.
Fig. 6. Pressure trend in the hermetic zone during LOCA 2x100% De 200 mm, no confinement spray

Fig. 7. Pressure trend in the hermetic zone during CL LOCA 1x100% De 500 mm, no confinement spray
Fig. 8. Pressure trend in the hermetic zone during CL LOCA 2x100% De 500 mm, no confinement spray.
fig. 9. Proposal of SULZER-EWI for the confinement upgrading
Fig.A.1. Containment filtered venting system (SULZER-EMI)
Fig. 2 WWER 440/V230 HERMETIC ZONE SECTIONAL VIEW - PRESENT STATE
I. Introduction

* Kozloduy site - 6 units

- 1-2 units WWER-440 (V230), (1974, 1975) - 1 commercial generation of WWER
- 3-4 units WWER-440(V230), (1981, 1982) - 1-st commercial generation (Modified)
- 5-6 units WWER-1000 (V320), (1987,-) - last commercial generation of WWER

* 1992 --> 35% electricity production

* Conceptual proposal

- upgrading of WWER-440 (V230) - units 3 & 4
- SULZER-EWI concept for filtered venting using:
  + HL filter - blowdown phase
  + LF filter for all phases after blowdown.

II. Description of WWER-440 (V230) confinement

* Design status
  - dry containment;
  - 22 interconnected steel lined compartments; (fig. 1,2)
  - 12000 m³ - Free volume;
  - 1 bar - overpressure;

* Protection of confinement
  - 9 flap valves (1+8)
  - spray system

* Design Basis Accident
  - SB LOCA Dy = 100 mm (32 mm - restrictive orifice)
  - spray system - ON
  - flap valves closed (fig.3)
  - spray system OFF
  - 1 flap valve opens (fig.4)
III. Upgrading of confinement - problems

* Present status - high safety concern
  - insufficient "defence in depth"
  - violation of the last physical barrier

* Accident without core melt
  - not designed for > 32 mm LOCA (fig. 5, 6, 7, 8)
  - confinement integrity - not guaranteed.

* Severe accidents
  - H₂ generation and explosion
  - High leak rate - release of radioactivity

* Actions to be performed
  - determination of structure ability to withstand > LOCA
  - evaluation of flap valve necessity and practicality
  - determination of H₂ control facilities to solve H₂ explosion problems
  - determination of SA filters practicality (with forced ventilation)
  - determination of cost effectiveness for specific units

IV. Conceptual design of V230 confinement upgrading (SULZER-EWI filters)

* General design criteria
  - new DBA - (with LBB -> 200 mm break)
  - integrity of present confinement structures (1 bar over pressure) - guaranteed
  - no direct release of radioactivity
  - during severe accidents - filtered venting

* Conceptual design - SULZER-EWI configuration with 2 filters
  - HF filters - blowdown phase (high steam flow)
    + condensation of all steam
    + condensation retention of active aerosols
    + decontamination factor for aerosols and elemental iodine 100 + 200 (low activity)
  - LF filter - after blowdown phase
    + decontamination factor
      1000 - for aerosols
      1000 - for elemental iodine
IV.3. Design data for filters

* HF filter
- 300+400 s - duration of operation
- medium - air/steam
- pressure - 1.6+2.0 bars
- temperature - 200°C
- mass flow - 900 kg/s
- volumetric flow - 1000 m³/s

* LF filter
- long time - duration (after blowdown)
- decay heat - 37 MW
- medium - saturated steam /noncondensible gases
- mass flow - 17 kg/s
- pressure - 2 bar
- temperature - 120°C
- volumetric flow - 15 m³/h

V. SULZER-EWI concept for WWER-440 (V230)

*Description of components (fig 9)
- removal of flap valves
- rupture disk installation
- duct installation - cross-section- 17 m² (20 m²)
- HF filter
  +110 m² cross section;
  +360 m³ initial water inventory;
  +special nozzles for intensive steam/gas and water contact
  + SULZER mixing elements
- LF filter
  + 2 isolation valves
  +80 m³ - water inventory
  +special nozzles
  + mixing elements
  +discharge to the stack

* Operation of components
- HF filter
  +1.6+1.6 - membrane ruptured (operation start)
  +steam/air condensation
  +4,0 m initial water column
  +operational pressure 1.6+2.0 bar
  +1.2+1.4 bar Water column weight stops the operation of HF filter
  - 1.2+1.4 bar - valve open
- LF filter
  + 1.8 m water column
  +ΔP=0.2 bar of LF filter

* Automatic operation - possible HF & LF filter in parallel

* Fan operation mode (suction mode)
- suction head (-5 kPa)
- higher leak rate
- misoperation of ventilation systems
VI. Development of project

* Four major phases
  - PC Concept phase (completed)
  - P1 Project phase
    + analysis;
    + Qualification test HFF
    + PSAR;
  - P2 Project phase
    + engineering
  - P3 Project phase
    + construction
    + Implementation

* P1 Project phase activities
  - LOCA Analyses
  - Confinement Pressure response
    + HFF & LFF
  - Qualification tests for HFF
  - Adaptation of Filter technology
  - Basic definition of Systems
  - PSAR
  - Cost & Schedule plans
  - Investment & Finance plans

VII. Conclusions

1. This concept fulfills all requirements of TECDOC-640 IAEA
2. H2 Hazard is mitigated
3. Next phase cost evaluation for KNPP units 3 & 4

Confinement penetrations

* Group 1: Ventilation Total
  + cut - off valves of system B-2
  + pressure relief valves of system B-4
  + butterfly valve of system B-4
  + butterfly valve of system P-2
  + fan's shafts of system P-1

* Group 2: Doors and suction holes
  + doors
  + suction holes of system B-3

* Group 3: Hatches and manholes
  + rectangular hatches of system P-1
  + manholes of system P-1
  + SG hatches
  + MCP hatches
  + MIV hatches
  + primary water purification system hatches
  + reactor vessel cover

* Group 4: Flap Valves
* Group 5: Piping penetration
* Group 6: Valve stem extensions
* Group 7: Electrical penetrations
  (48 modules)
IAEA CONSULTANTS’ MEETING
ON
CONTAINMENT AND CONFINEMENT PERFORMANCE
IN NPPS WITH WWER 440/213 AND 440/230 REACTORS

TECHNICAL BASIS FOR IMPROVING THE CONFINEMENT FUNCTION IN WWER-440/230 NPPS

A. Wanner
Elektrowatt Engineering Services Ltd.
Zurich, Switzerland

VIENNA, AUSTRIA
29 NOVEMBER - 3 DECEMBER 1993
EWI REPORT "IMPROVING THE CONFINEMENT FUNCTION IN WWER-440/230 NPPS"

HISTORY

SEPT. 1992:
IAEA WANTS AN OVERVIEW OF PROPOSED SOLUTIONS FOR CONFINEMENT IMPROVEMENT INCL. AN ASSESSMENT OF PROS AND CONS
ASSIGNMENT TO EWI UNDER EXTRABUDGETARY PROGRAMME

FEB. 1993
FIRST DRAFT SENT TO IAEA AND SWISS FEDERAL INSPECTORATE FOR SAFETY OF NUCLEAR INSTALLATIONS FOR COMMENTS

JULY 1993
FINAL REPORT TO IAEA, COMMENTS FROM IAEA AND SFI INCORPORATED

REPORT

PURPOSE
PROVIDE AUTHORITIES IN COUNTRIES WITH WWER-440/230 REACTORS WITH AN OVERVIEW (IDEAS) OF SUGGESTED MODIFICATIONS TO IMPROVE THE CONTAINMENT FUNCTION

IAEA WANTED ASSESSMENT OF PROS AND CONS

STRUCTURE
CH. 1: GENERAL DESIGN REQUIREMENTS INTERNATIONALLY RECOGNIZED FOR CONTAINMENT DESIGN FOR LWR AND HWR PLANTS

CH. 3-5: OVERVIEW OF PWR, BWR AND HWR CONTAINMENT FEATURES INCLUDING SPECIAL DESIGNS

CH. 6: PLANNED AND IMPLEMENTED MEASURES TO MAINTAIN CONTAINMENT FUNCTION DURING SEVERE ACCIDENTS

CH. 7: CONFINEMENT OF 440/230 NPPS
♦ DESIGN CHARACTERISTICS (7.1)
♦ WEAK POINTS (7.2)
♦ SUGGESTED MODIFICATIONS (7.3)
♦ ESTIMATED COSTS (7.4)

CH. 8: REFERENCES

CH. 9: FIGURES
### REPORT

#### SUMMARY

<table>
<thead>
<tr>
<th>Weak points</th>
<th>Proposed Measures for Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. NORMAL OPERATION</strong></td>
<td></td>
</tr>
<tr>
<td>HIGH LEAK RATE (4000 TO 6000 VOL% PER DAY AT PEAK ACCIDENT (80 KPA) OVERPRESSURE)</td>
<td>SEALING OF CONFINEMENT PENETRATIONS A MUST</td>
</tr>
<tr>
<td><strong>2. DESIGN BASIS LOCA</strong></td>
<td></td>
</tr>
<tr>
<td>CURRENT DESIGN BASIS LOCA NOT IN CONFORMANCE WITH INTERNATIONAL STANDARDS</td>
<td>REDEFINITION OF DESIGN BASIS LOCA (BASED ON LARGER BREAK AERA, E.G. 200 MM DOUBLE-ENDED PIPE BREAK)</td>
</tr>
<tr>
<td>STRUCTURAL INTEGRITY OF CONFINEMENT QUESTIONED (CAPABILITY OF ECCS, RELIABILITY OF SPRAY SYSTEM AND DUMP VALVES)</td>
<td>IMPROVE ECCS CAPABILITY TO AVOID FUEL DAMAGE</td>
</tr>
<tr>
<td></td>
<td>INCREASE SPRAY SYSTEM RELIABILITY TO AVOID DUMP VALVES OPENING</td>
</tr>
<tr>
<td><strong>3. BEYOND DESIGN BASIS LOCA</strong></td>
<td></td>
</tr>
<tr>
<td>STRUCTURAL INTEGRITY FOR LARGE BREAK LOCA (&gt; 200 MM) UNCERTAIN</td>
<td>EXTEND CONFINEMENT VOLUME AND ADD A PRESSURE SUPPRESSION SYSTEM AND/OR FILTERED PRESSURE RELIEF SYSTEM SIZED FOR LARGE BREAK SIZE OVERPRESSURE IN LIEU OF DUMP VALVES</td>
</tr>
<tr>
<td>RELIEF CAPABILITY OF DUMP VALVES FOR LARGE BREAK AERAS</td>
<td>REPLACE DUMP VALVES BY ADDING A PRESSURE SUPPRESSION SYSTEM</td>
</tr>
<tr>
<td>HIGH LEAK RATE DURING LONGTERM PERIOD</td>
<td>IMPROVE SEALING AND ADD SUCTION SYSTEM OR LOW-PRESSURE FILTERED VENTING SYSTEM</td>
</tr>
<tr>
<td>NO MITIGATION PROVISIONS AGAINST HYDROGEN EXPLOSIONS</td>
<td>ADDITION OF A HYDROGEN MITIGATION SYSTEM</td>
</tr>
<tr>
<td>UNDERPRESSURE CAPABILITY OF CONFINEMENT, LINER ANCHORING</td>
<td>VERIFY LINER ANCHORING AND STRUCTURE CAPABILITY, VACUUM BREAKER CAPABILITY, SPRAY INTERLOCK AT LOW PRESSURE</td>
</tr>
</tbody>
</table>
REPORT

REMARKS

♦ REPORT PROVIDES A SUMMARY OF PROPOSED MEASURES

♦ ONLY SOLUTIONS DESCRIBED FROM PUBLISHED SOURCES
  NO INFORMATION FROM PROPOSALS INCLUDED

♦ DESIGN BASIS AND APPROXIMATE DESIGN DATA GIVEN (IF AVAILABLE)

♦ NO INFORMATION FROM RUSSIA, UKRAINA, BULGARIA FOUND IN ENGLISH LANGUAGE

♦ NO ASSESSMENT OF PROS AND CONS OF INDIVIDUAL SOLUTIONS POSSIBLE DUE TO LACK OF INFORMATION

♦ PROVIDES A TECHNICAL BASIS FOR FURTHER DISCUSSIONS

♦ TO MEET IAEA'S ORIGINAL INTENT:
  - NEED TO ENLARGE INFO BASIS BY INCLUDING INFORMATION FROM RECENT DEVELOPMENTS
  - GOAL OF CONSULTANTS MEETING

MODE OF OPERATION: STAND-BY

UPGRADING OF CONFINEMENT OF NPP KOZLODUY-UNIT 3 AND 4
CONFINEMENT DESIGN OF WWER 440/230 NPPs

7.1 Design Characteristics of the WWER 440/230 Confinement

The so-called "hermetic confinement" of the WWER 440/230 reactor plant is a closed compartment system that consists of over 20 compartments and houses all the main equipment of the primary circuit that are under reactor pressure. The reactor building is shown in Fig. 7.1 and the confinement in Fig. 7.2. The net free volume of the confinement measures about 12'000 to 14'000 m³, which is relatively small compared to the volume in western PWR plants.

Inside the confinement are

- the pressure vessel,
- the 6 primary loops, each comprising a steam generator, a primary pump and the 2 loop isolation valves,
- the pressurizer.

In addition portions of the high pressure safety injection system piping, the (confinement) spray system piping and the confinement sump to collect the water in case of a LOCA are also located inside this enclosure.

Within the steam generator compartment containing the steam generators and the primary pumps there are three lines of nozzles which belong to the spray system that is used to reduce the containment pressure by steam condensing and to wash out the radioactive iodine from the atmosphere.

A recirculation ventilation system that includes air coolers (but no filters) removes the heat from the primary circuit components. The components of these recirculation systems are installed within the hermetic confinement with the exception of the electric drives of the ventilators. Therefore, the driving shafts must penetrate the wall of the hermetic confinement.

The equipment room within the confinement that houses the drives for the primary pumps and for the isolation valves of the individual loops are accessible during power operation. This room is connected to a ventilation system that takes suction from this room and discharges via particulate filters to the outside. The non accessible steam generator and primary pump rooms are ventilated by a separate ventilation system that
includes particulate and charcoal filters to reduce the amount of radioactive materials released to the environment. To prevent the accessible rooms from being contaminated graduated sub-atmospheric pressure levels are maintained by these ventilation systems.

Most of the rooms are connected with each other through openings that cannot be closed. Some of them are connected with the rest of the confinement through dump valves that can open only in the direction of the rest of the confinement. The walls and the roofs of the rooms also shield the adjoining accessible rooms. The upper region of the reactor pit is closed by a cover that can be removed during reactor refuelling.

A general description of the WWER-440 Model 230 can be found in Appendix I of /12/.

The design basis accident that governs the high pressure safety injection system design and pressure and temperature loading of the confinement structure is the rupture of the 100 mm diameter pressurizer spray line connected to the reactor coolant system (DBA LOCA). The assumed break location is such that the flow discharged from the broken line is restricted by a flow limiter with a nominal size of 32 mm in diameter. The accident peak pressure in the confinement is maintained below the dump valve opening pressure by the spray system provided that 2 out of 3 pumps are operable. The amount of radioactivity released to the reactor building for this accident is only a function of the confinement leakrate. The leakage is discharged through filters to the atmosphere via the building ventilation systems mentioned before.

The confinement structure is designed to withstand an overpressure of 1 bar during the DBA LOCA. Protection against higher accident pressures (e.g. as a failure of the spray system) is provided by the sequential opening of the 8 dump valves starting at an overpressure of about 0.8 bar. Discharge is then directly to the atmosphere (see Fig. 7.2) without passing through filters. In some plants there is a smaller sized dump valves that already opens at 0.6 bar overpressure. When all dump valves are open the confinement is protected against the peak accident pressure of a nominal diameter of 200 mm single-ended break which is the largest connecting line to the main primary loop. The WWER 440/230 emergency core cooling systems and the confinement structure are therefore not designed to handle a complete single- and double-ended break of a main loop pipe (DBA for western LWR).
7.2 Weak Points of WWER 440/230 Confinement Design

The design aspects and the operational experience of the WWER 440 Model 230 plants has been reviewed by several institutions and reactor suppliers during the past years e.g. /11/. The probably most recent evaluation was performed by the IAEA in the framework of this programme /12/. All of these investigations agree that the radioactive retaining (confinement) function of this enclosure does not meet the safety standard and the state of the technology as compared with the containment design concepts applied western light water reactor plants.

The major shortcomings are summarised in the following points (see e.g. /13/).

7.2.1 Normal operation

The major weak point is the actual high leakrate of the hermetic confinement which lies anywhere between 2000 to 6000 Vol %/day. The specified leakrate at test pressure (1.25 bar) should be approx. 600 Vol %/d /.../. The confinement barrier does therefore not fulfil its retaining function for radioactive substances. This retaining function is rather achieved by the lower pressure in the surrounding reactor building rooms. The building ventilation systems which maintain this lower pressure discharge to the atmosphere through filter systems by which means the release of radioactive aerosols and halogens can be reduced. From a radiological point of view of the public exposure, the high leakrate during normal operation does, however, not present an important weak point.

7.2.2 Within existing DBA LOCA conditions

The effectiveness of the containment function during these conditions is determined by:

- the reliability of the spray system function and dump valves
- the confinement leakrate

During a partial or total failure of the spray system on or more dump valves will open subsequently releasing radioactivity unfiltered into the environment. This containment principle is therefore violated. Even if the dump valves do not open, radioactivity is passing to the reactor building rooms due to the high leakrate. The actual performance
of the confinement dump valves and of the confinement spray system has only recently been fully checked in tests and assessed by an accident analysis in some countries. Also the influence of the leak rate of the pressure compartment on the behaviour of the confinement systems and radioactive releases is not known.

In addition, since subatmospheric pressure might result after initiation of the sprays, the ability of the structure and liner to withstand subatmospheric pressure is of concern.

7.2.3 Severe (i.e. beyond design basis) accident conditions

The major weak point of this confinement design compared with western containment concept lies in the inability to maintain its retaining function during a loss of coolant accidents resulting from large, double-ended pipe breaks. This is because in the original plant design such an event was definitely excluded from consideration with exception of the single-ended break of a 200 mm pipe connected to the primary circuit. During this accident all dump valves will open already in the early phase of the loss of coolant accident to limit the peak pressure thus protecting the confinement structure. Opening of the dump valves occurs before fuel damage is expected.

Mass and energy releases from larger breaks are not considered in the original confinement design due to the expected low probability of occurrence.

A preliminary analysis (/12/ in /13/) has indicated that a structural failure of the pressure compartment may not occur even with a large break LOCA unless a hydrogen explosion occurs. If this is true, the main problem would then shift to the prevention of a hydrogen accumulation within the confinement.

The high leak rate of the confinement would probably not be sufficient to prevent hydrogen accumulation in the upper parts of the confinement, e.g. in the pressuriser compartment. A major hydrogen explosion could cause failure of the confinement structure, increasing the accident severity and the release of radioactive material to the environment. Even if the confinement structure would maintain its integrity, the high leak rate would still result in significant releases. The main functional purpose of the confinement would therefore not be met. Achievements of upgrades to meet these purposes for a reasonable spectrum of events would greatly reduce the risk.

The followings additional remarks should be noted with regard to these items:
The mechanical resistance of the confinement is indicated to be 2.0 bar. In [11] it is stated that no evidence has been given by the designer and no pressure tests were performed at this pressure to verify this point. An earlier analysis performed by the former "Bauakademie der DDR" has indicated that the structure may fail (i.e. crack and exercise a big leak rate) under the combined pressure loadings and blowdown forces following the double-ended break of a primary system pipe (500 mm), even with the full safety system operating.

Other analyses have indicated that the existing confinement design is probably at least able to withstand the consequences of a single ended break of a 200 mm line, which is an accident already beyond the design basis. In this case the pressure in the confinement would exceed the opening pressure of the dump valves. The air steam mixture would therefore be released in the environment through the dump valves, which should reclose tight after the release. Initially the dump valves must open and close several times, until the spray system reduces the pressure below the opening pressure. The dump valves should then be closed before significant fuel damage occurs. The activity released to the atmosphere by the dump valves could then be restricted to a fraction of the activity contained in the reactor coolant system. Handling of this accident depends therefore greatly on the proper functioning of the confinement dump valves.

The confinement is lined by a welded steel sheet. The penetrations through the walls and ceilings for the doors, hatches, piping, cables and shafts were designed according to the design leak rate indicated above. The penetration design does not correspond to the current state of the art. There are several weak points, in particular at the ventilator shaft penetrations. The pressure compartment leak rate is thus high even at low overpressure. The confinement leak test is performed twice in each refuelling. The applied test pressure is 200 mm water column (which corresponds to an equivalent opening of 133 mm diameter) but it seems that the leak rate in the vicinity of the accident peak pressure could never be measured or calculated based on the test results. The estimated leak rate for the confinement runs anywhere from 2000 to 5000 vol. % per day. Therefore it is most likely that a considerable release of radioactivity to the atmosphere will occur already following a design basis accident. Leak rate tests at ambient temperature and at the test pressure of 1.25 bar indicated in the first four Greifswald units a leak rate well below the permissible leak rate of 3600 m³/h, however only for the original DBA involving a 32 mm equivalent break size /11/. 
• It seems that adequate confinement isolation is not provided in lines connected directly to the reactor system. Several lines have only one isolation valve, which is primarily a shortcoming in the reactor coolant system design. This is also a shortcoming of the present confinement design that does not isolate the entire reactor coolant system adequately in case of a single failure of the isolation valve.

• The spray system does not meet the single failure criterion since there is only a single line feeding the three spray headers. The design of the initiating logic regarding redundancy, spatial separation and independence from other logic systems does also not correspond to current safety standards in western plants.

• The constant discharge flow through the charcoal filters in the reactor building ventilation system during operation may result in fast degradation of the filter efficiency and therefore impair their use in a post accident clean-up operation.

7.3 Suggested Modifications to the WWER 440/230 Confinement

7.3.1 General recommendations

Considering the list of weak points as outlined in Chapter 7.2, a need to improve the safety of the current containment design has generally been recognised by all reviewers. In the document IAEA-TECDOC-640 which summarises the results of the safety review of the WWER 440 Model 230 plants the IAEA expresses the following conceptual recommendations related to the improvement of the present confinement. These recommendations have been ranked in Category III by the IAEA, which means they are of high safety concern and immediate corrective action is needed.

♦ Confinement Leaktightness

Overall effectiveness of confinement should be significantly improved. However, because confinement was not designed to completely control leak rate, it may not be practical to reduce the rate such that radioactivity in entirely contained.

♦ DBA conditions

It is necessary to evaluate the overall effectiveness of the confinement by an accident analysis that takes into account the following parameters:
• the actual leak rate of the pressure compartment

• the influence of the dump valves under various malfunctions (non opening, stuck open)

• the actual characteristics of the confinement spray system as measured by tests such as: time necessary for the sprays to start following a LOCA, efficiency of the sprinklers according to the flow provided by the pumps, temperature of the water coming from the reactor and the containment sump via the safety injection tank, etc.,

• the single failure criterion which should ensure the performance of the systems above the minimum required

• realistic assumptions concerning the primary coolant contamination

♦ Severe accident conditions

Solutions for hydrogen control should be investigated, such as H₂ ignitors, as well as the potential of filtered venting to reduce the radioactive leaks.

Implement practical means of controlling radioactive releases following severe accidents such as forced filtered venting and the use of H₂ ignitors. Following actions should be addressed:

• Determine ability of structure to withstand large blowdown forces.

• Evaluate and upgrade as necessary and practical relief valves.

• Determine potential for ignitors to significantly reduce H₂ explosion problem

• Reduce leak rate to practical levels that can be maintained following blow down.

• Based on results of above analyses, determine practicability of installing severe accident filter with forced ventilation of the containment to maintain slight vacuum and remove hydrogen from building up after the initial blowdown.

• Determine overall practicality, cost effectiveness for specific plant, implement as warranted.
• Unfiltered release to the environment in the initial phase of the large LOCA.

• Increase the confinement free volume by adding a volume in which the steam can condense and the non-condensable gases can expand.

Depending on the national regulatory requirements these backfitting modifications can either cover the full range of primary breaks up to and including the double ended break of a main primary loop piping or be restricted to the break of the largest line connected to the reactor coolant system, which is a 200 mm break. If the break of a main primary loop pipe (500 mm) is excluded, it would be mandatory that the leak before break concept is fulfilled for this break size.

A summary of proposed modifications to attempt to increase the confinement's capability to handle greater pipe break sizes are described below:

**Unfiltered venting**

Unfiltered confinement venting of the current WWER 440/230 containment for handling break sizes greater than 32 mm up to the 200 mm single ended break size was considered for the first phase of the accident. To cope with the double-ended break of a primary loop pipe (500 mm diam.) the discharge capacity from the confinement (from the steam generator/main coolant pump room to be precise) must be increased. In an early proposal /14/ this was accomplished by enlarging the actual venting cross section to approximately 30 to 40 m² (the ideal hydraulic cross section required is 18 to 20 m²) and by installing a water siphon as an isolation device. Fig. 7.3 shows the proposed system to which a filter system was added later for filtered venting during the later phase of the accident.

Using a water siphon was judged to have the following advantages compared with other isolation device such relief valves, rupture disks, check valves for the following reasons:

• High sealing capability of water

• Uncomplicated, simple design for the expected range of confinement compartment overpressures

• Technically feasible

• Allows for steam condensation to avoid water hammer effects

• High reliability for reclosure after opening
The proposed siphon opening pressure differential would be set somewhere between 30 to 50 kPa. The dominant emphasis of the siphon function is twofold: (1) Provide a reliable means to retain radioactivity after the venting phase by reclosing the vent line reliably, and (2) to minimise the risk of a water hammer. There is less emphasis on the steam condensation function since the radioactive source term during the initial blowdown phase, which consists mainly of the reactor coolant inventory, is small /14/.

Pressure equalisation between pressures upstream and downstream of the siphon will be completed within 30 s according to calculations. Future analyses have revealed that no fuel damage should occur during this time even in case of a (total /partial failure ?) of the emergency core cooling system. The radiological consequences (individual dose equivalent (IDE)) due to the short-term unfiltered venting using conservative assumptions for the radioactive inventory of the primary coolant were calculated to be insignificant according to /14/.

Direct venting of the confinement with a water siphon pool was considered as a viable first solution for the Bohunice Units 1 & 2 confinement upgrading as part of the "large" reconstruction phase.

The following problems areas were identified which require more detailed investigation:

- Elimination of jet impingement forces when the siphon opens rapidly
- Elimination of water hammer effects due to the collapse of steam bubbles during passage
- Prevention of water droplets entrainment (droplet separator be installed)
- Backflow of siphon water into the confinement when latter is at underpressure

This concept seems to be abandoned in favour of the following concept.

Jet condensers

In another proposal the present dump valves will again be eliminated and replaced by an opening of approximately 40-45 m² cross-section that will be connected to a hermetically closed, cylindrical concrete building (air trap building) in which the escaping steam will be condensed by so-called "jet condensers".

This system (shown in Fig. 7.4) is the proposed solution for the confinement backfitting of the Bohunice V-1 units (Units 1 & 2) and forms a part of the proposal.
made by the Power Research Institute (VUEZ) for that plant /16/. The design basis for the system is the double-ended break of the largest primary circuit pipe in the steam generator compartment (500 mm diam.).

By this design the confinement boundary will be extended to the air trap building in which a water column of 8 m (80 kPa) seals the confinement atmosphere from the environment. When the pressure in the confinement exceeds this value the jet condensers start operating. The steam component of the air steam mixture from the confinement condenses in water where a large portion of the radionuclides is retained in the pool water and the non-condensibles gases are trapped in the air space ("gas lock") of the air trap building. Jet condenser and water pool together have the same function as the pressure suppression pool for the BWR containment in western plants. The proposed solution envisages that one air trap building would in principal serve one unit. For two-unit plants, the gas lock space would be kept to 50% of the required space for cost reasons, but by connecting the two buildings this would give the necessary 100% volume. The separation of both air trap buildings is assured by hydraulic seals provided by special design of the extensions at the inlet nozzles of the jet condensers.

The jet condenser design (see Fig. 7.5) is characterised by providing minimum resistance to air-steam mixture and effective steam condensation, two essential requirements regarding the low overpressure capability of the present confinement. For this reason other pressure suppression designs with deep submergence and high inertia of water columns were not considered suitable. Several design options of jet condensers for particular applications have been developed and tested by the Nuclear Power Plant Institute (VNIINAES) in Moscow. More details on the jet condenser design can be found in /15/.

The volume of the piping leading to the air trap building is estimated at 7'200 m³. The cold water volume required for steam condensation is estimated at 1400 m³. The total volume of the gas lock will be about 32'000 m³ /16/.

**Addition of a WWER 213/440 type pressure suppression system**

It seems somewhat logical to add a pressure suppression system of the type used in the WWER 440 Model 213 plants (see Fig. 7.6) to the Model 230 plants. The current design of the 320 Model may require certain modifications for the 213 Model but with probably little effort. It appears from /16/ that the cost for the realisation of this additional pressure suppression were substantially higher than for the proposed solution using jet condensers and that may have been the reason that this idea was no
longer considered for the large reconstruction of the Bohunice V-1 units.

Other solutions

A number of other modifications have been proposed to increase the current confinement capability for greater break spectrum to extending the existing confinement by adding additional volume in which the steam fraction of the escaping air-steam mixture would condense.

These proposals include for example:

- to connect a large dimension steel building equipped with a passive spray system actuated by the air-steam flow /14/.

- to connect to each unit a sufficiently large volume in the form of parallel large diameter pipes in which condensation would be achieved by an active spray system operating directly at piping entrance and indirectly by spraying the pipe outside surface /14/.

Another solution that may also improve the present confinement retaining capability could consist in connecting a vacuum building including an automatic spray system similar to the design for the PHWR reactor plants. As in the PHWR multi-unit stations one vacuum building could serve both units of a WWER 440 Model 230 nuclear power station.

7.3.2.3 Filtered Containment Venting System

A filtered venting system (FCVS) is another proposed system to protect the integrity of the confinement of the 213 Model plants against high accident pressures during large DBA-LOCA and severe accident scenarios /10/. Contrary to the previous described designs the passive FCVS does not need a large pressure reduction facility.

The proposed FCVS configuration consists of a high flow filter for the initial blowdown and a low filter for post blowdown phase. In view of the very high initial steam flow, the high flow filter system has to be designed to allow the condensation of nearly all steam released from the confinement. During condensation the radioactive aerosols and elemental iodines will largely be retained in the water.

The DBA-LOCA for this system is postulated as a double-ended guillotine break of a 200 mm line on the primary side. Larger break sizes were excluded from DBA
considerations as a result of the Leak Before Break study. The proposed system is shown in Fig. 7.7.

The system should be capable to handle initially 1000 kg/s at an inlet pressure of 2 bar and about 325 degrees C and should have a limited filtration effectiveness, i.e. a decontamination factor of approximately 200 for aerosols and 100 for elemental iodine. The low filtration effectiveness is justified since no core damage is expected during the initial, short blowdown phase. The high release rate requires the replacement of the existing dump valves (with a cross section of approximately 8 m²) by a piping system with an equivalent cross section of approximately 17 m². Rupture discs provided in the piping system would ensure passive system initiation. A vacuum breaking system may be connected to the connecting duct. A low flow filter system of higher effectiveness for the post-blowdown phase of a large LOCA is required in view of the higher activity releases, a minimum decontamination factor of 1000 for aerosols and elemental iodine is required. The filter elements have been extensively tested over a wide range of operating parameters and are already installed in the FCV systems of LWR nuclear power plants.

Operation of both filters is as follows:

At a confinement pressure of 1.5 to 1.8 bar the rupture opens and releases the air/steam mixture to the high flow filter. The water has to be expelled from the vertical inlet duct and the lower plenum before the steam fraction starts to condense. Initially the water level in the filter is at approx. 4 m and after blowdown this level increases. After blowdown the pressure in the filter and in the confinement equalise at about 1.2 bar and the weight of the water column in the filter stops automatically the discharge. When the pressure inside the confinement starts to increase the valves to the low flow filter are manually opened and the filter starts to operate. During this phase all flow will be directed to the low flow filter since the high flow filter is isolated by a water seal. The low flow filter operates at a lower pressure (about 1.8 m of water column) compared with the high flow filter.

Conceptually it would seem also possible to operate both filter systems in parallel and without valves thus providing for an automatic changeover depending on the pressure. This option still remains to be investigated.
7.3.2.4 Improvement of the Confinement Spray System

The current confinement spray system reduces the confinement pressure to a value below the dump valves opening pressure for the current 32 mm design basis LOCA. Should the confinement spray system fail, the current design basis LOCA would cause these valves to open. If the effectiveness of the spray system is further increased, larger break sizes can be handled without requiring the existing valves to open. It would also reduce the leakage of radioactivity after a small loss of coolant accident, considering the low leaktightness of the present confinement.

Modifications to improve the reliability and the effectiveness of the confinement spray system are necessary in the following areas:

- As the confinement spray system actuation logic is not redundant and a single failure can cause failure of the system to start, modifications are required to provide an adequate redundancy from sensor to actuator. Mechanically the existing system also does not comply with the single failure criterion because of the single pipe riser and two common headers. In view of the large upgrading program for the Bohunice V-1 units it was proposed to provide two redundant, separate trains for the sprinkler system taking suction either from the borated water tank or the confinement sump (see Fig. 7.8)

- The effectiveness of the spray system could further be increased by starting the spray sooner after detection of an excessive pressure. In order to start the spray pump operating sooner may have implications on the diesel load sequence. /13/.

7.3.2.5 Increasing the leak tightness of the confinement

There is a general agreement to reduce the considerable high leak rate of the confinement (see Chap. 7.2) As leak paths exist primarily at the penetrations (electrical, mechanical, doors, cover plates) measures for confinement tightening must concentrate on these locations.

Work on confinement tightening by applying special sealing techniques and latest sealing material has already started resp. completed in some WWER 440/230 plants. The overall goal is to reduce the leak rate by about an order of magnitude (i.e. 200 400 Vol% per day), a value that is still high compared with design leak rates (about 0,25 Vol. % per day) in western containment where measured design leak rates are still below. Results of the effects of this work has not yet been reported.
However, even after the mentioned retightening work, a leak rate comparable to that in western containments cannot be achieved in this way. This is primarily due to the general inadequate penetration design in these plant design. A significant improvement of this situation can only be achieved by a complete redesign of the penetrations in accordance with modern containment penetration designs. This work must be done during a large plant reconstruction phase.

7.3.2.6 Improving confinement isolation

The lines penetrating the confinement boundary are not consistently equipped with two containment isolation valves in series as in western light water reactors. This particularly important for the lines connected to the reactor coolant system.

A proposal to upgrade isolation of the confinement of the Bohunice plant foresees the installation of either two pneumatically driven, separately controlled isolation valves or one pneumatically operated valve and one check valve in each line that penetrates the confinement/16/.

This principle is in line with the general practice. When applied it is essential that one valve is installed on either side the confinement penetration. If this is not feasible (e.g. due to space problems) it is acceptable that both isolation valves are mounted as close as possible to the outside of the confinement.

The lines that are in direct contact with the confinement atmosphere, i.e. ventilation ducts, are also not consistently equipped with isolation valves. Therefore confinement isolation also be improved by equipping these ducts with two fast closing isolation valves.

7.3.2.7 Reducing the confinement pressure after accidents

Depending on the nature and extent of the tightening measures the confinement leak rate may still remain considerably high in comparison with western containments. Systems to further reduce the post-accident confinement pressure or even to bring it slightly below the atmospheric pressure after an accident may therefore be desirable from a radiological point of view, e.g. for the plant personnel who is surveying the plant status or initiated actions at various locations in the plant after an accident.
In the following two reported proposals reduction of the post-accident confinement pressure is accomplished by taking advantage of the FCVS if such a system is installed for overpressure protection. The first idea would be to further lower the post-accident confinement pressure operating by the FCVS down to lower confinement overpressures. For this purpose it is important that the filter system is designed and capable to operate at low overpressures and with adequate retention efficiency.

**Suction system**

In a recent proposal /15/ it is suggested to add a blower in a bypass to the passive FCVS to provide a direct and controlled discharge to the environment (see Fig. 7.8). The passively acting FCVS would thus be upgraded by an actively operating suction system. The latter should operate in a differential pressure range that is determined by the minimum allowable negative pressure in the confinement and the maximum resistance of the FCVS to blow-through. By selecting an appropriate pressure operating range is anticipated that the blower may operate automatically within this range. For two units one suction system connected by corresponding piping would be sufficient. Additional piping would be installed to permit to send the filtered air back to the confinement to mix and to clean the confinement air as shown in Fig. 7.9.

**Use of the low flow Filtered Confinement Venting System**

In Section 7.3.2.2 a FCVS is described that includes a filter system of low capacity, but of high filtration effectiveness to protect the confinement after the blowdown phase. The design flowrate is 17 kg/s, corresponding to the residual heat after 300 s, at a confinement pressure of 2 bar abs. The system could also be used to lower pressure in the confinement either as a passive system or a system equipped with a fan as shown in Fig. 7.7. The filters should be equipped with filter elements that retain their effectiveness simultaneously and with small pressure drops at low inlet pressures (similar to those used at Beznau NPP) should be used /10/.

**7.3.2.8 Preventing confinement liner damage due to excessively low pressure**

After a LOCA air will escape from the confinement, either through leakage, through the existing dump valves or through the systems that are added to increase the capability to handle a larger break spectrum. Upon completion of the blowdown phase all steam shall be condensed by sprinkler (spray) system action and a subatmospheric pressure close to the allowable value of -10 to -15 kPa /14/) could be attained in the confinement. The structural and sealing capability of the existing confinement against
recommended if hydrogen control is solely entrusted to this system. The reason was that success of a deliberate ignition was not ensured even if correctly placed in the confinement space.

A better solution appears to be the newly developed catalytic recombiners since these permit to recombine the hydrogen well below the flammable concentration and can operate in atmospheres with a high steam content. These recombiners have been developed in Germany but have not yet been installed in a PWR nuclear power plant as their approval (the German BWR containments are inerted) is still under discussion.

### 7.3.5 Reducing the risk of confinement failure caused by gradual overpressurisation

If the residual heat from the confinement cannot be removed (e.g. by a total failure of the heat removal systems) a gradual pressure increase that can ultimately fail the containment can occur. The FCVS or an autonomous, dedicated emergency heat removal systems that removes residual heat from the secondary side in a PWR plant (often combined with core cooling capability) can be used for this purpose. This subject is part of the proposals for the upgrading of the emergency core cooling capability of the WWER 440/230 plants.

### 7.3.6 Corium cooling after pressure vessel failure

Should the capability to cool the core fail, the core will melt and relocate at the bottom of the pressure vessel. Shortly afterwards the pressure vessel would fail and the molten core as well as part of the pressure vessel would fall to the bottom of the reactor pit. This space is normally dry and is not flooded by the safety systems after an accident. Concrete erosion would then follow the fall of the core.

A system to flood the reactor pit after fuel damage detection could be added if, for example, a probabilistic risk analysis should indicate a strong necessity for the integration of such a feature. Such a decision would be comparable with the accident management measures taken for the newer Swedish BWR. and the new EPR currently in design stage. The envisaged system would provide corium cooling after pressure vessel failure if the corium falls into the water in the reactor pit in a fragmented form.

This presupposes that the reactor coolant system has been depressurised to avoid the high pressure core melt accident.

The reactor pit could also be flooded up to the level of the top of the core, thus
providing cooling of the core from the outside of the pressure vessel. This is similar to the provision of the containment flooding concept. Such a core cooling concept is currently under investigation by a western PWR vendor as an alternative to core catcher. The validity of the concept for the WWER 440/230 still needs to be demonstrated.

By either method, in conjunction with a filtered venting system through which the steam produced by the residual heat of the corium could be evacuated, could considerably reduce the radioactivity released after a core meltdown accident.

### 7.4 Estimated Costs for the Modifications

The references quoted above do not give figures on costs for the various proposals. The first priority of the plant operator is to find a suitable design that satisfies the requirements of the national regulatory body. Firm backfitting solutions have not yet been reported to our knowledge. In addition costs would differ from country to country operating this type of reactor and depends also on the split between local and foreign participation.

In a recent study for the European Bank for Reconstruction an attempt was nevertheless undertaken to estimate the costs for confinement backfitting measures. According to this investigation the following investment cost were estimated:

- Increase leak tightness: 5 Mio. US$
- Containment Venting System 21 Mio US$

These figures are global figures and do, e.g. for the containment venting system, not reflect any specific design.
7.1 WWER 440, Model 230, Reactor Building

7.2 WWER 440, Model 230, Confinement
Fig. 4 VENTING SYSTEM FOR NPP V-1-ONE OF THE VARIANTS FOR HERMETIC ZONE UPGRADING.

1. HERMETIC ZONE
2. BACK PRESSURE SAFETY VALVE ROOM
3. CONNECTING PIPING
4. HEADER
5. VACUUM BREAKING SYSTEM
6. CONNECTING PIPING
7. Siphon Pool
8. SHOCK ABSORBERS
9. DROPLET SEPARATOR
10. VENTING TO ATMOSPHERE
11. POOL AUXILIARY SYSTEM
12. CONNECTING PIPING
13. COMBINED FILTER
14. STACK

7.3 WWER 440, Model 230, Proposed Relief System

Legend: 1 Reactor Pressure Vessel 5 Jet Condensers
        2 Dump Valves 6 Filter of FCVS
        3 Hermetic Confinement 7 Air trap Bldg. # 2
        4 Air Trap Bldg. # 1

Fig. 7.4 WWER 440, Model 230, Proposed Relief System with Jet Condenser (shown for 2 Units)
Fig. 7.5  Jet Condenser Design (schematic)

MC ... mixing chamber

steam-air mixture

non-condensables

water

7.6  WWER 440, Model 213, Pressure Suppression System
7.7 WWER 440, Model 230, Proposed Relief System with Filtration

Sprinkler (Spray) System

Fig. 7.8 Proposed upgrading for ECCS and Sprinkler System for WWER 440 Model 230 Plants
Fig. 7.9 WWER 440, Model 230, Proposed Relief System with Jet Condenser with Suction System (shown for 2 Units)

Fig. 7.10 Proposed Vacuum Breaker Design
MODE OF OPERATION: BLOWDOWN PHASE

PARTIAL FLOW

$P_{\text{conf}} \sim 5 \text{ m H}_2\text{O (50 kPa) overpressure}$

FULL FLOW

$P_{\text{conf}} \sim 6 \text{ to } 8 \text{ m H}_2\text{O (60 to 80 kPa) overpressure}$
MODE OF OPERATION: POST-BLOWDOWN PHASE

**P_{conf} = 2.5 \text{ m H}_2\text{O (25 kPa) overpressure}**

**FAN IN OPERATION**

MODE OF OPERATION: POST-BLOWDOWN PHASE

**P_{conf} = 0.2 \text{ m H}_2\text{O (2 kPa) underpressure}**

FROM CONFINEMENT

HF-FILTER

UPGRADING OF CONFINEMENT OF NPP KOZLODUY-UNIT 3 AND 4
IAEA CONSULTANTS' MEETING
ON
CONTAINMENT AND CONFINEMENT PERFORMANCE
IN NPPS WITH WWER 440/213 AND 440/230 REACTORS

REVIEW OF ANALYTICAL WORK ON BUBBLER
CONDENSER CONTAINMENT IN SLOVAKIA
(DESIGN BASIS ACCIDENTS)

J. Mišák
Nuclear Regulatory Authority
Bratislava, Slovak Republic

VIENNA, AUSTRIA
29 NOVEMBER - 3 DECEMBER 1993
REVIEW OF ANALYTICAL WORKS

COMPUTER CODES: TRACO V/Mod 2 (see description)
             CONTAIN

VERIFICATION OF CODES:

* EXPERIMENTS:
  - Batelle Institute, Frankfurt (Biblis model, 1 : 64),
    short-term pressure distribution in subdivided containment
    (fig. )
  - VTI Moscow results for bubble condenser
  - SVUSS Bechovice experimental results on bubble condenser
    (fig. )

* COMPARISON WITH CODES:
  - BURST (Hungary)
  - CONTEMPT-LT
  - CONTAIN
  - DDIFF-1 (pressure waves)

SPECTRUM OF BREAKS ANALYSED:

COLD LEG: 2 x 500, 250, 200, 107, 90, 25, 13 MM
HOT LEG: 2 x 500
PRESSURIZER LEAKS: 90 MM, SAFETY VALVE STUCK OPEN

SECONDARY SYSTEM
BREAKS: STEAM LINE BREAK, FEEDWATER LINE BREAK

CONTROL ROD EJECTION: 58.8 CM² LEAK FROM THE
REACTOR VESSEL

DEAERATION LINES: φ 13 MM, CONNECTED TO SG COLLECTORS
                 OR TO REACTOR HEAD
REVIEW OF ANALYTICAL WORKS (contd.1)

SENSITIVITY STUDIES:
(MOSTLY FOR FULL COLD LEG BREAK ONLY)

* NODALIZATION
* SPATIAL PRESSURE WAVES
* CARRY-OVER COEFFICIENTS
* HEAT TRANSFER WITH STRUCTURES
* NUMBER OF SPRAY PUMPS
* NUMBER OF VALVES INTO AIR LOCKS
* REDUCED AMOUNT OF WATER IN TRAYS

WEAK POINTS OF ANALYSIS:

* SPATIAL, NON-EQUILIBRIUM PROBLEMS DESCRIBED BY LUMPED PARAMETERS (OR 1D) EQUILIBRIUM MODELS
* INTERNAL SUBDIVISION OF CONTAINMENT NOT MODELLED SUFFICIENTLY IN DETAIL
* SEPARATION OF LIQUID CONSIDERED IN SIMPLIFIED WAY (CARRY-OVER COEFFICIENTS)
* HEAT EXCHANGE WITH STRUCTURES DESCRIBED ROUGHLY, STRONG INFLUENCE ON THE PROCESS
* Full steam condensation in water trays considered
* Water carry-over to air-locks not considered
* Local effects in water trays not addressed, even if it is in accordance with available experiments (level oscillations, pressure oscillations, water carry-over, steam channeling)
* Backward water expulsion from water trays and passive spraying described in simplified way, by quasi-stationary approach
* Analyses of accidents not performed for sufficiently long time interval
* Time period after reaching subatmospheric pressure in the containment not analysed sufficiently
MAIN REFERENCES FOR ANALYSIS


COMPARISON EXPERIMENT - TRAC0V

OBR. 25. EXPERIMENT - BIBLIS A C2 -

P [MPa]

0.16
0.14
0.12
0.10

0
0.5
1.0
1.5
2.0

Experiment

- μ = 0.8
- c1 = 0.4, c2 = 0.1
- α1-4 = 0 kW/m² · °C
- α2 = 1 kW/m² · °C
- α1-4 = 6 kW/m² · °C
- α2 = 1 kW/m² · °C
- μ = 0.8
- c1 = 0.4
- α1-4 = 6 kW/m² · °C
- α2 = 1 kW/m² · °C
- μ = 0.8
- c1 = 0.4
- α1-4 = 6 kW/m² · °C
- α2 = 1 kW/m² · °C

ΔP [MPa]

0.03
0.02
0.01

0
0.5
1.0
1.5
2.0

Experiment

1 (P1 - P3)
2 (P2 - P3)
3 (P4 - P3)
μ = 0.8
- c1 = 0.4, c2-5 = 0.1
- α1-4 = 6 kW/m² · °C
- α2 = 1 kW/m² · °C
- α1-5 = 0 kW/m² · °C
COMPARISON EXPERIMENT - TRACO V
FOR BUBBLE CONDENSER MODEL SVŮSS BĚCHOVICE

P1 - MODE 1
P8 - AIR LOCK
a - CALCULATION: TRACO
b - EXPER.. - SVŮSS Běchovice (°C)

TI - NODE 1
TA - SPACE BELOW TRAYS
T8 - AIR LOCK

PASSIVE SPRAYING
VARIOUS NODALIZATION SCHEMES

4-NODES SCHEME

6-NODES SCHEME
VARIOUS NODALIZATION SCHEMES
SCHEME WITH 23 NODES

Diagram showing various nodalization schemes with 23 nodes, including volume and area measurements.
PRESSURE WAVES CALCULATED BY TRACO V
FOR COLD LEG BREAK (2x500 MM)

NODALIZATION USED FOR ANALYSIS

17 340 m$^3$
17

9 100 m$^3$
1400 m$^3$/water
15

8025 m$^3$
8

14

12

13

11

10

9

8

7

6

5

4

3

2

1

SC compartments: 10x1320 m$^3$

air locks

vessel trays

bubble tower

Corridor

2x500 mm
PRESSURE WAVES CALCULATED BY TRACO V
FOR COLD LEG BREAK (2x500 MM) (contd. 1)

RESULTS

PRESSURE IN THE BREAK NODE

SPATIAL PRESSURE DISTRIBUTION
FOR DIFFERENT TIME POINTS
OPENING OF WATER SEALS IN TRAYS

GOVERNED BY
* WATER COLUMN INERTIA
* PRESSURE INCREASE IN FRONT OF SEALS

Results of parametrical calculations:

\[ P = P_0 + k \cdot T \]
\[ /k/ \text{ MPa/s} \]
1 - 0.360
2 - 0.180
3 - 0.090
4 - 0.045
5 - 0.020

Decrease of water level in upstream part of a seal for linear pressure increase

FOR SLOW PROCESSES: ONLY PRESSURE INCREASE IS IMPORTANT, OPENING AT DP = 4 + 5 kPa

FOR COLD LEG RUPTURE: TYPICAL PRESSURE INCREASE IN FRONT OF TRAYS IS 30 kPa/s, OPENING TIME IS 0.4 s, OPENING DP IS 12 kPa

NOTE: FOR SOME CALCULATIONS WITH DISTRIBUTED PARAMETERS (PRESSURE WAVES), PRESSURE INCREASE REACHED ~90 kPa/s, CORRESPONDING OPENING TIME WILL BE ~0.28 s, OPENING DP ~25 kPa
PRESSURE-TEMPERATURE TRANSIENT 
DURING BLOWDOWN (COLD LEG RUPTURE) 

Blowdown: \(-30 \pm 50 \text{s}\)

Maximum conservative parameters 
(no heat absorbtion, CRF = 1.0)

- SG COMPARTMENT PARAMETERS (AT 9 \(\pm\) 10 s): 226 kPa, 121.6 °C

- AVERAGE TEMPERATURE INCREASE IN TRAYS: 14.5 °C

- PRIMARY COOLANT CATCHED IN TRAYS: 83 TONS

- REMAINING MASS OF AIR IN SG COMPARTMENT: 6 %

- MASS OF AIR IN AIR LOCKS: 170 %

- SG COMPARTMENT PRESSURE AT THE END OF BLOWDOWN: 198 kPa

Effect of heat exchange with structures

- REDUCTION OF MAX. PRESSURE: 7 \(\pm\) 13 kPa

- REDUCTION OF COOLANT MASS CATCHED IN TRAYS: 15 \(\pm\) 20 TONS

- REDUCTION OF TEMPERATURE INCREASE IN TRAYS: 4 \(\pm\) 6 K

- REDUCTION OF PRESSURE AT THE END OF BLOWDOWN: 15 \(\pm\) 17 kPa
PRESSURE-TEMPERATURE TRANSIENT
DURING BLOWDOWN (COLD LEG RUPTURE)
(contd. 1)

Effect of carry-over coefficient (additional)
(reduction from CRF = 1.0 to 0.1)

- REDUCTION OF MAX. PRESSURE: 8 \div 9 \text{ kPa}
- REDUCTION OF COOLANT MASS CATCHED IN TRAYS: \text{33 TONS}
- REDUCTION OF TEMPERATURE INCREASE IN TRAYS: \text{2 K}
- REDUCTION OF PRESSURE AT THE END OF BLOWDOWN: \text{1 kPa}

Effect of parameters distribution along the height of condenser power (D E T A I L E D A N A L I S I S)

- PRESSURE DIFFERENCES ALONG THE HEIGHT NEGligible
- CONSIDERABLE DIFFERENCES IN WATER TEMPERATURE INCREASE IN TRAYS: 12.6 \div 21.6 \text{ K}
- MASS OF COOLANT CATCHED IN LOWEST FLOOR OF TRAYS BY 65 \% HIGHER THAN IN HIGHEST FLOOR OF TRAYS

Effect of number of check-valves into air-locks on maximum pressure (kPa)

<table>
<thead>
<tr>
<th>NUMBER OF VALVES</th>
<th>CRF = 0.1</th>
<th>CRF = 1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>208.9</td>
<td>217.6</td>
</tr>
<tr>
<td>24</td>
<td>198.1</td>
<td>201.1</td>
</tr>
<tr>
<td>48</td>
<td>194.1</td>
<td>199.3</td>
</tr>
</tbody>
</table>
PHASES OF PASSIVE SPRAYING

a) filling of the collector  
b) collector overflow  
c) draining of the collector

a) initial situation in the tray  
b) situation for  
c) water expulsion
THERMODYNAMIC PRESSURE DIFFERENCES ACROSS WALLS INSIDE THE SYSTEM FOR COLD LEG BREAK (CALCULATION BY TRACO V WITH 6 NODES)

PRESSURE DIFFERENCES:

- ACROSS WATER TRAYS: $+12$ (?) $-9$ kPa
- BUBBLE CONDENSER TOWER
  - AIR LOCKS: $+68$ $-100$ kPa
- SPACE ABOVE WATER TRAYS
  - AIR LOCKS: $+63$ $-100$ kPa
PRESSURE - TEMPERATURE TRANSIENT
IN THE BUBBLE CONDENSER FOLLOWING
COLD LEG BREAK (TRACO V)

PRESSURE IN SG COMPARTMENTS
AND IN AIR LOCKS

PRESSURE IN SG COMPARTMENTS
PRESSURE - TEMPERATURE TRANSIENT IN THE BUBBLE CONDENSER FOLLOWING COLD LEG BREAK (TRACO V)

TEMPERATURE IN SG COMPARTMENTS

TEMPERATURE IN SG COPARTMENTS
PRESSURE - TEMPERATURE TRANSIENT IN THE BUBBLE CONDENSER FOLLOWING COLD LEG BREAK (TRACO V)

TEMPERATURE IN AIR LOCKS

TEMPERATURE OF WATER IN TRAYS
EFFICIENCY OF SPRAYING

- DEGREE OF UTILIZATION OF THE DROPLET THERMAL CAPACITY

DEFINITION: \( \eta_{SP} = \frac{T_{SP} - T_{SPO}}{T_{M} - T_{SPO}} \)

\( T_{SP} \) - average temperature of droplet
\( T_{M} \) - steam-air mixture temperature

\( \eta_{SP} \) DEPENDS ON:
- thermodynamic parameters of both droplet and atmosphere
- droplet size
- length of path for heat exchange between droplet and atmosphere

Methodology for analysis

*)

Code SPRAY C.C.
- DEVELOPED BY ISPRA

*) C. Desogus, H. Holtbecker: SPRAY C.C. - SPRAY C.M. - SPRAY E.V.

BASIC ASSUMPTIONS:

- FREE VERTICAL FLOW OF A SPHERICAL WATER DROPLET AT EQUILIBRIUM VELOCITY
- HOMOGENOUS STEAM-AIR ATMOSPHERE
- CONDENSATION ON THE SURFACE BY HEAT-TRANSFER COEFFICIENT, CHANGE OF DROPLET SIZE CONSIDERED
- UNIFORM TEMPERATURE INSIDE THE DROPLET
EFFICIENCY OF SPRAYING (contd. 1)

CONCLUSIONS FROM CALCULATIONS:

1. If $\eta_{SP}$ is reached for given droplet radius $r_{SP1}$ and steam mass fraction in the mixture $S_1$ at fulling distance $X_{SP1}$, then for other conditions the same efficiency is reached at distance

$$X_{SP2} = X_{SP1} \left(\frac{r_{SP2}}{r_{SP1}}\right)^{5/2} \left(\frac{\psi_{S2}}{\psi_{S1}}\right)^{1/2}$$

$\Rightarrow$ strong dependency on droplet radius,
weak dependency on mixture composition

2. $\eta_{SP}$ is the same for the same time of droplet's fall (duration of heat exchange) - important for non-vertical fall of the droplet.
Recalculation of time needed to reach the same efficiency

$$\tau_{SP2} = \tau_{SP1} \left(\frac{r_{SP2}}{r_{SP1}}\right)^2 \left(\frac{\psi_{S1}}{\psi_{S2}}\right)^{1/2}$$

3. $\eta_{SP}$ reduced with increasing $T_{SP0}$ and by decreasing temperature of atmosphere $T_M$. 
EFFICIENCY OF SPRAYING (contd. 2)

PRACTICAL RESULTS FOR BUBBLE CONDENSER

Active spray system:

- 3 spray collectors at height 7.7 ± 9 m above the floor
- droplet radius 0.5 ± 0.75 mm

⇒ EFFICIENCY ≈100 %

Passive spraying:

- 11 floors of collectors, distance between floors ~3.4 m
- spraying through steel plate with φ 7 mm holes, droplets with diameter 5 ± 6 mm
- outflow droplet velocity ~2.5 m/s, angle ~80 ° to vertical direction, free fall velocity 8 ± 8.6 m/s.

EFFICIENCY (conservative, based on vertical distance of floors)

DROPLETS φ 5 mm

First floor: 0.185 ± 0.18 (change during spraying)
Last floor: 0.833 ± 0.810
Average (all floors): 0.60 ± 0.58

DROPLETS φ 6 mm

First floor: 0.120 ± 0.115
Last floor: 0.703 ± 0.673
Average: 0.48 ± 0.45
RESULTS OF CALCULATIONS BY THE SPRAY C.C. CODE:

FOR SPECIFIC VALUES OF $r_{SP}$, $\varphi_s$, $T_{SPO}$, $T_M$ SHOWN IN FIGURES, FOR OTHER VALUES OF $r_{SP}$, $\varphi_s$ IS POSSIBLE TO USE FORMULAE GIVEN.

QUESTIONS - OPEN ISSUES:

- VALIDITY OF THE MODEL (EXPERIMENTAL CONFIRMATION)

- AVAILABILITY OF MORE SOPHISTICATED MODELS

- MORE REALISTIC EVALUATION OF PASSIVE SPRAYING

REFERENCE:

Spraying efficiency vs length of a droplet fall for different temperatures of sprayed atmosphere of saturated steam and air $r_{sp}=1\text{mm}$, $\phi=0.6$, $T_{sp}=30^\circ\text{C}$
Spraying efficiency vs time for different temperatures of sprayed atmosphere of saturated steam and air

\( r_{SP} = 1 \text{mm}, \varphi_S = 0.6, T_{SP \theta} = 30^\circ C \)
EFFICIENCY OF SPRAYING (contd. 4)

Minimum temperature of the atmosphere, which can be achieved by the spray system operation:

\[ T_{MIN} = 0.2414 \left( X h_L + (1-X) h_{SP} - 5.16 \right) \]

\[ X = \frac{G_L}{(G_L + G_{SP})} \]

\[ [T_{MIN}] = ^\circ C \]

- \( G_L \) - coolant outflow mass flow rate [kg/s]
- \( h_L \) - coolant enthalpy [kJ/kg]
- \( G_{SP} \) - spray flow [kg/s]
- \( h_{SP} \) - spray water enthalpy [kJ/kg]

Graph: T_MIN vs. \( h_L \) with \( G_L = 5 \) kg/s and spray water temperature 30 °C
CONCLUSIONS

* NO VIOLATION OF DESIGN LIMITS HAS BEEN INDICATED BY CALCULATIONS DONE

* NO DIRECT NEED FOR MODIFICATIONS WAS IDENTIFIED BY DBA ANALYSIS

* SOPHISTICATED CODES SPECIFICALLY DEVELOPED FOR BUBBLE CONDENSERS WILL BE VERY HELPFUL TO CONFIRM PREVIOUS CONCLUSIONS

* LARGE SCALE EXPERIMENTS COULD REDUCE DOUBTS ABOUT FUNCTIONING OF THE BUBBLE CONDENSER

* FUNCTIONING OF THE CONTAINMENT SHALL BE BETTER INVESTIGATED FOR MEDIUM SIZE BREAKS; THESE BREAKS SHOULD BE ANALYSED OVER SUFFICIENTLY LONG TIME

* A BASIS FOR LIMITATION OF THE CONTAINMENT LEAKAGES SHOULD BE DEVELOPED OR DEFINED
APPENDIX 1

SHORT DESCRIPTION OF TRACO V CODE

TRACO V/MOD 2

1. DESIGNATION OF THE PROGRAM
TRACO V is a complex code for the calculation of space- and
time-dependent pressures and temperatures in containments of
different types (full-pressure, pressure suppression, etc.) or
in the hermetic compartments of PWR during LOCA for both
short-term and long-term transients. Analysis of processes in
the primary circuit should be performed by a separate code.
Time functions of the break flow and enthalpy obtained from
such analysis are used as boundary conditions for containment
transients.

2. BASIC ASSUMPTIONS AND METHOD OF SOLUTION
TRACO V calculates simultaneously the flows between internal
containment subvolumes and heat exchange with the
heat-conducting structures.

Internal containment volume is assumed to be subdivided into
arbitrary number of nodes (subvolumes), each of them can
contain the two-component mixture of air-superheated steam or
the two-phase two-component mixture air-saturated steam-water.
Equal temperatures of all components and uniform pressure are
assumed for each node. Non-equilibrium temperature
distribution within the containment should be modelled by
appropriate nodalization. Non-ideal phase separation can be

A.1
accounted for through the input carry-over coefficients. Gaseous components in each node are considered to be ideally mixed. Total volume of the node is constant, but gaseous space can be reduced by increasing volume of the liquid. Thermodynamic properties of water are described by analytical expressions, air is treated as an ideal gas.

Individual nodes can be arbitrarily interconnected by means of arbitrary number of openings or flow channels (tubes). The flow area of any opening can be either constant, or it can abruptly change at given pressure difference between nodes. The subcritical and critical flow of the steam-air-water droplets mixture is calculated by the "frozen" flow model (without phase changes). Hydrostatic pressure differences due to water seals (e.g., condensation pools) between nodes are accounted for. Liquid flow model is used to keep the liquid volume in a specified node under prescribed value. Quasi-stationary momentum equation is usually used to calculate a mixture mass flow rate, but a non-stationary equation with flow inertia is also available for pressure waves calculation.

One-dimensional heat-conduction equation in various geometries is solved for an arbitrary number of heat-conducting structures, possibly composed of different material layers. Heat transfer coefficients are either specified as input time functions or calculated from mixture properties in individual nodes.

Normal or accidental containment leakages are also accounted for. Operation of the spray system, emergency core cooling system, ventilation system and fan coolers are also considered. Cooling of spray water in heat exchangers (various types) is modelled.

Transient behaviour of the system is described by the set of ordinary non-linear differential equations for mass inventories of coolant and air and for the temperatures for each node. This set is completed by heat-conduction equations for heat.
structures and one-dimensional mixture momentum equations for flow channels. The mixture mass and energy balance equations are solved by the simple 1-st order Euler method. The heat conduction equations are transformed into an implicit scheme, which is solved by the method of factorization. The mixture momentum equation is solved analytically within one time step.

3. INPUT AND OUTPUT CHARACTERISTICS
As input data for calculation are specified geometrical and hydraulic parameters of the internal containment volume, initial space distribution of temperature and air humidity, carry-over coefficients for individual compartments, geometry and materials for heat-exchange walls, specification of leaks, spray system, recirculation system, ECCS, heat exchangers, time functions of break flow and enthalpy and other time functions of coolant mass flow rate and thermal power supplied to any node.

As results of calculation are obtained time functions for pressures, temperatures, post-accident compositions of atmosphere in individual compartments, mixture flows through openings and junctions, leakages to environment, temperature profiles in heat-exchange structures, etc. The code has a parallel graphic processor allowing monitoring of any 4 curves from results (during computation).

4. STATUS OF PROGRAM VERIFICATION
The program has been verified on the basis of available experimental results. For short-term period of the processes in a full-pressure containment, experimental results from Batelle-Institut, Frankfurt (model of the containment of NPP Biblis, scale 1:64) were used for the code validation. Calculation of processes in the bubble condenser (barbotage system) was checked by means of experimental results from VTI Moscow and from Czechoslovak institute SVUSS, Bechovice

A.3
Prague. For long-term transient in the full pressure containment the results were successfully tested by comparison with US code CONTEMP-LT, for analysis of pressure wave propagation with German code DDIFF-1. In all above mentioned cases the agreement with experiments and other calculations was very good provided that carry-over coefficients, flow contraction coefficients and heat transfer coefficients were estimated properly.

5. REFERENCES

IAEA CONSULTANTS’ MEETING
ON
CONTAINMENT AND CONFINEMENT PERFORMANCE
IN NPPS WITH WWER 440/213 AND 440/230 REACTORS

REVIEW OF EXPERIMENTAL AND ANALYTICAL
WORK ON BUBBLER CONDENSER
CONTAINMENT IN CZECH REPUBLIC

J. Kujal
Nuclear Research Institute
Řež, Czech Republic

VIENNA, AUSTRIA
29 NOVEMBER - 3 DECEMBER 1993
Analysis of the bubble condenser tower shaft
The main objective:
To determine internal pressure level at which the hermetic boundary failure should be expected in the bubble tower shaft and identify the probable location of failure area.
Assumptions:
- Combination of normal operation loads (weight), loads resulting from DBA conditions: temperature distribution and internal pressure loads was taken as the resulting loading of the structure.
- The capability of the liner to carry tensile stress was taken into account.
- Single structure model, the effect of neighbour buildings and structures was described by means of boundary conditions (elastic - type) and at the bottom of the shaft also elastic boundary conditions were used. Finite element code SAP6 (3000 elements).

Results:

<table>
<thead>
<tr>
<th>p &lt; 0.5 [MPa]</th>
<th>hermetic boundary leaktightness is preserved</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.54 &lt; p &lt; 0.66 [MPa]</td>
<td>the stresses in some elements are equal to maximum allowable stress</td>
</tr>
<tr>
<td>0.5 &lt; p &lt; 0.8 [MPa]</td>
<td>increasing probability of the failure of the hermetic boundary</td>
</tr>
<tr>
<td>p &gt; 0.8 [MPa]</td>
<td>rupture of reinforced concrete structure</td>
</tr>
</tbody>
</table>

Both side walls are the region of probable occurrence of failure spots.
Literature


Tab. 1 The Modelling Conditions of the SVÚSS Test Facility

<table>
<thead>
<tr>
<th>Component</th>
<th>NPP Mochovce Volumes m³</th>
<th>Volumes in Ratio 1:2011 m³</th>
<th>Facility Components Volumes m³</th>
<th>Modell Exploitation Ratio %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Vessel and Tubing System</td>
<td>218,7</td>
<td>0,109</td>
<td>0,267</td>
<td>41,5</td>
</tr>
<tr>
<td>Steam Generator Boxes and Corridor</td>
<td>12740,0</td>
<td>6,385</td>
<td>3,43</td>
<td>184,7</td>
</tr>
<tr>
<td>Blind Compartments</td>
<td>6000</td>
<td>2,984</td>
<td>6,56</td>
<td>45,5</td>
</tr>
<tr>
<td>Localisation Shaft</td>
<td>6500</td>
<td>3,232</td>
<td>2,741</td>
<td>117,9</td>
</tr>
<tr>
<td>Water Pool</td>
<td>1400</td>
<td>0,696</td>
<td>0,696</td>
<td>100</td>
</tr>
<tr>
<td>Cap-gap system Wettwell</td>
<td>6500</td>
<td>3,232</td>
<td>4,309</td>
<td>75,0</td>
</tr>
<tr>
<td>Additional Air Traps</td>
<td>16470</td>
<td>8,324</td>
<td>11,08</td>
<td>75,1</td>
</tr>
<tr>
<td>Corrected Add Air Traps Volume</td>
<td>16470</td>
<td>8,324</td>
<td>8,08</td>
<td>103,0</td>
</tr>
<tr>
<td>Drywell Volume</td>
<td>25240</td>
<td>12,55</td>
<td>12,73</td>
<td>98,6</td>
</tr>
<tr>
<td>Wettwell Volume</td>
<td>22970</td>
<td>11,422</td>
<td>15,39</td>
<td>74,2</td>
</tr>
<tr>
<td>Corrected Wettwell</td>
<td>22970</td>
<td>11,422</td>
<td>12,38</td>
<td>92,9</td>
</tr>
</tbody>
</table>
Fig. 5: Melcor Calculation of PSE
Pressure in pressure vessel

Fig. 6: Melcor Calculation of PSE
Pressure before PSS
Summary of findings

1) Thermal and technological settings for PSS inside hermetic volumes of VVER-44%/213 are correct and reproducible. Performance with some specific features (passive spraying) is necessary to increase efficiency of thermal capacity of water in the bubble tower. Additional technological elements ensuring this function (special check valves, withholding and collecting device of water pouring-off from water trays).

The PSS can withstand twice higher overload in comparison with DBA coming from flow of noncondensable gases, the flow cross section of the DN500 check valves to airlock volumes imposes limitation of overloading of the system because of pressure increase in the volume of PSS.

2) Generic checking of seismic resistance of PSS shows in some extent contradictory results. For combined loadings of two types-nominal operation + maximum computational earthquake and DBA + design earthquake - stress in the PSS piping exceed limiting values.

Also dynamic forces in PSS bearing system for combined loading of nominal operation and maximum computational earthquake exceed limiting values (≈ 10%).

At the analytical modelling of DBA, effects of pressure shock were not included.
Summary of findings - continued

3) Efficiency of the spray system depends on the flowrate of the coolant, temperature of water, and on the contents of air in the atmosphere. Coming from available data for air concentration in the hermetic volumes, design flow rates and temperatures of water the spray efficiency is sufficient. Experiment confirmed the design assumptions on spray efficiency if modelling conditions (pushing out of air and steam - air mixing) correspond to the NPP conditions.

4) VUEZ Tlmače results show different state of hermetic volumes for particular NPP units. Containment tightness of the older units is lower than design magnitude. Progression of corrosion does not impose limitation on lifetime of the units.
**Table I.: Description of accident sequences**

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Description</th>
<th>Data Source(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S22B</td>
<td>small break LOCA ($d_e = 40$ mm), blackout [2], calculated with data set [1]</td>
<td></td>
</tr>
<tr>
<td>S22C</td>
<td>small break LOCA ($d_e = 40$ mm), spray system failure [3], calculated with data set [1]</td>
<td></td>
</tr>
<tr>
<td>S23I</td>
<td>medium break LOCA ($d_e = 100$ mm), only HPIS available [3], calculated with data set [1]</td>
<td></td>
</tr>
<tr>
<td>S23II</td>
<td>medium break LOCA ($d_e = 100$ mm), only HPIS available without ECCS heat exchanger [3], calculated with data set [1]</td>
<td></td>
</tr>
<tr>
<td>S23B</td>
<td>medium break LOCA ($d_e = 100$ mm), blackout [3], calculated with data set [1] and operation leakage 6% of air volume per 24 hours</td>
<td></td>
</tr>
<tr>
<td>S23B-2</td>
<td>medium break LOCA ($d_e = 100$ mm), blackout [4], calculated with data set [1] and operation leakage 18% of air volume per 24 hours</td>
<td></td>
</tr>
<tr>
<td>S23B-VC</td>
<td>medium break LOCA ($d_e = 100$ mm), blackout and vented containment [5], calculated with data set [1]</td>
<td></td>
</tr>
<tr>
<td>S23BB</td>
<td>medium break LOCA ($d_e = 100$ mm), blackout, concrete composition from Jaslovske Bohunice NPP [6], calculated with data set [1]</td>
<td></td>
</tr>
<tr>
<td>S23BB1</td>
<td>medium break LOCA ($d_e = 100$ mm), blackout, concrete composition from Temelín NPP [6], calculated with data set [1]</td>
<td></td>
</tr>
<tr>
<td>S1B*</td>
<td>medium break LOCA ($d_e = 100$ mm), blackout [7]</td>
<td></td>
</tr>
<tr>
<td>S1D*</td>
<td>medium break LOCA ($d_e = 100$ mm), HPIS and LPIS systems failure (both in injection and recirculation phases) [7]</td>
<td></td>
</tr>
<tr>
<td>S24B</td>
<td>medium break LOCA ($d_e = 200$ mm), blackout, calculated as small LOCA (blown down phase) [8], calculated with data set [1]</td>
<td></td>
</tr>
<tr>
<td>A200B</td>
<td>large break LOCA ($d_e = 200$ mm), blackout, calculated as large LOCA (blown down phase) [8] and [9], calculated with data set [1]</td>
<td></td>
</tr>
<tr>
<td>AB-2</td>
<td>large break LOCA ($d_e = 2 \times 500$ mm), blackout [9], calculated with data set [1] and operation leakage 18% of air volume per 24 hours</td>
<td></td>
</tr>
<tr>
<td>AB-ESC</td>
<td>large break LOCA ($d_e = 2 \times 500$ mm), blackout, calculated by ESCADRE code [10]</td>
<td></td>
</tr>
<tr>
<td>AB*</td>
<td>large break LOCA ($d_e = 2 \times 500$ mm), blackout [11]</td>
<td></td>
</tr>
</tbody>
</table>
TMLB-SD transient with MCP seals damage, blackout [11]

............. the sequence was analyzed in VÚJE Trnava
<table>
<thead>
<tr>
<th></th>
<th>CU</th>
<th>SFP</th>
<th>SCM</th>
<th>CC</th>
<th>G1C</th>
<th>SVH</th>
<th>NWBT</th>
<th>RPVF</th>
<th>SCC</th>
<th>HB/C</th>
<th>END</th>
</tr>
</thead>
<tbody>
<tr>
<td>S22B</td>
<td>45.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>120.1</td>
<td>145.6</td>
<td>155.8</td>
<td>165.6</td>
<td>251.2</td>
<td>251.9</td>
<td>250.6</td>
<td>250.3</td>
<td>257.9</td>
<td>250.50/2</td>
<td>413.90/1</td>
</tr>
<tr>
<td>S22C</td>
<td>it is not severe accident</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S22D</td>
<td>it is not severe accident</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S22II</td>
<td>5650.9</td>
<td>5767.2</td>
<td>5782.27</td>
<td>5667.77</td>
<td>5960.17</td>
<td>5960.86</td>
<td>6539.28</td>
<td>6340.29</td>
<td>7169.48</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S22B</td>
<td>31.45</td>
<td>49.52</td>
<td>55.51</td>
<td>67.76</td>
<td>154.27</td>
<td>154.96</td>
<td>173.73</td>
<td>251.77</td>
<td>251.81</td>
<td>173.73/2</td>
<td>7091.0</td>
</tr>
<tr>
<td>S22B</td>
<td>30.31</td>
<td>48.15</td>
<td>52.05</td>
<td>66.17</td>
<td>152.71</td>
<td>153.40</td>
<td>151.38</td>
<td>248.71</td>
<td>249.75</td>
<td>151.35/1</td>
<td>7090.0</td>
</tr>
<tr>
<td>S22B</td>
<td>31.6</td>
<td>49.7</td>
<td>55.8</td>
<td>64.8</td>
<td>151.2</td>
<td>152.2</td>
<td>249.3</td>
<td>250.3</td>
<td>147.30/2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S22B</td>
<td>391.40/2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S22B</td>
<td>605.30/3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S22B</td>
<td>825.60/3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S22B</td>
<td>765.60/2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S22B</td>
<td>7151.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1Bx</td>
<td>35.5</td>
<td>54.0</td>
<td>58.7</td>
<td>73.9</td>
<td>141.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1Bx</td>
<td>260.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1Bx</td>
<td>179.90/2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1Bx</td>
<td>560.00/2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1Bx</td>
<td>7200.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1Bx</td>
<td>76.20/1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1Bx</td>
<td>280.00/1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1Bx</td>
<td>340.00/1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1Bx</td>
<td>660.00/2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1Bx</td>
<td>7200.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S24B</td>
<td>6.97</td>
<td>16.37</td>
<td>21.12</td>
<td>33.21</td>
<td>96.61</td>
<td>97.29</td>
<td>198.77</td>
<td>198.61</td>
<td>332.83/1,2</td>
<td>7200.0</td>
<td></td>
</tr>
<tr>
<td>A200B</td>
<td>26.17</td>
<td>43.67</td>
<td>47.17</td>
<td>69.17</td>
<td>158.42</td>
<td>159.17</td>
<td>109.72</td>
<td>265.17</td>
<td>266.21</td>
<td>109.70/1</td>
<td>7196.22</td>
</tr>
<tr>
<td>Event identification</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CU ........ Core uncovery [min]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SFP .... Start of F.P. release [min]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SCM .... Start of core melting [min]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CC ..... Core collapse [min]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G1C .... Grid 1 collapse [min]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SVH .... Start of RPV head heating up [min]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NWBT ... No water in bubbler tower [min]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RPVF ... RPV failure [min]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SCCI ... Start of core/concrete interaction [min]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HB/C ... Hydrogen burning [min][number of compartment]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>END .... End of calculation [min]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model</td>
<td>HI/C</td>
<td>MP</td>
<td>MT</td>
<td>PEND</td>
<td>HP</td>
<td>VP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>------</td>
<td>----</td>
<td>----</td>
<td>------</td>
<td>----</td>
<td>----</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S22B</td>
<td>250.30/2</td>
<td>0.500</td>
<td>1550.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>415.90/1</td>
<td>0.410</td>
<td>1540.0</td>
<td>0.255</td>
<td>140.0</td>
<td>250.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S22C</td>
<td></td>
<td></td>
<td></td>
<td>0.145</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S22I</td>
<td></td>
<td></td>
<td></td>
<td>0.100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S22II</td>
<td></td>
<td></td>
<td></td>
<td>0.350</td>
<td>28.0</td>
<td>58.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S21B</td>
<td>173.73/2</td>
<td>0.505</td>
<td>1557.0</td>
<td>0.505</td>
<td>146.0</td>
<td>214.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S21B-2</td>
<td>131.55/1</td>
<td>0.203</td>
<td>1257.0</td>
<td>0.225</td>
<td>160.0</td>
<td>220.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S21B-VC</td>
<td>147.20/2</td>
<td>0.287</td>
<td>1506.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>591.40/2</td>
<td>0.307</td>
<td>1332.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>603.30/2</td>
<td>0.354</td>
<td>1315.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>855.40/3</td>
<td>0.346</td>
<td>1404.0</td>
<td>0.107</td>
<td>160.0</td>
<td>205.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S22B</td>
<td>173.73/2</td>
<td>0.508</td>
<td>1547.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>765.60/2</td>
<td>0.561</td>
<td>1562.0</td>
<td>0.270</td>
<td>120.0</td>
<td>296.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S22B1</td>
<td>173.73/2</td>
<td>0.508</td>
<td>1547.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>495.80/2</td>
<td>0.453</td>
<td>1311.0</td>
<td>0.270</td>
<td>120.0</td>
<td>294.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1Bs</td>
<td>179.90/2</td>
<td>0.517</td>
<td>1532.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>560.00/2</td>
<td>0.351</td>
<td>966.0</td>
<td>0.220</td>
<td>165.0</td>
<td>170.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1Ds</td>
<td>76.20/1</td>
<td>0.216</td>
<td>1086.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>280.00/1</td>
<td>0.228</td>
<td>1138.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>340.00/1</td>
<td>0.253</td>
<td>1130.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>660.00/2</td>
<td>0.390</td>
<td>1519.0</td>
<td>0.120</td>
<td>160.0</td>
<td>200.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S24B</td>
<td>332.85/1</td>
<td>0.441</td>
<td>1515.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>332.85/2</td>
<td>0.457</td>
<td>1532.0</td>
<td>0.230</td>
<td>160.0</td>
<td>215.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A200B</td>
<td>109.70/1</td>
<td>0.194</td>
<td>1196.0</td>
<td>0.255</td>
<td>155.0</td>
<td>215.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AB-2</td>
<td>76.76/1</td>
<td>0.220</td>
<td>1170.0</td>
<td>0.250</td>
<td>155.0</td>
<td>215.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AB-ESC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ABs</td>
<td>72.70/1</td>
<td>&lt;0.240</td>
<td>&lt;1200.0</td>
<td>0.227</td>
<td>155.0</td>
<td>165.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TMILB</td>
<td>725.50/2</td>
<td>0.350</td>
<td>&lt;1250.0</td>
<td>0.228</td>
<td>155.0</td>
<td>215.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TMILB-SDs</td>
<td>597.20/2</td>
<td>0.300</td>
<td>1350.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>603.00/1</td>
<td>0.260</td>
<td>&lt;500.0</td>
<td>0.218</td>
<td>150.0</td>
<td>210.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Containment parameters

HB/C ... Hydrogen burning [min/number of compartment]
MP ..... Maximum pressure at hydrogen burning [MPa]
MT ..... Maximum temperature at hydrogen burning [K]
PEND ... Pressure in the end of calculation [MPa] (u-goes up, d-goes down, s-slowly)
HP ..... Horizontal depth of concrete penetration [cm]
VP ..... Vertical depth of concrete penetration [cm]
Containment integrity threats can be qualitatively assessed and summarized in the following table:

<table>
<thead>
<tr>
<th>Description of threat</th>
<th>Sequences</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S21B S22B S23B A200B AB TB S22H S21G S23II</td>
</tr>
<tr>
<td>Normal leak (18%/day)</td>
<td>Y Y Y Y Y Y Y Y Y</td>
</tr>
<tr>
<td>Long-term overpressure</td>
<td>+ + + + + + + + + +</td>
</tr>
<tr>
<td>Short-term overpressure due to hydrogen combustion</td>
<td>++ ++ 0 0 0 ++ ++ ++ 0</td>
</tr>
<tr>
<td>Containment base meltthrough</td>
<td>++ ++ ++ ++ ++ ++ + +</td>
</tr>
<tr>
<td>Cavity door meltthrough</td>
<td>++ ++ ++ ++ ++ ++ ++ +</td>
</tr>
<tr>
<td>Early overpressure due to steam or. noncondens gases.</td>
<td>0 0 0 0 0 0 0 0 0 0</td>
</tr>
<tr>
<td>Steam explosion in cavity</td>
<td>0 0 0 0 0 0 0 0 0 0</td>
</tr>
<tr>
<td>Insulation fault (door open, etc.)</td>
<td>+ + + + ++ ++ ++ +</td>
</tr>
<tr>
<td>DCH</td>
<td>+ + 0 0 0 + + + + 0</td>
</tr>
<tr>
<td>Containment bypass</td>
<td>0 0 0 0 0 ++ 0 0 0 0</td>
</tr>
</tbody>
</table>

Symbols used:

Y......yes, very probable
++......probable
+......less probable
0......need not be considered
?......improbable, but we are not sure
The main disadvantageous design features of the VVER-440/213 containment

- the rebar mass in the accident localization system is about 115 kilograms per cubic meter of reinforced concrete (175 ÷ 260 kg/m³ typically used in U.S. constructions),
- design of hermetic rooms did not consider the maximum computational earthquake intensity (8° of MSK scale), this feature is not so important for Czech NPPs,
- high leakage rate from unspoilt accident localization system, (range from 6% to 18% of net volume per 24 hours),
- the rectangular shape of accident localization compartments is not advantageous from point of view possible over/underpressurization of the rooms,
- the hydrogen mitigation system is designed only for hydrogen generation under nominal operation and accident conditions including design basis accident. At beyond DBA when the mass of hydrogen produced can reach 1000 kg and generation rate becomes very high additional efficient recombination system is necessary,
- relatively narrow reactor cavity can hardly master highly energetic events,
- relatively low thickness of the reactor cavity wall or bottom,
- placement of hermetic door in the reactor shaft wall at the reactor cavity bottom level could bring about relatively early penetration of melted core into non-hermetic rooms,
- the absence of filtered venting system,
- no indication of the containment atmosphere composition (hydrogen burning).
The VVER-440/213 Containment Integrity/Leak Threats

1. Long term overpressurization of the containment by noncondensible gases during melted core-concrete interaction. The containment design pressure is 0.25 MPa and in some cases long-term containment pressure is well above this pressure.

2. Short-term overpressurization of the containment during hydrogen combustion (or carbon monoxide). Another highly energetic events (DCH, steam explosion) were not considered.

3. Low leaktightness of the unfailed containment results in relatively high source term several orders higher than source terms from unfailed containment of western PWRs. For example maximum leakages to environment from unfailed containment reach for AB sequence and leakage rate 18% of total volume/day 30 tons of steam, 50000 m³ of gases, more than 50% of noble gases, and 13% of fission product decay heat carriers.

4. The meltthrough of the containment basemat slab or cavity walls threatens containment integrity because of relatively thin cavity walls.

5. High temperature of the containment atmosphere during combustion of inflammable gases.
Pressure suppression safety system of the accident localization for the VVER-440/213 NPP

Main objectives of the study:

1) Verification of physical principles of the pressure suppression system (PSS) in the containment and impact of possible deviations from anticipated function on a validity of the preoperational safety report

2) Generic checking of seismic resistance of the operational part of PSS coming from the present knowledge of possible seismic loads in the NPP site

3) Influence of the spray system on the PSS function and accident localization system

4) Checking of the NPP Jaslovské Bohunice hermetic volumes from point of view tightness and ageing
WWER-440/213 NPP with vented containment

(Draft of summary report)

Nuclear Research Institute
Řež, Czech Republic

November 1993
TABLE 1: Timing of main events accompanying the progression of S23 sequence (NC = non-vented, VC = vented containment). HA = hydroaccumulators. First variant of venting path.

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Time (min.)</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NC</td>
<td>VC</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>8.5</td>
<td>8.4</td>
</tr>
<tr>
<td></td>
<td>30.5</td>
<td>31.6</td>
</tr>
<tr>
<td></td>
<td>48.1</td>
<td>49.7</td>
</tr>
<tr>
<td></td>
<td>52.3</td>
<td>53.8</td>
</tr>
<tr>
<td></td>
<td>66.2 (54.8%)</td>
<td>64.8 (57.0%)</td>
</tr>
<tr>
<td>S23B</td>
<td>131.3</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>132.9 (27.3%)</td>
<td>131.2 (29.9%)</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>147.2</td>
</tr>
<tr>
<td></td>
<td>250.2</td>
<td>249.3</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>391.3</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>603.3</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>825.4</td>
</tr>
</tbody>
</table>
TABLE 3: Timing of main events accompanying the progression of 3 severe accident sequences (NC = non-vented, VC = vented containment)

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Event</th>
<th>Time (min.)</th>
<th>NC</th>
<th>VC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AB</td>
<td>Core uncovery</td>
<td>19.9</td>
<td>19.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Start of fission products release</td>
<td>35.9</td>
<td>35.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Start of core melting</td>
<td>40.1</td>
<td>41.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Core collapse (% of core is melted)</td>
<td>61.1 (52.7%)</td>
<td>62.5 (53.8%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Collapse of the first support grid (% of Zr reacted)</td>
<td>129.9 (25.0%)</td>
<td>137.0 (24.5%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RPV bottom head failure</td>
<td>253.6</td>
<td>266.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>First hydrogen ignition (compartment No.)</td>
<td>72.6 (No.1)</td>
<td>165.5 (No.2)</td>
<td></td>
</tr>
<tr>
<td>S23B</td>
<td>Core uncovery</td>
<td>30.5</td>
<td>30.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Start of fission products release</td>
<td>48.1</td>
<td>48.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Start of core melting</td>
<td>52.3</td>
<td>52.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Core collapse (% of core is melted)</td>
<td>66.2 (54.8%)</td>
<td>63.5 (56.7%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Collapse of the first support grid (% of Zr reacted)</td>
<td>132.9 (27.3%)</td>
<td>129.7 (30.1%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RPV bottom head failure</td>
<td>250.2</td>
<td>246.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>First hydrogen ignition (compartment No.)</td>
<td>131.1 (No.1)</td>
<td>148.8 (No.2)</td>
<td></td>
</tr>
<tr>
<td>TB</td>
<td>Core uncovery</td>
<td>677.4</td>
<td>679.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Start of fission products release</td>
<td>707.8</td>
<td>709.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Start of core melting</td>
<td>723.4</td>
<td>725.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Core collapse (% of core is melted)</td>
<td>762.1 (43.6%)</td>
<td>764.1 (44.3%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Collapse of the first support grid (% of Zr reacted)</td>
<td>832.3 (24.3%)</td>
<td>828.1 (24.0%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RPV bottom head failure</td>
<td>852.3</td>
<td>847.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>First hydrogen ignition (compartment No.)</td>
<td>- (No.2)</td>
<td>847.1 (No.2)</td>
<td></td>
</tr>
</tbody>
</table>
Table 4: AB sequence. Hydrogen combustion characteristics for non-vented and vented containment. $P_{\text{max}} =$ calculated pressure in compartment 3 did not exceed 0.112 MPa.

<table>
<thead>
<tr>
<th>No</th>
<th>Comp.</th>
<th>$t_b$ (min.)</th>
<th>$\Delta t_b$ (sec)</th>
<th>$P_{\text{max}}$ (MPa)</th>
<th>$T_{\text{max}}$ (K)</th>
<th>$\text{MH}_2$ (kg)</th>
<th>MCO (kg)</th>
<th>Q (GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.</td>
<td>1</td>
<td>73</td>
<td>0.87</td>
<td>0.22</td>
<td>1175</td>
<td>157</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>2.</td>
<td>1</td>
<td>166</td>
<td>0.85</td>
<td>0.31</td>
<td>1360</td>
<td>52</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3.</td>
<td>1</td>
<td>640</td>
<td>4.24</td>
<td>*</td>
<td>1259</td>
<td>49</td>
<td>293</td>
</tr>
<tr>
<td></td>
<td>4.</td>
<td>1</td>
<td>1275</td>
<td>4.52</td>
<td>*</td>
<td>1272</td>
<td>95</td>
<td>659</td>
</tr>
<tr>
<td></td>
<td>5.</td>
<td>1</td>
<td>1840</td>
<td>3.74</td>
<td>*</td>
<td>1292</td>
<td>51</td>
<td>378</td>
</tr>
<tr>
<td></td>
<td>6.</td>
<td>1</td>
<td>1843</td>
<td>3.96</td>
<td>*</td>
<td>1242</td>
<td>45</td>
<td>339</td>
</tr>
<tr>
<td></td>
<td>7.</td>
<td>1</td>
<td>2570</td>
<td>3.98</td>
<td>*</td>
<td>1258</td>
<td>50</td>
<td>388</td>
</tr>
<tr>
<td></td>
<td>8.</td>
<td>1</td>
<td>2574</td>
<td>4.45</td>
<td>*</td>
<td>1215</td>
<td>44</td>
<td>382</td>
</tr>
<tr>
<td></td>
<td>9.</td>
<td>1</td>
<td>3523</td>
<td>3.52</td>
<td>*</td>
<td>1240</td>
<td>48</td>
<td>394</td>
</tr>
<tr>
<td></td>
<td>10.</td>
<td>1</td>
<td>3538</td>
<td>3.73</td>
<td>*</td>
<td>1144</td>
<td>42</td>
<td>348</td>
</tr>
<tr>
<td></td>
<td>11.</td>
<td>1</td>
<td>4610</td>
<td>3.82</td>
<td>*</td>
<td>1254</td>
<td>48</td>
<td>402</td>
</tr>
<tr>
<td></td>
<td>12.</td>
<td>1</td>
<td>4636</td>
<td>3.74</td>
<td>*</td>
<td>1123</td>
<td>41</td>
<td>348</td>
</tr>
<tr>
<td></td>
<td>13.</td>
<td>1</td>
<td>5235</td>
<td>3.90</td>
<td>*</td>
<td>1201</td>
<td>46</td>
<td>386</td>
</tr>
<tr>
<td></td>
<td>14.</td>
<td>1</td>
<td>5768</td>
<td>3.96</td>
<td>*</td>
<td>1201</td>
<td>46</td>
<td>388</td>
</tr>
<tr>
<td></td>
<td>15.</td>
<td>1</td>
<td>5985</td>
<td>4.07</td>
<td>*</td>
<td>1213</td>
<td>44</td>
<td>373</td>
</tr>
</tbody>
</table>

- $t_b$ (min.) ...... time of hydrogen ignition
- $\Delta t_b$ (sec) ...... duration of ignition
- $P_{\text{max}}$ (MPa) ...... maximum compartment pressure
- $T_{\text{max}}$ (K) ...... maximum temperature of compartment atmosphere
- $\text{HN}_2$ (kg) ...... mass of hydrogen burned
- MCO (kg) ...... mass of carbon monoxide burned
- Q (GJ) ...... energy released at ignition
Table 6: TB sequence. Hydrogen combustion characteristics for non-vented and vented containment. \( P_{\text{max}} = * \) ... calculated pressure in compartment 3 did not exceed 0.112 MPa

<table>
<thead>
<tr>
<th>No</th>
<th>Comp.</th>
<th>( t_a ) (min.)</th>
<th>( \Delta t_a ) (sec)</th>
<th>( P_{\text{max}} ) (MPa)</th>
<th>( T_{\text{max}} ) (K)</th>
<th>( \text{NH}_2 ) (kg)</th>
<th>( \text{MCO} ) (kg)</th>
<th>( Q ) (GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>847</td>
<td>0.90</td>
<td>0.30</td>
<td>1316</td>
<td>48</td>
<td>0</td>
<td>5.9</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>2174</td>
<td>4.51</td>
<td>*</td>
<td>1053</td>
<td>67</td>
<td>7</td>
<td>9.0</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>2590</td>
<td>3.99</td>
<td>*</td>
<td>1284</td>
<td>55</td>
<td>300</td>
<td>8.3</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>2595</td>
<td>4.50</td>
<td>*</td>
<td>1268</td>
<td>45</td>
<td>317</td>
<td>9.8</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>3125</td>
<td>4.92</td>
<td>*</td>
<td>1355</td>
<td>89</td>
<td>678</td>
<td>8.7</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>3479</td>
<td>3.75</td>
<td>*</td>
<td>1310</td>
<td>47</td>
<td>375</td>
<td>17.7</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>3665</td>
<td>4.03</td>
<td>*</td>
<td>1261</td>
<td>45</td>
<td>367</td>
<td>9.5</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>4319</td>
<td>3.97</td>
<td>*</td>
<td>1293</td>
<td>49</td>
<td>400</td>
<td>9.3</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>4843</td>
<td>3.79</td>
<td>*</td>
<td>1303</td>
<td>48</td>
<td>405</td>
<td>10.0</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>5169</td>
<td>4.35</td>
<td>*</td>
<td>1295</td>
<td>47</td>
<td>396</td>
<td>9.8</td>
</tr>
<tr>
<td>11</td>
<td>3</td>
<td>5388</td>
<td>4.02</td>
<td>*</td>
<td>1246</td>
<td>45</td>
<td>380</td>
<td>9.3</td>
</tr>
<tr>
<td>12</td>
<td>3</td>
<td>6223</td>
<td>4.04</td>
<td>*</td>
<td>1299</td>
<td>48</td>
<td>406</td>
<td>9.9</td>
</tr>
</tbody>
</table>

- \( t_a \) (min.) ..... time of hydrogen ignition
- \( \Delta t_a \) (sec) ..... duration of ignition
- \( P_{\text{max}} \) (MPa) ..... maximum compartment pressure
- \( T_{\text{max}} \) (K) ..... maximum temperature of compartment atmosphere
- \( \text{NH}_2 \) (kg) ..... mass of hydrogen burned
- \( \text{MCO} \) (kg) ..... mass of carbon monoxide burned
- \( Q \) (GJ) ..... energy released at ignition
6. Conclusions and key problems

Presented concept of FVCS for VVER-440/213 type nuclear power plants brings a solution of two serious drawbacks of their design arising in connection with severe accidents:

- venting eliminates completely risk of containment failure due to long-term overpressurization. With exceptions of pressure peaks during flammable gases ignition containment keeps stable pressure slightly above atmospheric pressure,
- uncontrolled leakage of fission product to surrounding environment is substantially reduced even for extremely untight containments.

FVCS can be effectively installed at this NPPs and a special design features can be used; e.g. all parts of the venting/filtering system can be located inside of containment (in practically empty spaces of air/traps). Installation of FVCS has a minor influence on severe accident progression in primary system. On the other hand, FVCS effectively prevents hazards of flammable gases ignition in hermetic boxes, where a safety systems of vital importance are located.

Nevertheless, FVCS brings some problems:

- total destruction of suppression pool system is much more probable,
- another hazards is connected with much higher frequency of flammable gases ignition in air traps and subsequent underpressurization below minimal design pressure.

This problems can be solved by proper technical measures and combination of inner atmosphere inertization and reduction of hydrogen concentration:

- for atmosphere inertization the most proper period is after venting majority of original atmosphere to air traps, followed by pressure decrease. Inertization have to be effective especially at time RPV vessel bottom head failure, when initiation of hydrogen deflagration is most probable,
- installation of igniters in air traps can effectively reduce the hydrogen concentration in this space - hypothetical intervals between subsequent ignitions are relatively long,
- hazardous drops of pressure in air-traps can be prevented by installation of fast-acting check valves at outer side of air-traps.
AB; ORIF. VENT. FROM CONT.
Total pressure in compartments

CS to ext. atm.

\[ \Delta P = 0.015 \text{ MPa} \]
\[ P = 2 \mu \text{m}^2 \]

orif. factor = 0.45
1 - pressure vessel
2 - discharge tube
3 - membrane starting device
4 - steam generator boxes
5, 6 - corridor and localisation shaft
7 - bubble condenser
8 - volume upstream
9 - air trap
10 - back flow valve (DN 500)
11 - automatic blocking valve (DN 250)
21 - separator
26 - air trap water filling
27 - sprinkler
Experimental research on VVER pressure suppression system

Objectives:

- function verification during various loadings
- special parts function verification
  auto blocking valves
  spray system
- separate effects research
  bubble condensation
  wall condensation
  self pouring - off
  dynamical loading

Experimental facility:

- volume scaling factor 1 : 2011
- high pressure part
  12 MPa, 300°C
  75 kW
- low pressure part
  0.26 MPa
  0.696 m³ water volume in water tray

Measurements:

- pressure and pressure differences
- temperatures
- mass decrease
- rest of water in volumes after experiment
- visual observations
Characteristics of experiments:

- discharge orifice diameter
  5 mm - small and medium leaks
  10 mm - large leaks
  20 mm - design basis accident
  32.5 mm - over DBA accident
- initial pressure range
  10 $\div$ 12 MPa
- initial temperature range
  250 - 270°C
- pre-test experiments
  determination of hydraulic characteristics
  tightness test
  pouring-off velocity

Experimental results:

- small differences in drywell pressures
- pouring-off at most experiments
- dependence on discharge orifice diameter
  time duration
  pressure peak increasing in drywell volume
- bubble condenser effect

Conclusions:

- good reproducibility
- strong dependence on leakage rates
- lack of acoustoic effects
- pulse character of bubble condensation
IAEA CONSULTANTS’ MEETING
ON
CONTAINMENT AND CONFINEMENT PERFORMANCE
IN NPPS WITH WWER 440/213 AND 440/230 REACTORS

REVIEW OF EXPERIMENTAL AND ANALYTICAL
WORK ON BUBBLER CONDENSER
CONTAINMENT IN HUNGARY

Z. Techy
Institute of Electrical Power Research VEIKI
Budapest, Hungary

VIENNA, AUSTRIA
29 NOVEMBER - 3 DECEMBER 1993
CONTAINMENT SMALL SCALE EXperiments

SCOPE: STUDY OF THE BEHAVIOUR OF THE CONTAINMENT-LOCALISATION SYSTEM IN ACC. CONDITIONS

SCALING: 1:40 BY LINEAR DIMENSION
1:63000 BY VOLUME
LINEAR DIMENSIONS OF THE BUBBLER TRAY SEGMENT 1:1

SCALING LAWS: DERIVED FROM THE SPATIALLY UNIFORM MASS AND ENERGY BALANCE EQUATIONS

MAIN PARTS OF THE SYSTEM

1. HIGH PRESSURE VESSEL-SCALE MODEL OF THE PRIMARY SYSTEM
   WATER MASS: 2.5 KG (MAX 4 KG)
   ELECTRIC HEATING, P = 6 KW
   P = 125 BAR, T = 295 C
   BALANCE EQUIPMENT FOR MEASURING THE WEIGHT OF THE WATER STORAGE

2. VESSEL N2, V = 0.5 M3
   INCLUDING THE FOLLOWING 2 PARTS
   - BOTTOM PART: SCALE MODEL OF THE PRIMARY SYSTEM COMPARTMENTS,
     V = 0.374 M3
   - UPPER PART, V = 0.126 M3, INCLUDING
     - THE BUBBLER CONDENSER TRAY SEGMENT, WATER MASS 24 KG
     - SCALE MODEL OF THE VOLUME ABOVE THE CONDENSER TRAYS

3. VESSEL N3, V = 0.5 M3
   SCALE MODEL OF THE AIR TRAPS
   V = 0.264 M3 (THE REST IS FILLED)
FIG 7.

CONTAINMENT SMALL-SCALE TEST FACILITY
SPECIFIC FEATURES OF THE FACILITY

- BLOWDOWN FLOW RATES DERIVED FROM THE MEASUREMENT OF WATER MASS
- BALANCE EQUIPMENT WITH HINGE JOINTS TO EXCLUDE HARDWARE MASS AND HORIZONTAL JET FORCES
- LOW INERTIA FORCE METER CELL

- BLOWDOWN ACTUATED BY ELECTRICALLY HEATED MELTING FUSE

- INSIDE ISOLATION OF THE EQUIPMENT (VESSELS) BY A 10 MM THICK POLIFOAM FOAM WITH CLOSED PORES. MODELING LAWS REQUIRE TO DECREASE THE HEAT TRANSFER IN THE SCALE MODEL BY 1:36
INSTRUMENTATION

1. WEIGHT MEASUREMENT - LOAD CELL, MODEL 7926
   MANUFACTURER: MOM KALIBER, HUNGARY
   RANGE: 16 N

2. PRESSURE - PIEZORESISTIVE PRESSURE TRANSDUCERS
   MANUFACTURER: ENDEVCO CO, CALIF., US
   RANGE: 8510 B-50: 0-3.5 BAR
          8510 B-2000: 0-138 BAR

3. TEMPERATURE - THERMOCOUPLES
   NiCr-Ni THERMOCOAX TYPE
   O.D. 1MM, EPOXI END COATING
   TIME CONSTANT < 0.8 SEC

DATA ACQUISITION SYSTEM

- MAX. NUMBER OF MEASUREMENT CHANNELS: 31
- REGULAR: SCHLUMBERGER MODEL 14 CHANNEL MAGNETIC TAPE RECORDER
- THERMOCOUPLE SIGNALS - AMPLIFIER
- CONTROL OF THE MOST IMPORTANT PARAMETERS:
  HEWLETT-PACKARD MODEL 86B COMPUTER
  HP MODEL 3421 DATA ACQ. UNIT, 30 CHAN
  FLOPPY DISC AT THE END OF THE TEST
- DATA EVALUATION - SOFTWARE DEVELOPED AT VEIKI FOR HIGH FREQUENCY SIGNALS
Fig. 3. Data acquisition system
EXPERIMENTS PERFORMED

- SCOPING TESTS HAVE BEEN PERFORMED IN 1990 TO MODEL TWO PRIMARY SYSTEM BREAK SIZES: 500 MM AND 178 MM DIA

TEST RESULTS ARE INCLUDED FOR THE 500 MM MODEL CASE.

- RESULTS SHOW GOOD AGREEMENT WITH THE PRECALCULATED VALUES.

IMPROVEMENT OF THE MEASUREMENT SYSTEM HAS BEEN PERFORMED IN 1991

Fig. 5. Mass of water in the high pressure vessel (primary system water mass) versus time
Fig. 6. Pressure transient in the volume below the tray (drywell pressure)
2. Design Basis Accident (DBA) load for a containment

The largest short term challenge for the containment is examined in this chapter. This DBA accident means a double ended break of one main circulating pipe in cold leg, with other words this is a large break loss of coolant accident (LBLOCA). The primary system calculations which support the steam and water source for containment calculations were performed by the Russians [5].

Different codes were used for the containment calculation. The containment pressure and temperature transient in case of a LBLOCA is modeled by different lumped parameter codes. In VEIKI the BURST program family [6] have been developed. The main feature of the BURST-ST code are:

- Fixed 6 compartment nodalization (Table 1),
- Thermodynamic equilibrium model,
- Orifice flow model for transfers between volumes,
- Developed for short term containment transients.

For long-term calculation the BURST-NLT code has been developed. This is a 3 compartments model of the VVER-440/213 containment. Non-equilibrium thermodynamic model has been built in this code. The code able to calculate the reverse flow of water from the bubbler condenser. The MARCH3M [7] severe accident code was also used for LBLOCA calculation of VVER-440/213 containment. The used MARCH3M model has the fairly similar features, related to containment modeling, as the BURST-NLT model.

The CONTAIN 1.12 code [8] developed at Sandia National Laboratories as an advanced tool for containment analysis can be also used for VVER type containment. The CONTAIN code has flexible nodalization.

For comparison, the maximum pressure values calculated by different codes are listed below:

<table>
<thead>
<tr>
<th>Code</th>
<th>Number of volumes</th>
<th>Max. pressure (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BURST-ST</td>
<td>6</td>
<td>0.212 (Fig.4)</td>
</tr>
<tr>
<td>BURST-NLT</td>
<td>3</td>
<td>0.22 (Fig.5)</td>
</tr>
<tr>
<td>MARCH3M</td>
<td>3</td>
<td>0.23</td>
</tr>
<tr>
<td>CONTAIN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.228</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>0.23 (Fig. 6)</td>
<td></td>
</tr>
</tbody>
</table>

Recently performed sensitivity analyses with the CONTAIN code have shown that the results are greatly influenced by the hydraulic data, like hydraulic resistance, contraction factors of the containment, especially in the localization system. The range of the results in terms of the maximum containment pressure is 0.21-0.235 MPa, depending on the selected hydraulic data. This uncertainty margin of the maximum pressure peak during LBLOCA consists of the different codes and models. Using conservative assumptions for thermohydraulic data, the maximum peak pressure has never exceeded the containment design pressure 0.25 MPa.

During the first phase of the accident, the primary system water inventory discharges and boils off, causing a pressure and temperature transient in the
containment. The pressure transient starts with a rapid, 5-7 seconds long pressure increase, reaching a maximum value of 0.23 MPa. Simultaneously with the pressure the temperature also increases, it achieves 390 K. In this phase the water on the trays condenses the steam. The steam-air mixture first flows upward through a vertical gap. Each gap is capped, the gas mixture at the cap changes its direction and flows downward in another gap. This gap is closed by water, the opening time is about 0.4 s in case of LBLOCA. This time is necessary to speed up the water by the pressure difference. Then the steam-air mixture can go through the water column from the bottom of the pool to the top of the water pool (Fig. 7). The steam condensation takes place as the steam rises upward. According to the test of the Soviet designer and to our test [8], the steam contained in the mixture bubbling through a thin (0.5 m) water layer is fully condensed. The air will flow into the air traps as long as a sufficient pressure difference exists.

From 8 s after the initial event the pressure decreases as a result of the decreasing blowdown flowrate and the absorbing effect of the localization system. The pressure declines to about 0.18 MPa, at which value it equilibrates with the pressure of the air traps. Condensation causes further pressure decrease in primary system compartments, where the steam ratio will be about 45 vol%. Between 40 and 50 s, it depends of the code and model, the negative pressure difference pushes back the water of the bubbler condenser trays (Fig. 8) into the localization tower. As a result of additional condensation caused by the large water inventory, the containment pressure and temperature drop sharply. The temperature decreases approximately to 373 K. About 1300 tonnes of water is pouring as a passive spray through a perforated plate (Fig. 3).

This phenomena lead to 0.11-0.14 MPa containment pressure with a large uncertainty margin. Given the lack of large scale experiments, the simultaneous operation of several condenser units in different levels cannot be tested. Therefore the exact values of the water speed through the perforated plate, the water droplets diameter, the effective cooling way in the tower are unknown.

The air traps are equipped with check valves, so their withhold the air inventory, received during the first phase of the accident. The pressure in the air traps slowly decreases due to cooldown.

The active spray system starts after about 80 s, then the containment pressure slowly decreases. In every cases the containment pressure reaches subatmospheric pressure after 12 min (Fig. 8). The time depends on the number of working spray lines, water temperature and water droplets. According to CONTAIN calculations it needs about 4 minutes to decrease the containment pressure under atmospheric if 2 from the 3 spray lines inject water in to the box compartment. The water injection automatically switches off when the containment pressure drops under 0.085 MPa.

3. Degraded conditions of the localization system

The operation of the large, dry containments, even with subdivided layout has been well studied both experimentally and analytically. The localization system of VVER reactors is, however, a unique equipment with simultaneous condensers, whose ability to operate without damaging dynamic effects should
be demonstrated. In the present situation the operation of the containment without the pressure suppression function can represent interest to reveal the ultimate protecting potential of the containment.

Therefore, we have studied the pressure and temperature transients of the VVER-440/213 containment in case of a LBLOCA assuming partial or total loss of water from the trays of the localization system. The water is distributed on 12 elevations of condenser trays, which are located in a 40 m high tower. The same structure consist of the 4 air traps. We have postulated that part of, or the total of water inventory has been pushed back to the main containment sump, prior to the accident.

The considered cases included:
1. Localization system in design condition - 100% availability
2. Loss of the total water inventory - 0% availability
3. Loss of water from 6 elevations of condensers - 50% availability
4. Loss of water from 9 elevations of condensers - 25% availability
5. Loss of water from 3 elevations of condensers - 75% availability

Note: A single condenser results in bypass of the other two elevations of condensers, connected to the same air trap, so three elevations of condensers will be actually disabled if conservative assumptions were used. In practice when the pressure of the air trap on the damaged level is higher then the pressure of the other air traps the disabled two elevations start to condense steam.

Detailed assessment of component malfunctions leading to loss of localization system water inventory has not been performed. The degradation has been postulated to study the enveloping protecting potential of the containment with and without localization system.

The calculations were performed with the BURST-ST, and BURST-NLT codes, developed at VEIKI, and with the CONTAIN 1.1 code [1.17], and repeated in this study with the CONTAIN 1.12 code with a revised data base. Maximum containment pressures, obtained with the CONTAIN 1.12 code are as follows:

<table>
<thead>
<tr>
<th>Availability of the localization system</th>
<th>Max. containment pressure, bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 %</td>
<td>2.3</td>
</tr>
<tr>
<td>0 %</td>
<td>3.95</td>
</tr>
</tbody>
</table>

The BURST program family gives slightly smaller peak pressures than the CONTAIN code.

For the partially degraded states of the containment system, there are intermediate values between the indicated values. The analyses show that the localization system is designed with a substantial reserve in terms of water inventory. Design pressure of the containment (2.5 bar) is reached in case of 25% loss of the water inventory (75% of availability).

Further conclusions depend on the value of the containment safety margins. If the structural analyses show that the failure pressure is above the 3.95 bar value, then the containment evidently withstands the DBA loads without relying on the localization system. In the opposite case, the appropriate operation of the containment can be proved by large scale experimental testing.
Table 1. Subdivision of the containment for transient calculations

<table>
<thead>
<tr>
<th>Notation of comp.</th>
<th>Name of the volume</th>
<th>Volume, m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>V3</td>
<td>Connection channel and part of localisation shaft extended to the condenser water seals</td>
<td>5000</td>
</tr>
<tr>
<td>V4</td>
<td>Total volume of the bubbler condenser chambers, including the water inventory</td>
<td>8000</td>
</tr>
<tr>
<td>V5</td>
<td>Air traps (A 257, 510, 616, 704)</td>
<td>16800</td>
</tr>
<tr>
<td>V6</td>
<td>Dead end compartments, connected to the SG and MCP comp. (A 01, 005, 0032, 010, 011, 012, 210, 211, 209)</td>
<td>6000</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>48,540</td>
</tr>
</tbody>
</table>

LIST OF FIGURE CAPTIONS

Fig. 1. Cross section of the VVER-440/213 containment building
Fig. 2. Plan view at 10.5 m elevation
Fig. 3. Schematic view of the localization tower
Fig. 4. BURST-NLT code nodalization and calculated pressure
Fig. 5. BURST-ST code nodalization and calculated pressure
Fig. 6. CONTAIN 1.12 code nodalization and calculated pressure
Fig. 7. Principle of bubbler condenser/spray function
Fig. 8. DBA long term pressure and temperature transient calculated by CONTAIN code
Fig. 9. Loss of the total water inventory from the trays before LBLOCA
Fig. 1  Zs. Téchy, G. Lajtha, R. Taubner
Fig. 3  Zs. Tóchy, G. Lajtha, R. Taubner
WATER INV. IN THE LOC. SYST.. 100 % PRESSURES

Fig. 4  Zs. Téchy, G. Lojtha, R. Taubner
Fig. 5 Zs. Téchy, G. Lajtha, R. Taubner
Fig. 6  Zs.Tőchy, G.Lajtha, A.Taut...
1. BEFORE ACCIDENT - $p_1 = p_2$

2. FIRST PHASE OF THE ACCIDENT (blowdown) $p_1 > p_2$
   BUBBLER CONDENSER

3. SECOND PHASE OF THE ACCIDENT (water backflow from trays)
   PASSIVE SPRAY $p_1 < p_2$

Fig. 7 Zs. Tóthy, G. Lajtha, R. Tautner
CONTAIN 1.12 VVER21c VERS.93 SMINT

VVER-440/213 LBCCA (break: 200%, DBA)
CONTAINMENT PRESSURES degr. cond.

Fig. 9 Zs. Tóth, G. Lajtha, R. Taubner
CONTAINMENT RELATED STUDIES PERFORMED IN POLAND

M. Kulig
National Inspectorate for Radiation and Nuclear Safety
Warsaw, Poland

VIENNA, AUSTRIA
29 NOVEMBER - 3 DECEMBER 1993
Containment related studies performed in Poland

Overview

M. J. Kulig

Experimental work

* Thermal hydraulic phenomena in bubbler condenser under DBA conditions - Technical University of Warsaw/ Institute of Atomic Energy, Swierk

* Very early phase of containment phenomena under DBA conditions - Warsaw Technical University and IEA (under IAEA Research Contract 4782 RB and TC RER/9/004)

Analytical studies

* Development/adaptation of thermal hydraulic computer codes, Warsaw Technical University, IAE-Swierk

* Thermal hydraulic containment phenomena under DBA conditions, Warsaw Technical University, IAE-Swierk (under IAEA RC 4782 RB)

* Thermal hydraulic analyses of possible malfunctions of the containment system, Warsaw Technical University, IAE-Swierk (under IAEA RC 4782 RB)

* Strength analyses of bubbler condenser structure, IAE-Swierk (under IAEA RC 4782 RB)

* Containment behaviour under BDBA conditions (selected cases), IAE-Swierk (under IAEA contract RC 4782 RB)
Thermal hydraulic phenomena in bubble condenser

Experiments at the Technical University of Warsaw

- Single shelf 800x180x3800 mm, limited similarity (no check valves)
  air-steam mixture velocity up to 3.5 m/s

Main findings

* Thermal effectiveness confirmed

* Process oscillations observed for lower range of investigated flow rates due to relatively low pressure loss characteristics of the channel

* Intensive carry-over of water to the shelf upper plenum (wet well)
Steam-air mixture flow through water shelf
(experiment performed at the Technical University of Warsaw)

Pressure drop in the condenser shelf (500 mm of water)

Pressure drop in the condenser shelf (dry channel)
Very early phase of DBA - Containment Aerodynamics

Experimental work performed at the Technical University of Warsaw and IAE, Swierk

Objective of the study

Gathering qualitative and quantitative information on coolant flow phenomena under very early phase of the DBA to be used in bubbler condenser strength analysis

Experimental facility

* integral configuration well represented (1:54 scale)
* dummy used for water shelves (no water)
* coolant flow simulated by compressed air
* large number of measuring points (velocities and pressures)
* partial visualization of the flow.

Overview of experiments

* two versions of bubbler condenser tower (original design, PAKS design)
* model with and without separating wall in the inlet channel
* outlet flow from the break according to RELAP4 code calculations (conservative assumptions - HF-HM correlation with contraction coefficient 1.0)
* time period covered 0 - 0.7 s (real time)
* pressure history recorded for numerous points distributed in the condenser tower, the connecting channel and SG compartments, points on the shelves selected on both front and horizontal surfaces of the shelves (5 levels, 14 - 19 measurements at each shelf)
* results recorded in graphical form (converted into real parameters based on similarity conditions - Euler Number, Strohal Number)
* water lock opening time calculated on the basis of measured pressure history and the appropriate mathematical model
Schematic diagram of the model for investigation of very early phase of DBA containment phenomena.
Distribution of pressure measurement points

- front surface of water shelves

- inlet channel from SG compartments

Distribution of velocity measurement points in the condenser tower
Coolant flow from ruptured RCS
Flow velocity measured in the connecting channel

Pressure measured at the selected shelf levels (face surface)
Pressure measured at point P2, K6.

a - face of the shelf
b - horizontal surface
Pressure measured at point P1, K6

- a - face of the shelf
- b - horizontal surface
Variation of the pressure in the localization tower
measured and calculated curves
Calculation of water lock opening time

Energy balance equation for cross section 1 and 2

\[
\frac{\rho}{2} \frac{u_1^2}{2} + p_1 - \rho \varepsilon x = \frac{\rho}{2} \frac{u_2^2}{2} + p_2 - \rho \varepsilon h + \rho \frac{d}{dt} \left( u_1 \cdot (h-x) \right)
\]

\[ p_2 = \rho \varepsilon h \quad u_1 = \frac{dx}{dt} \]

u - water velocity in the channel

\(\rho\) - water density
Results of the experiment

* No shock wave is generated in the SG compartments nor in the condenser tower. The pressure wave (not shock wave) generated at the point of RCS rupture was considerably weakened in the course of wave propagation within the building (enhanced due to complex shape of the containment).

* The perforated shield plate at the tower entrance - not necessary to damp the pressure wave (positive influence by decreasing dynamic pressure in the front surface of the shelves).

* The wave process - little influence on pressure transient in the condenser tower (can be neglected in strength calculations of water shelves).

* The velocity transients measured in the inlet channel connecting SG compartment with the tower show the existence of strong eddies (the eddies increase local velocity to the values of order 100 m/s; such a velocity was reached at 20 s after the initiating event).

* The maximal overpressure measured at the condenser shelves (at the moment of water lock opening - estimated analytically as 0.27 s is 0.035 MPa).

Analytical studies

Codes Development

* BOTER - Technical University of Warsaw
  - modular and adaptable T/H code
  - various models of phase separation for water injected to the compartment, flow rate data supplied by the user
  - medium in the containment compartments - homogenous mixture, equilibrium model
  - no surface heat transfer and accumulation

* HEPRO - 2/GK main frame CDC adaptation of SKODA code based on Ae 5568/Dok (IAE, Swierk)

* HEPRO - 2/PC PC adaptation of HEPRO-2, slightly modified (IAE, Swierk, Technical University of Silesia)

* HEPMOD1-A PC code based on the same assumptions and models as HEPRO-2 (IAE and TUS); modified numerical method - improved stability, accuracy and computer running time (integral balance method).

* CONTAIN - PC; WWER-440 input data preparation.
Analysis of T/H phenomena

Technical University of Warsaw - BOTER code

Main insights

* Maximal pressure in SG compartments 0.214 MPa (at ~ 7 s)
* Maximal temperature of water in the condenser shelves far from saturation point (64 °C)
* Nonuniform distribution of load between shelves (64 - 43 °C - the 3-rd and the highest shelf)
* Sensitivity study concerning efficiency of steam condensation on spray water droplets.

Institute of Atomic Energy

HEPRO-2/GK, HEPRO-2/PC and HEPMOD1-A

* Slightly different assumptions concerning break outflow rate
* Series of calculations
  - proper function of the system
  - possible malfunctions of the system

![Graph showing blowdown phase](image)
Nodalization used in calculations by BOTER code - blowdown phase
1 - SG compartment (with broken pipe)
2 - SG compartment
3 - water condenser tower - inlet shaft
4 - water condenser shelves - outlet plenum (wet well)
5 - air trap compartment
6 - other leaktight compartments in the reactor building

Nodalization used in calculations by BOTER code - later phase
1 - SG compartment (with broken pipe)
2 - SG compartment
3 - water condenser tower - inlet shaft
4 - water condenser shelves - outlet plenum (wet well)
5 - air trap compartment
6 - other leaktight compartments in the reactor building
Pressure transient calculated by BOTER code - condenser fully operable

Pressure transient calculated by BOTER code - one shelf empty
Air fraction at the inlet to the highest (1) and the lowest shelves (2).

Pressure in the SG compartment - various efficiency of steam condensation on active spray droplets

Pressure in the SG compartment - various efficiency of steam condensation on passive spray droplets
Proper functioning of the containment

* Thermal efficiency of the condenser sufficient
* Maximal pressure - 2.36 - 2.38 MPa (at ~ 12 s)

Containment system malfunctions

- air trap compartment manhole open
- ventilation line between air trap and SG box open
- blockage of the check valves in two shelves
- loss of water inventory in two shelves
- loss of water inventory in three shelves
- loss of water inventory in all shelves

Main insights

* Loss of air trap leaktightness affects only system capabilities to decrease system pressure in long time-frame; maximum pressure peak decreases; no effect on passive spray (initiation at 28 - 30 s).
* The loss of shelf water inventory and the blockage of check valves - the maximum pressure peak increased; total loss of water - the pressure peak increased by 40 %.
1. ventilation line between the SG and the air trap compartments open
2. open manhole to air trap compartment
3. containment system fully operable
4. blockage of the check valves in two condenser shelves
5. loss of water inventory in two shelves.

Pressure variation in SG compartment for various malfunctions of the containment system (HEPRO-2/PC, IAE-Swierk, Poland).
1 - basic case, containment system fully operable
2 - AB' scenario, no ECCS and RBSS
3 - three shelves empty, ECCS operable
4 - all shelves empty, ECCS operable

Pressure transient in SG compartment following LB LOCA
HEPMOD1-A, IAE/STU (1990)
IAEA CONSULTANTS’ MEETING
ON
CONTAINMENT AND CONFINEMENT PERFORMANCE
IN NPPS WITH WWER 440/213 AND 440/230 REACTORS

REPORT ABOUT THE ACTIVITIES OF AN
INTERNATIONAL WORKING GROUP ON BUBBLER
CONDENSER CONTAINMENT RESEARCH WORK

H. Karwat
Technische Universität München
Garching, Germany

VIENNA, AUSTRIA
29 NOVEMBER - 3 DECEMBER 1993
Minutes of the Working Group Meeting

"VVER-440 Bubble Condenser Containment Research Work"

held at Kiev (Ukraine)
25./26.11.92

1. On occasion of the multi-lateral symposium on Safety Research for VVER-Reactors in Cologne/Germany, July 7-9, 1992 a concerted action has been recommended to study the dynamic behaviour of the bubble condenser containment system of VVER-440/213 reactors under design basis accident and severe accident conditions. At this occasion it was recommended to form an international working group to prepare a list of priorities for items to be studied on basis of existing test facilities.

2. The first working group meeting took place at the premises of Energoproject, Ukraine, hosted by the Ukrainian State Committee on Nuclear and Radiation Safety, Kiev.

3. The meeting was opened by V.N. Glygalo, Director of the Technical Science Centre on Nuclear and Radiation Safety, Derzhatomnagljad of Ukraine. He welcomed the participants to this meeting (see Appendix I). Several CSFR participants could not attend the meeting due to cancellation of their flight because of local weather conditions at Prague. During his introductory remarks V.N. Glygalo stated that the Ukraine intends to reactivate the ZUETES research facilities at Zugres, Ukraine to eventually form a national research centre. V. Petroschenko gave an overview on the developmental history of the LSM (Large Scale Model)-Project, from which the bubble condenser test rig is a part.

4. H. Karwat, Chairman of the International Working Group, outlined the main goal of setting up the International Working Group. The mandate of the working group is originating from the recommendations of the multi-lateral symposium on Safety Research for VVER-Reactors, held in Cologne in July 1992. The ultimate goal of the first and poss-
ibly subsequent meetings is to prepare a technical specification for an internationally agreed bubble condenser containment research project. In this context, the topics to be discussed by the working group have been explained in detail with reference to the invitation letter dated 14.10.92.

A two-step approach is considered necessary: A first rough specification will serve to provide the basis for the estimation of the necessary funding of an international project. The detailed specification of a test matrix and details concerning the instrumentation and the data managing systems may be the objectives of later meetings.

5. A detailed discussion of the phenomena to be studied within the frame of a future research project took place. From the operators' point-of-view particular interest was expressed with respect to study the possibilities for reliable periodic leaktightness testing. It was concluded that this item is closely related to the locally adopted testing procedure and to the associated organizational precautions of a nuclear power plant. Other participants raised some open questions of scaling which must be answered in context with the interpretation of the experimental results obtained from small test facilities. Reference was made to several earlier experiments performed within the former Soviet Union to hitherto support the design of the bubble condenser containment concept of VVER-440/213 plants.

6. H. Wolff gave a detailed presentation on the application of the DRASYS-code and the supplementary code development work considered necessary to improve the simulation of specific features of the bubble condenser containment. Earlier application of the DRASYS has indicated the need for model validation and improvements, but the general physical formulations within the code can be applied already to the specific gap-cap system characterizing the bubble condenser. B. Schwinges presented a list of phenomena which must be covered by the analytical simulation models and the corresponding experimental validation work. In total, 23 processes or phenomena have been identified the importance of which was assessed by the working group in a preliminary stage. Certain recommendations have been presented concerning necessary experimental investigations.

7. G. Kopchinsky informed the working group on ongoing activities in the Ukraine in connection with the reassessment of the safety of the Rovno nuclear power station (equipped with a bubble condenser containment). He referred to several problems uncovered for the interpretation of the analyses of the behaviour of the localisation system as well as of the experimental data hitherto available to the Ukrainian State
Committee on Nuclear and Radiation Safety. Kopchinsky stressed the importance of the availability of the ZUETES large scale bubble condenser test rig and mentioned his most recent discussion of this matter with OECD representatives in Paris.

8. Z. Téchy presented a list of phenomena to be studied experimentally from the point-of-view of the Hungarian utilities elaborated for a possible CONTAIN application. Proposals were made for phenomena to be studied within separate effects test rigs as well as within the integral large scale facility at LSM-ZUETES. These proposals largely cover most of the items also derived from the point-of-view of the analytical simulation by DRASYS and its validation (see section 6).

9. The working group discussed the items proposed to be studied with priority in future experiments. It confirmed the need for experimental studies according to the lists presented in appendix II. These lists of items may be supplemented by some more details pending on further code development steps in the future.

10. J. Murani and K. Soplenkov described an alternative jet pump condenser concept to limit the pressure rise during a loss-of-coolant accident should it occur to a VVER-440 reactor. It was told that technical proposals based on the jet condenser concept have been prepared for containments at Rovno and some CSFR facilities. Close cooperation between interested partners in the CSFR and the research laboratories in Elektrogorsk (Russia) has been initiated. A jet condenser unit has been mentioned to be tested presently at Elektrogorsk, but a large scale test demonstrating the efficiency of several such units within a VVER-440 containment building seems to be necessary as well in the future. Certain studies to apply this concept also as a "filtered venting system" are presently performed at Temace (CSFR) on behalf of the Cechoslovak regulatory body CSKAE.

11. Having concluded about the phenomena which in general should be studied with high priority the working group attempted to discuss which of them could be studied within the frame of separate effects tests and which of them must be the objectives of well instrumented large scale integral tests. Experts from Hungary and the CSFR offered to involve the small scale test rigs at VEIKI, Budapest and SVUSS, Bechovice/Prague in a suitable separate effects test programme. Details should be discussed with the local experts at Budapest or Bechovice to elaborate the possibilities and necessities for additional instrumentation in particular.
12. Concerning the existing possibilities at the ZUETES facility in Zugres the discussion was somewhat confusing. The main question to be clarified by the local Ukrainian experts concerns the technical condition of the ZUETES facility at which an internationally agreed research project could be started. From a letter dated Sept. 18, 92 written by the Ukrainian State Committee on Nuclear and Radiation Safety to the chairman it was understood that the pressure vessels and the interconnecting pipe work forming the ZUETES bubble condenser test facility at Zugres would be finalized and pressure-tested at the beginning of the international project. Pending a definitive clarification with respect to the state of the integral test facility as offered for the incorporation into an international project the supplementary equipment (instrumentation, data acquisition and data processing systems) and all necessary or desired facility modifications (e.g. to obtain suitable Eigenfrequency behaviour of the bubble condenser structures) will be discussed on occasion of the next working group meeting.

13. With an attempt proposed by V. Kolochko to continue the discussion at the premises of the Ukrainian State Committee on Nuclear and Radiation Safety the working group meeting was closed. On behalf of all participants the chairman expressed his gratitude to N. Kolochko for the local organization and the hospitality offered to the participants at Kiev. A date for the next meeting remains subject to future negotiations.

Garching, 16.12.92
A. PHENOMENA TO BE STUDIED EXPERIMENTALLY

- Overall dynamic characteristics of the system: pressure and temperature transient
- Pressure loads on condenser units
- Pressure oscillations due to condensation effects
- Simultaneous operation of several condenser units
- Hydraulic characteristics of the check valves
- Water expulsion from the condenser: the influence of pressure gradients on the mechanisms of spillover or syphon flow
- Wave formation in the condenser
- Condensation effectiveness depending on the height of water level
- Extent of water carry-over from condenser pool
- Sprinkler efficiency
B. SEPARATE EFFECTS EXPERIMENTS

- Hydraulic characteristics of single condenser units under different flow conditions
- Water expulsion from the condenser: the influence of pressure gradients on the mechanism of spillover or syphon flow
- Condensation effectiveness depending on different factors
- Extent of water carry-over
C. INTEGRAL LARGE SCALE EXPERIMENTS

- Overall dynamic characteristics of the system: pressure and temperature transient
- Pressure loads on the condenser units
- Pressure oscillations due to condensation effects
- Thermohydraulic behaviour of different condensers steam load, heatup, temperature transient at simultaneous operation
- Condensation cooling of the atmosphere by the expelled water from the condenser trays
- Sprinkler system interaction
Minutes of the Working Group Meeting

"VVER-440 Bubble Condenser Containment Research Work"

held at Rez (Czech Republic)

4./5.3.93

1. The 2nd meeting of the Working Group "VVER-440 Bubble Condenser Containment Research Work" took place at the Hotel VLTAVA in Rez near Prague, Czech Republic. The meeting was opened by J. Macek of the Nuclear Research Institute (NRI), Rez who welcomed the participants (see Appendix 1).

2. The minutes of the first meeting of the working group, held at Kiev 25./26.11.92 were briefly discussed and adopted. The technical-physical phenomena to be studied by either separate effects tests or integral large scale experiments have been confirmed also by those experts not present at the Kiev-Meeting.

3. Mr. Suchanek (SVUSS, Bechovice) gave a detailed presentation on the design concept of the Czech bubble condenser test facility located at Bechovice near Prague. The facility consists of two halves of a cap-gap arrangement of the VVER-440/213 bubble condenser system with original dimensions. The components of the test facility are basically 1:2000 volumetrically scaled models of the main structures of a prototype containment. Appendix 2 provides an overview on the main components of the test rig and its instrumentation.

4. Approx. 16 integral tests have been performed so far. Several test parameters were varied, e.g. the size of the blowdown break nozzle, the water volume of the water tray, the flow area of the check valve between the bubble condenser and the air trap etc.. Some typical results were shown illustrating the principal function of the concept.

5. Several commissioning tests served to measure the thermodynamic characteristics of the test rig which should become a subject of a detailed analysis to support the interpretation of the main experiments.
6. Mr. Parduba (NRI, Rez) presented the results of first MELCOR-calculations aimed to analyze Bechovice test results. The MELCOR-Version 1.8.1+ was available which was run on a Hewlett Packard VECTRA-486 Computer. Considerable difficulties have been experienced in the analytical simulation of this type of experiments by the MELCOR-code. Recalculating the "as-measured" blowdown rates from the small pressure vessel was one of the major problems. Further attempts to improve the MELCOR-application to the Bechovice test rig are planned.

7. In context with the discussion of code applications the GRS-representatives presented some specific DRASYS-features complementing information given already during the Kiev-Meeting. It was unanimously expressed opinion of all experts that detailed descriptions of all codes involved in the analyses of the bubble condenser system (DRASYS, HEPRO, TRACO etc.) so far not yet publicly available (e.g. MELCOR, CONTAIN etc.) should be provided to the members of this Working Group to better define code validation needs.

8. A visit to the bubble condenser test facility at Bechovice was arranged by the Nuclear Research Institute (NRI). Detailed discussions addressed the possibilities to limit heat losses and to complement the available instrumentation as well as the possibility to perform well-controlled separate effects tests at the site. External steam supply would be possible requiring the installation of a short additional supply line. Overall, the visit provided a positive impression on the existing experimental possibilities. Steam supply with 4 MPa, 400 °C is possible. The test rig is ready for another series of 20 experiments presently planned for execution in 1993. Main objectives of the next experiments to be studied with priority are oscillatory condensation phenomena, mechanisms of the passive sprinkler activation, the influence of sonic waves caused by pipe rupture on components of the condenser pool. A special Czech task group will assess structural eigen-frequencies of a prototype facility in comparison to the structural properties of the test rig at Bechovice.

9. A listing of the presently installed instrumentation of the bubble condenser test rig will be provided by SVUSS.

10. During the concluding discussion the experts considered the bubble condenser test rig at Bechovice as a facility suitable for generating code validation data within the limits of the given design. In particular, separate effects tests could be performed under well-controlled operating conditions addressing all features characterizing of a single gap-cap system. Oscillatory condensation, air-water phase separation, condensation
efficiency with reduced water inventory and the hydraulic characteristics of the gap-cap system could be studied as well. Integral experiments (performed utilizing the existing high pressure energy reservoir) require a detailed knowledge of the achieved blowdown rates injected into the bubble condenser model. The addition of more sophisticated mass flow instrumentation may reduce some uncertainties. Limits are visible however. Available experience obtained during other containment experiments (Battelle-Frankfurt and HDR) have been mentioned in this context.

11. Dr. Chesna (Lithuania) gave a detailed presentation on the design features of the pressure suppression system installed within the Lithuanian IGNALINA nuclear power plant. The IGNALINA nuclear power plant is a 1500 MWe nuclear power station of the RBMK-type. Roughly, 80% of the compartments housing the IGNALINA primary coolant system will be vented through a pressure suppression system specifically designed for this reactor station. The remaining 20% of the coolant circuit (primarily the steam drum compartments) would not be connected to this system. The IGNALINA pressure suppression system consists of two interconnected buildings, each containing 5 vertically distributed flat water pools (trays). The steam-air mixture coming from the location of the pipe rupture is directed into the water pools through approx. 20 m long round tubes of 800 mm diameter connected to rectangular vertical downcomers submerged into the water pools. Exiting the lower end of the rectangular downcomer gaps the air-steam mixture is directed downwards into the water pools. No 180° flow turn similar to the gap-cap system of the VVER-440/213 bubble condenser is designed.

12. So far, the concept of the IGNALINA pressure suppression system has been firstly analyzed by the application of the CONTAIN-code. Additional studies with the German DRASYS-code and the Swedish COPTA-code have been started. GRS has been asked to identify certain features of the IGNALINA PSS which should be studied by experiments to validate code assumptions.

Presently, one important feature for code adjustment would be the transition from the round tube header into the vertically oriented narrow rectangular downcomer gap. Considering other aspects the application of presently available codes does not appear to be too much a problem.

13. It was agreed that possibilities should be investigated as to test a typical IGNALINA downcomer arrangement within one of the existing test facilities. Structural response of the water pools (trays) upon condensation-induced loads were not considered as a
high priority problem because the IGNALINA water pools are designed as massive concrete structures.

14. The IGNALINA nuclear power plant would be willing also to financially support specific experiments if considered necessary. Dr. Chesna would highly appreciate if the Working Group could monitor the possibilities of IGNALINA-specific pressure suppression system experiments. Close contacts to the IGNALINA Safety Advisory Group (ISAG) would be helpful in this context.

15. Unfortunately, experts from the Ukraine could not attend the meeting due to unavailability of tickets to Prague. Hence, all open questions concerning the availability of the ZUETES test facility at Zugres remaining from the first Working Group Meeting could not be further discussed. The Working Group took note of a fax-message from Kiev received on 4.3.93 at the Nuclear Research Institute, Rez. According to this message the Ukrainian side expects the termination of the mechanical construction of the ZUETES bubble condenser test facility to require hard currency in the range up to US-$ 200.000. Further clarification of this matter would have required at least one expert from the Ukraine to be present at the meeting.

16. Another message was received from Mr. B. Gordon, a Russian expert participating in the first meeting in Kiev in November 1992. This message was also discussing problems anticipated for the execution of bubble condenser experiments within the large scale ZUETES test facility. The Working Group again felt an urgent need for clarification of several statements provided in Mr. Gordon's message. The representative from Russia, Mr. Proklov (Kurchatov-Institute) felt himself not in the position to comment the message.

17. Concerning the situation with respect to the ZUETES large scale test facility no progress has been made during the meeting. At least, some participants felt a need to look for an alternative possibility for large multistage bubble condenser testing. Any firm recommendation has not been given however.

18. Mr. Murani (VUEZ, Tlmace) provided information concerning the most recently obtained results with respect to the alternative jet pump condenser concept. The jet pump condenser concept is supposed to improve the confinement system capabilities existing for the BOHUNICE nuclear power plant; a VVER-440/230 nuclear power station without bubble condenser containment. It was told that one full-size jet pump condenser unit has been successfully tested at the VNIIAES test facilities in Kashira not to
far away from Moscow. Between 200 and 300 such jet pump condenser units may finally be installed within a new building connected to the present confinement building. The connecting point will be at the location of presently installed so-called "safety flaps". Hitherto these flaps are supposed to open the VVER-440/230 confinement to the atmosphere in case of a LOCA-induced overpressure.

19. The Slovak Authorities (like the former CSFR Atomic Energy Commission) have approved backfitting of the BOHUNICE nuclear power plant with a jet condenser building serving both units of this type at the site. After backfitting the maximum design overpressure of the confinement (0.1 MPa) would not be exceeded even in case of a double ended rupture of a 500 mm recirculation line.

20. Pending a more detailed description of the concept and the test results obtained so far from the jet condenser test rig some open questions could arise requiring additional testing to also facilitate the analysis of the entire system.

21. Additional information has been given concerning the installation of filtered venting suitable for VVER-440/213 units. Other information concerned possible improvements of confinement penetrations at these facilities reducing leakage.

22. Before closing the meeting the location and date of another Working Group Meeting was addressed. It was agreed that this question will be decided in accordance with progress concerning the possibilities for integral testing. Other items to be followed are the elaboration of a separate effects tests concept and the distribution of detailed descriptions of relevant simulation codes. On behalf of all participants the chairman expressed his appreciation of the excellent local organization of the meeting and the hospitality offered to all participants during the meeting.

Garching, 24.3.93
Minutes of the Working Group Meeting  
"VVER-440 Bubble Condenser Containment Research Work"  
held at Bratislava (Slovak Republic)  
15./16.9.1993

1. The third meeting of the working group "VVER-440 Bubble Condenser Containment Research Work" took place at the premises of the Nuclear Regulatory Authorities in Bratislava, Slovak Republic. Mr. J. Zlatnansky, Slovak Nuclear Regulatory Authorities opened the meeting welcoming the participants (see Appendix 1). Mr. Holmstrom, OECD Nuclear Energy Agency (NEA), Paris indicated the willingness of the NEA to monitor the status and progress of research work associated with the understanding of the behaviour of bubble condenser containments under the umbrella of its Committee on the Safety of Nuclear Installations (CSNI). CSNI will be informed at its forthcoming meeting in December 1993 about the outcome of this working group meeting and a proposal for international collaboration will be made to the Committee.

2. The invitation to this meeting was also transmitted to several countries which on occasion of a CSNI-Special Meeting on VVER Safety Research Cooperation in April 1993 expressed their interest in a close connection to this research activity. In this context experts from the Netherlands and Italy attended the working group meeting for the first time.

3. The proposed agenda was accepted without modification.

4. The minutes of the second meeting of the working group, held at Rez 4/5.3.93 were briefly discussed and confirmed. The recommendation to provide detailed descriptions of all codes capable to analyse bubble condenser system properties has not been followed by the participants. Due to the urgency of relevant analytical support for this
research activity the recommendation was reiterated after some reasons for the delay had been explained.

Presentation and discussion of the technical project NABUCCO

5. Mr. M. Suchánek presented the main features of the NABUCCO research project proposed by the National Research Institute for Machine Design (SVUSS-Břežovice), Prague, Czech Republic. He made reference to the NRIMD technical report no. 93-05P04E and the associated appendix A which has been distributed in advance to most of the participants together with the invitation to this meeting. Some new participants received the report during the meeting.

6. NABUCCO has been drafted as an integral test facility concept including the simulation of the VVER-440/213 hermetic compartment system, the bubble condenser tower and the air trap building. Involved volumes and the available energy flow will be scaled 1:50 (with respect to the Mochovce prototype plant). The primary circuit will be modelled as a simplified energy source involving a 7 m³ pressure vessel. Of particular importance is the simulation of the bubble condenser system which will be represented by 4 original elements of the gap-cap systems installed in the Mochovce nuclear power plant.

7. Main focus of the NABUCCO project is oriented towards the research into the dynamic behaviour of the bubble condenser structures under various modes of the bubble condenser operation during a postulated loss-of-coolant accident (LOCA). Of particular interest will be the interaction between the bubble condenser structures and the oscillatory condensation mode.

8. An original bubble condenser element consists of 9 parallel gap-cap systems. It is formed by an arrangement of partially reinforced thin-walled plate-type structures which are assembled by welding processes. Structural eigenfrequencies of the condenser elements may differ from one nuclear power plant to another. Hence, it seems of importance also to evaluate the structural eigenfrequency behaviour of applied gap-cap systems in other nuclear power plants.

9. NABUCCO is presently designed to arrange 4 original elements in 2 levels (2 elements per level). This concept should to the largest possible extent preserve the structural eigenfrequency characteristics of the 4 units of the Mochovce NPP.
10. Another concept is still under discussion which may involve 3 or 4 staggered levels of gap-cap systems. However, the benefit of increasing the number of levels must be carefully assessed.

11. Main goal of the present concept is to study the degree of uniformity of thermohydraulic processes occurring in horizontal direction. Full focus on vertical impacts as well would probably require more than an upgrade to only 3 or 4 staggered levels. This aspect was discussed later in connection with the overall evaluation of all proposed research concepts.

12. Following the presentation by Mr. Suchánek a detailed discussion of the proposed project took place. Questions were raised with respect to supporting analytical work, the use of alternative structures (e.g. originating from Greifswald), the completeness of the instrumentation, the design of the connections between the main components (e.g. between the bubble condenser and the air trap) and the further availability of the existing single gap-cap system test rig in Bechovice.

13. The use of gap-cap system elements installed at Greifswald is not possible without modification. The material used for the Greifswald caps is different. Replacement by stainless steel caps would be necessary in this case to preserve the characteristics of most of the bubble condenser towers existing.

14. The design of the model of the hermetic compartments requires supporting analyses before it should be frozen. The energy supply and the design of the blowdown line may be another object for further intensive discussions and analyses to warrant the preservation of plant-typical LOCA properties and parameters. GRS will provide some supporting information obtained from the analyses of the safety of the Greifswald nuclear power plant.

15. Some participants questioned the need for the NABUCCO design in general. It was said that up to until the last working group meeting in Rez in March 1993 no firm commitment was visible with respect to the reactivation of the Zugres test facility. During the evaluation of an alternative concept it became evident that the preservation of structural properties of the gap-cap system elements may be of utmost importance in performing relevant experiments with respect to the interaction of condensation oscillations and structure dynamic response. Earlier experiments with the single gap-cap unit at Bechovice have indicated that oscillatory processes must be expected during certain phases of a LOCA. Tests must show that resonance effects may not endanger the
integrity of the structures. To this end the investigation into spatial effects of horizontally extended structures seems to be inevitable.

16. Subsequently it was asked whether the design of NABUCCO could be changed in that way using all 4 elements arranged in a single level. Available space inside the building where NABUCCO should be located would be a main restriction. Furthermore, the present concept may be sufficient as it involves the entire length of the main flow direction between the gas shaft connecting to the hermetic compartments and the air trap building of a nuclear power plant. In so far, the use of only two elements might be sufficient.

17. The preliminary table of instrumentation envisaged for NABUCCO may be subject to revision after supporting analyses have been performed which should show the needs of a useful code validation activity.

Presentation of the common Ukrainian-Slovak proposal to reactivate the Bubble Condenser Test Rig at Zugres

18. Mr. Baláž introduced the background of the common Ukrainian-Slovak proposal to reactivate the bubble condenser test rig located at Zuetes (Zugres, Ukraine). He referred to the earlier working group meetings where the need for a large test facility was already clearly expressed. The Slovak Power Equipment Research Institute (VUEZ), Tímace, Slovak Republic, at first discussed the idea with Russian and Ukrainian experts in May 1993 on occasion of meetings in connection with the jet condenser research work. Later the proposal was also discussed with the Ukrainian and Slovak authorities which adopted the project as an official common Ukrainian-Slovak proposal. The draft program of the project has been distributed together with the invitation to this meeting.

19. Mr. Kolochko provided general information about the technical features of the existing test rig structures. He concentrated his presentation mainly on the organisational aspects of the collaboration of involved Ukrainian and Slovak institutes and on the provisional evaluation of project costs. Some information has also been provided concerning the instrumentation to monitor facility parameters relevant for the steady state operation of the test rig.

20. The test rig consists of 3 components: a model for the hermetic compartment system simulation, a model for the bubble condenser tower involving of 9 levels with
3 gap-cap systems at each level and a model of the air trap building divided into 3 subvolumes, each connected to 3 bubble condenser levels. Main parameters of interest are seen in possible differences of the behaviour of the different levels of the bubble condenser tower in vertical direction. (Later during this meeting the concern about the possibility of vertically different behaviour of the condenser levels was addressed by a GRS analysis for a nuclear power plant. See also section 34).

21. Mr. Kuznetsov provided supplementary information about the test goals for the Zuetes test rig. He confirmed the possibility of chugging problems to become of interest. However, he mentioned a main goal of the gap-cap system design was to exclude chugging effects. The main goal of constructing the Zuetes test rig was to obtain an integral confirmation of the function of the bubble condenser tower. Earlier analyses in the former Soviet Union have indicated the possibility that the bubble condenser tower may exhibit different behaviour at the different condenser levels extending over a height of approx. 40 m. The basic function of the gap-cap system has already been studied by experiments performed in the late 70ies and early 80ies in test rigs available in the former Soviet Union. During these tests chugging effects were not registered.

22. A provisional list of instruments to be installed in the Zuetes test rig has been provided. This list presently covers the steady state operation at the beginning of an experiment only. Additional instrumentation to monitor dynamic processes during the experiment are presently in evaluation. A more detailed list will be presented in November 1993.

23. It was mentioned that the cost estimation distributed in Bratislava might not yet cover the necessary funding for the additional instrumentation to monitor the dynamic phases of the experiment.

24. The partners supporting the reactivation of Zuetes have been asked to provide small but clear drawings showing the main technical features of the installation. Available drawings for fabrication purposes cannot be reduced to be included in the project description.

25. Following the presentations mentioned under sections 18 to 24 a detailed discussion of the main phenomena to be studied within the Zuetes test rig followed. As mentioned under section 21 it is obvious that not all structural properties of gap-cap system arrangements existing in nuclear power plants are preserved by the chosen design of the Zuetes gap-cap system. A detailed structural analysis of the existing design should
be performed, if the interaction with the oscillatory condensation mode would be an aim of the envisaged experiments.

26. Presently, the main interest on the Zuetes test rig focuses on the non-uniform behaviour of the various levels of the gap-cap system arrangement.

27. Supporting analyses have been recommended to assess the suitability of the chosen design. In reply to questions Mr. Kolochko mentioned that supporting analyses are expected to come from involved Ukrainian research organisations. It was recommended to include such activities within the cost estimation of the project. Otherwise delays in executing the necessary activities must be expected.

**Discussion of the Feasibility of Presented Projects**

28. Mr. Husarček from the Slovak Nuclear Regulatory Authorities stated the importance of a multi-gap-cap unit research work to understand and assess the reliability of the bubble condenser containment concept. He was supported by Mr. Hátle who requested a careful evaluation of the proposals before decisions can be made. Close collaboration between the involved Czech, Slovak and Ukrainian experts was requested to speed up the decision process.

29. In reply to a question by Mr. Kramara it was pointed out that the working group is not in the position to decide which experiments would satisfy regulatory needs. This decision must remain a matter of discussions with the national regulatory bodies. Mr. Kolochko mentioned that certain requirements may become visible from the assessment of the Rovno nuclear power plant which is presently underway.

30. Some discussion was devoted to assess whether the proposed projects duplicate efforts or complement each other. In this context it was requested to draft test matrices for both project proposals to allow an assessment of the complimentary nature of both projects at the next working group meeting. Furthermore the structure dynamic properties of both test rigs must be carefully evaluated in terms of the degree of preservation of those properties existing in nuclear power plants. Due to the unbalanced descriptions of both projects this assessment was not considered possible for this meeting.
Information on Research Work in connection with the Development of the Jet-Condenser concept for backfitting VVER-440/230 nuclear power plants

31. Mr. Kuznetsov provided an overview on experiments executed at Zuetes in connection with testing of the jet condenser concept. He mentioned the design properties of the jet condenser arrangement which allows a better thermal utilization of a condensation pool. Keeping pressure oscillation effects away from the pool walls was said to be one of the advantageous features of the system. He concluded that the jet condenser tests confirm the capabilities at Zuetes to execute large scale tests now.

32. Specific advantage would be achieved by improving the efficiency of the jet condenser concept also under small break LOCA conditions. From the test results obtained so far the experts have concluded that the jet condenser concept will satisfy the goals set forth for backfitting VVER-440/230 facilities.

Other Technical Proposals

33. Prof. Mazzini described some more ideas for the reconstruction or backfitting of VVER-440/230 NPPs. He focused on the use of a common vacuum building to be connected to several units at a given site (e.g. 4 units at Kozloduy). A similar proposal has already been communicated on occasion of a meeting held in Varna, Bulgaria in 1987. The vacuum building includes a pressure suppression system unit, very similar to other Western pressure suppression system concepts. A written communication was promised to back-up the oral communication.

34. For the information of participants attending the working group at the first time Mr. Wolff gave a presentation about the main features and capabilities of the DRASYS pressure suppression system code. The present status of the work was illustrated by results obtained on occasion of a study performed for a nuclear power plant with bubble condenser. The facility was simulated by a 17 node representation. Several transient parameter have been shown which may be of relevance for the scaling and design of test rigs as well as for a first determination of operation conditions. In reply to several questions it was the impression that for the time being the DRASYS-code is the only code to predict the frequency of the oscillatory condensation modes or of chugging events. Examples have been shown which were obtained earlier for the analytic interpretation of Marviken- and GKM-experiments. Mr. Kuznetsov mentioned the availability of a Russian code for simulating chugging frequencies.
Short term recommendations

35. Mr. Zlatňanský reiterated the need for urgent process of research into the behaviour of bubble condenser systems. He requested close collaboration between the involved institutions eventually resulting in a joint project proposal. He promoted financial assistance also for the period of project definition which must be considered as a pre-project requiring considerable efforts of the involved national research institutions in the Slovak Republic, the Ukraine and the Czech Republic. The OECD-Secretariat will evaluate the possibility to help with a small amount of money to speed-up the preparation of the project proposals, and offered administrative support in formulating the projects.

36. After some discussion the partners drafting project proposals agreed on a deadline for submission of revised proposals. 15. December 1993 was chosen, allowing an early distribution to the participants of the Working Group before the next meeting. It was unanimously recommended to hold the next meeting on January 17th and 18th, 1994. Mr. Téchy offered to host the next meeting in Budapest.

37. In closing the meeting the chairman expressed his appreciation for the excellent local organisation and the hospitality offered to all participants during the meeting.

38. On September 17th, 1993 the Mochovce nuclear power plant was visited by most of the participants. Particular attention was given to the bubble condenser arrangements and the interconnection to the hermetic compartment systems of one of the four units installed at the site. The visit contributed to an improved understanding of the particularities of the bubble condenser tower and gave an excellent insight in the structural design solution applied.

Garching, 14.10.93
STEAM CONDENSATION IN WATER POOLS

U. Simon
Siemens AG
Karlstein, Germany
Steam condensation in water pools

Earlier experimental programmes in Western countries

USA: Qualification programmes for GE BWR containments
   Separate programmes for Mark I, Mark II and Mark III containments

Japan: JAERI test programme for Mark II containments

Sweden: Marviken test programme

Germany: Qualification programme for KWU BWR containments;
   separate test setups for Mark 69 and Mark 72 containments
   Verification programme for GE Mark II containments
   Verification programme for commercial naval reactor containment

General aims of the earlier KWU test programmes

- Licensing support
- Improvement of data base for thermohydraulic containment analysis (codes)
- Validation of analytical simulation models
- Design optimization
- Avoid containment damage
Specific design data which were covered by the KWU test programmes

- Maximum dynamic loads on containment walls (quasi-static loads and condensation oscillation loads)
- Maximum loads on submerged structures
- Maximum loads on the condensation/mitigation devices
- Fatigue loads of the system components
- Functionality of the check valve

Geometries tested in the earlier KWU test programmes

- open-ended pipes, diameters 150 mm 200 mm 600 mm
- load mitigation devices (quenchers) of different geometries and different sizes
- nozzle-type quencher, full-scale and quarter scale

Phenomena studied in the tests

- Air clearing
- High flow-rate steam condensation (steam injection at critical flow-rate): jet-type condensation
- Intermediate flow-rate steam condensation: condensation oscillation
- Low flow-rate steam condensation: chugging
- Low and very low flow-rate steam condensation: condensation effectiveness at high water temperatures and low submergence
- Steam-air flow: condensation oscillation
Steam condensation in water pools

Test parameter ranges in the earlier KWU test programmes

(1) maximum load for air clearing

(2) maximum chugging load
   (condensation at low water temperature)

(3) maximum condensation oscillation load
   (condensation at elevated water temperatures)

Submergence varied between 4.5 and 0.5 m

Consultants’ Meeting on the Containment Performance in NPPs with WWER 440 Reactors, Vienna
29 November - 3 December 1993
IAEA CONSULTANTS’ MEETING
ON
CONTAINMENT AND CONFINEMENT PERFORMANCE
IN NPPS WITH WWER440/213 AND 440/230 REACTORS

ACTUAL DEVELOPMENTS IN
HYDROGEN CONTROL

Mrs. G. Preusser
Siemens AG
Offenbach, Germany

VIENNA, AUSTRIA
29 NOVEMBER - 3 DECEMBER 1993
**DELIBERATE IGNITION**

- Early combustion
- Ignition - concentrations as low as possible close to the ignition limit
- Splitting one global deflagration into a big number of small volume deflagrations
  - deflagrations timely and locally dispersed

**CATALYTIC RECOMBINATION**

- Utilization of periods with not ignitable containment atmosphere to reduce the bulky part of H₂
  - steam inertisation
  - low H₂ - release gradients
  - burn out of rest H₂

- Low flame velocities
- Low pressure loads
- Low temperature loads

- Low pressure loads (vented burn)
- Low temperature loads

- Additional mitigation of temperature and pressure loads

**DELIBERATE IGNITION**

- Approx. 150 igniters spread over the total containment volume
- Component diversification: - catalytic powered igniters
  - battery powered igniters

**CATALYTIC RECOMBINATION**

- Approx. 50 catalytic recombiners spread over the total containment volume

---

Fig. 5: Basic Idea

Fig. 6: Technical solution / Dual H₂ - Reduction System
Fig. 12: Spark Igniter with Batteries WZB 89

1 Fuse link
2 Batteries
3 Electronics
4 Pressure Switch
5 Temperature Switch
6 Electrodes
7 Contact safety device
8 Heat Insulation
9 Evaporative cooling
10 Mounting

Fig. 13: Spark Igniter WZB 89/ Main technical data

- Actuating temperature: 70 to 160 °C (adjustible)
- Actuating pressure: 0.1 to 5.5 bar (adjustible)
- Catalytic actuation: > 3Vol.-% H₂ (catalytic coated temperature switch)
- Spark frequency: ≥ 5 min⁻¹
- Dischargetime of batteries: ≥ 14 day
- Spark energy: > 10 mJ
- Ignition voltage: ≤ 30 kV
- Spark generation: ≤ 4.5 bar
- Ignition in saturated steam/air mixtures: directly after exceeding ignition limit (test certificate TÜV - Typenprüfung Nr. KSA 10/80 PB01)
- Design temperature: 350 °C (for 0.5 h)
- Design pressure: 180 °C (for 1 h)
- Radiation resistance: 125 °C (for ≥ 14 days)
- Design pressure: 6 bar
- Radiation resistance: Total dose 72 kGy at dose rates between 500 bis 10000 Gy/h
- Size: 200 mm Ø, 390 mm height
- Weight: approx. 15 kg
Fig. 16: Igniter and recombiner qualification
Test facilities
SIEMENS

Thermal Aging (Normal Operation)

Radiation (Normal Operation)

Vibration (Normal Operation)

Radiation (DBA and Severe Acc. Conditions)

Thermodynamic Load (Design Basis Acc.)

Multiple Combustion (Severe Accident Conditions)

Long-Duration Function (Severe Accident Conditions)

1 bar; 125 °C; 360 h

50 kGy; 500 Gy/h; 100 h

acc. to IEEE 382, IEC 68-2-6

10 kGy 10000 Gy/h 1 h
7 kGy 1000 Gy/h 10 h
5 kGy 500 Gy/h 1 h

1...6 bar; 40...160 °C; 2,6 h

2,5 bar; 125 °C; 1,5 h
2,5 bar; 350 °C; 0,5 h

2,3 bar; 125 °C; until the batteries are empty (≥14 days)

1 Mounting
2 Cover
3 Housing
4 Catalytic Coils
5 Central Pipe
6 Pt - Ignition Wires

Fig. 17: Spark Igniter Qualification program

Catalytic igniter WZK90
Fig. 22: Igniter tests performed
**Function principle**
- Gas - ignition on catalyst surface heated by exothermic reaction

**Catalyst**
- Platinum

**Catalyst Basis**
- High temperature resistant metallic foil with active intermediate layer (washcoat)

**Actuating**
- No active start up mechanism required. Self starting if H₂ and O₂ is present.

**Ignition in saturated steam - air - mixtures**
- Directly after exceeding ignition limit

**Temperature resistance**
- Short term heating: Unlimited multiple ignition on the ignition limit
- Long term heating: Nearly unlimited in H₂ - air - steam mixtures with H₂ consumption ≤ 10 Vol.-%

**Design pressure**
- Open construction. Pressure difference over housing approx. 0 bar

**Radiation resistance**
- Unlimited

**Resistance against potential catalytic poisons**
- Against representative poison species and concentrations expected during normal operation and severe accidents

**Size of housing**
- 130 mm Ø, h = 270 mm

**Weight**
- Approx. 2 kg

**Fig. 23: Catalytic igniter WZK 90/ Main technical data**

---

**Photochemical Ignition Load (Design Basis Acc.)**
- Ignition in Air/ Steam/ H₂ - Mixture
- Ignition in the Presence of Airborne Impurities
- Ignition after Submergence
- Ignition after Methyl - Iodine Load
- Ignition Test after Pressure with welding vapours and solvent fumes
- Ignition Behaviour in Different Air/ Steam/ Mixtures
- Ignition Behaviour under Forced Flow Convection

**Fig. 25: Catalytic Igniter WZK 90/ Qualification program and conditions**
- Resistance to thermal ageing
- Resistance to radiation (operational radiation, exposure to radiation following a core melt accident)
- Resistance to chemical impurities in the reactor containment atmosphere (catalyst poisons, solvent and welding fumes, smoke from oil and cable fires)
- Recombination rates under various ambient conditions
- Endurance test
- Vibration resistance test

Tests performed as part of catalytic recombiner qualification
Recombination tests with the model FR 90-100 with:

a) 4% H₂, 1.0 bar, dry at room temperature
b) 4% H₂, 2.2 bar, dry at room temperature
c) 4% H₂, 2.2 bar, 40% steam, 56% air
d) 5% H₂, 2.9 bar, 50% steam, 45% air
e) 5% H₂, 3.8 bar, 60% steam, 35% air
f) 10% H₂, 4.0 bar, 60% steam, 30% air
g) 15% H₂, 4.0 bar, 60% steam, 25% air

Reproduction of test d) with 2 different catalyst carriers, one of them with catalytic sheets from a other manufacturing series

Function of the recombinator after prestress from hydrogen burns

Function of the recombinator after oil and cable burns

Long duration test for > 48 h with > 4 Vol.-% hydrogen by stoichiometric hydrogen- and oxygen exposure of the recombiner inside test vessel

Fig. 27: Qualification of recombiner
The tests involve subjecting the plate to a flow of test gas containing hydrogen and measuring temperature increase. A simple, easy-to-transport test facility is available for this purpose which allows performance of the test within a few minutes at the place of installation.

Qualification

The functional capability of the catalyst has been tested within the scope of TÜV Type Tests during numerous experiments under environmental conditions typical for accidents.

Functional capability was demonstrated under the following conditions:

- at differing pressures
- at differing temperatures
- at differing steam concentrations
- at differing hydrogen concentrations
- with gas mixtures containing impurities
- following hydrogen combustion
- following submersion in water
- following an oil fire and a cablefire

Furthermore tests have been performed on optimized recombiners to determine throughputs with varying containment pressures and hydrogen concentrations at the inlet and a recombination test was performed with a full-scale FR 90/1-1500 in the Battelle multi-compartment containment model.

Further Applications

- Replacements for hydrogen recombiners for design-basis accidents
- Recombination of radiolysis oxygen in inerted containments (no nitrogen injection necessary, no switchover of an nullus offgas to exhaust)
- Recombination of radiolysis gas in wet scrubbers of venting systems to maintain inert conditions

Fig. 3: Hydrogen Recombination Capacity of FR 90/1-320, 960, 1500

Fig. 29: Catalytic recombiner capacity
Extract of product information
COMPARISON OF DESIGN CRITERIA FOR BUBBLER CONDENSER CONTAINMENTS AND OTHER CONTAINMENT TYPES

A.Strupczewski
Safety Assessment Section
Division of Nuclear Safety
International Atomic Energy Agency

VIENNA, AUSTRIA
29 NOVEMBER - 3 DECEMBER 1993
Bubbler condenser containment concept was devised nearly 20 years ago, when the safety regulations in force in the former USSR were different from those observed at the time in Western countries. As the years went by, the engineering practice in designing and building bubbler condenser containments was gradually modified. In the case of latest bubbler condenser containments for WWER 440/213 units most of the contemporary requirements for reactor containment systems are satisfied.

However, no established set of documents exists which would determine all pertinent requirements in a consistent way and provide guidance for regulatory review of this type of containment. Since the importance of the containment for NPP safety is evident, the Regulatory Bodies in the countries operating WWER 440/213 units will have to undertake the task of setting up the necessary guidance, e.g. by creating an equivalent of the Standard Review Plan being in force in the USA.

The comparisons presented in this paper are aimed to present the scope of General Design Criteria and specific criteria for bubbler condenser containment design calculations and to provide the first evaluation of the actual status in this domain for WWER 440/213 bubbler condenser containments.

The criteria and regulations shown below have been taken from German, US and IAEA rules, in particular from:
2. KTA Safety Standard, Steel Containment Vessels, Part 2, Analysis and Design, KTA 3401.2
3. General Design Criteria for NPPs, App. A to 10 CFR 50
4. Design Limits and Loading Combinations for Metal Primary Reactor Containment System Components, RG 1.57
7. ASME Boiler and Pressure Vessel Code, Section III, Division 2, "Code for Concrete Reactor Vessels and Containments, Article CC-3000, Design," ASME
8. ASME Boiler and Pressure Vessel Code, Section II, Division 1, Subsection NE "Class MC Components", ASME.
9. ASME Boiler and Pressure Vessel Code, Section III, Division 1, Subsection NB, "Class 1 Components", ASME
10. Pressure and temperature transient analysis for LWR containments, ANSI/ANS - 56.4-1983
11. Subcompartment pressure and temperature transient analysis in LWRs, ANSI/ANS- 56.10-1982
12. PWR and BWR containment spray system design criteria, ANSI/ANS 56.5-1979
## GENERAL DESIGN CRITERIA
### FOR NPP CONTAINMENTS

**In FRG: KTA Safety Standards**
RSK Guidelines for PWRs,
III ed. October 1981

<table>
<thead>
<tr>
<th>CONTAINMENT, GENERAL</th>
<th>Equivalent for WWER</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1 All RCS shall be accommodated in a containment with the exception of pipes of smaller diameter, e.g. instrument pipes to the extent this is necessary in terms of engineering and if a break of such pipes would involve only minor radiation exposures.</td>
<td>Yes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DESIGN BASES</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.2 The containment ...will be able to cope with the static, dynamic and thermal stresses under accident conditions without exceeding the postulated leak rates.</td>
</tr>
</tbody>
</table>

Differential pressures developing in the course of the pressure equalization processes during the DBAs will not damage the containment vessel and its safety related internals. The stability of partition walls and/or internals must be warranted for the expected differential pressures which may occur. The assumptions for calculating codes which are not confirmed by experiments must be made in a conservative way. | Yes |
The safety margin to be added on the maximum differential pressures calculated in this way shall be at least 15% and must not be smaller than 0.1 bar.

For the calculation of jet forces acting on containment structures, the most unfavourable break positions must be chosen.

A 15% safety addition shall be considered for loads expected on safety related internals by jet forces and missiles.

5.3 STRUCTURAL LAYOUT

Containment, its isolating valves and cooling systems as well as internals necessary for its function and the measuring and control equipment shall be protected against missiles and jet forces.

The stability and integrity of internals and compartments has to be demonstrated by calculations.

The containment vessel must be surrounded by a concrete shell. The annulus must permit an inspection, it must be possible to maintain sufficient long term subpressure in the annulus, and to vent it via filters and stack.

The concrete shell of the reactor building shall sufficiently shield the environment against direct radiation.

---

1 Safety margins are not expressly determined

2 The extent of calculations and the acceptance criteria are not determined

3 Does not apply to concrete containments of WWER 440/213
The concrete shield of the reactor building shall protect the plant against external events.

The entire electrical and mechanical equipment inside the containment necessary for the management of incidents must be designed such as to cope with the environmental conditions expected during the accident.

Cables and pipes inside the containment which are necessary for the control of incidents must be positioned redundantly and physically separated.

The safe handling of the hydrogen within the containment shall be assured.

* For postulated DBA = DB LOCA

**5.4 DESIGN CONDITIONS AND MATERIAL REQUIREMENTS**

The requirements for design, materials and further processing shall be agreed in all detail between the reactor vendor, manufacturer and the regulatory body.

Containment design shall enable nondestructive examinations, particularly of the welds.

---

4 The spectrum of external events is site specific, generally less comprehensive than for PWRs.

5 For DBA, i.e. LBLOCA, but not for Beyond DBA conditions

6 Practice has been changing over the years, presently it is close to satisfying this requirement

7 In limited extent
STRESS AND STABILITY ANALYSIS

The stress and stability analysis shall be performed on the basis of the theory of elasticity. If necessary, the plastic behaviour of components of the support structure shall be included in these analyses [2, section 5.1]

The allowable stress values shall be related to the 0.2% strain limit or the yield strength at the respectively relevant temperatures.

The loading conditions shall be correlated to the service limit levels 0, 1, 2 or 3. The level 1 service limit is correlated to normal operation and loss-of-coolant incidents occurring more frequently than 5 times during NPP lifetime. The level 2 service limit is correlated to all remaining loading conditions where the loads from external events occur. In the case of service limit level 3, for which an RCS pipe rupture is an example, the loads acting on the containment include dead weight, overall internal pressure, local pressure increase, external loading and loading moments [2, section 3.4]

In the case of service limit levels 0 and 1 the permissible stresses are as follows:

1. For the static analysis (not considering residual stresses)
   1.1. Primary general stresses:
           maximum $0.67 \times \sigma_{0.2}$
   1.2 Superposition of primary general and primary local membrane stresses:
           maximum $0.75 \times \sigma_{0.2}$
   1.3 Superposition of primary bending stresses and primary membrane stresses in accordance with 1.1 and 1.2 above
           maximum $0.75 \times \sigma_{0.2}$
   1.4 Superposition of primary and secondary stresses in the disturbed area including the stresses resulting from temperature influences
           maximum $2 \sigma_{0.2}$ of 1.2, however not larger than 500 N/mm²

8 No such grading is in force for WWER units

9 Differently formulated but generally equivalent rules are applied
1.5 When external events (such as aircraft crash, earthquake) are considered, the permissible maximum stresses under 1.1 through 1.4 may be increased by a factor of 1.25.

2. Peak stresses shall be covered within the frame of a fatigue analysis.

3. In case of a large number of load cycles, the safety coefficient of 2 shall be used against fatigue strength.

In the case of level 2 service limit the limit values of permissible stresses may be increased by 10% and in the case of level 3 service limit - by 25%. [2, section 5.1, 5.2.5]

For all parts of the containment only certified materials shall be used.

Ductile condition of the material will be maintained at all locations and during all operating and incident related plant conditions.

The reference NDT temperature shall be at least 33 K below the lowest operating temperature [1].

**PENETRATIONS**

All pipe penetrating the containment and connected to the pressure retaining boundary must be protected by at least two isolating valves.

For pipes containing primary coolant and connected to the pressure retaining boundary one isolating valve shall be installed inside and one outside the containment close to containment wall.

Isolating valves which are not part of measurement lines must be remotely controlled or passively closing with sufficient leaktightness. For safety relevant leak cross sections the signal generation for the closing of these isolating valves must be reliably assured.

---

10 Permissible stresses are higher for DBA than for normal service, although the precise formulation is different

11 No specific requirement, since the containment is made of concrete
It must be possible to safely cope with a spontaneous rupture of a pipe equipped with such valves.

Penetrations which have to be closed to maintain the containment function must be protected by multiple arrangement of the isolating valves in sequence. In case of accidents, the isolating valves must be activated automatically. The isolating valves and their power supply must be independent from each other. Sufficient local separation must be requested. The isolating valves must be protected against missiles. The same applies to their power supply and the associated control unit. Each individual valve must fully comply with the specified leak-tightness conditions. The isolating valves must function perfectly under all possible accident conditions.

The cross sections of ventilation lines leading to the containment must be as small as possible, close quickly and reliably and remain tight for a sufficient period of time.

The containment compartments must be subject to periodic tightness inspection during operation [1].

Locks and isolating devices of the ventilation system must be connected to a leakage suction system which allows to return leakages into the containment.

12 Requirement not specified

13 No such system exists
POSTULATED LEAK CROSS SECTIONS IN THE RCS PIPES

Concerning the load assumptions for reaction and jet forces on pipes, components, component internals and buildings an instantaneous leak (linear opening behaviour, opening time 15 ms) with a cross section of 0.1 \( F \) (\( F = \) open cross-section) shall be postulated for different break positions.

The prediction of the containment vessel design pressure as well as the prediction of the pressure differences inside the containment vessel must be based on leak cross sections (of the RCS pipes) up to 2 \( F \).

The US General Design Criteria (10 CFR 50, App.A)

Acceptance criteria for the design of the concrete containment

Acceptance criteria for the design of the concrete containment is based on meeting the relevant requirements of the following regulations:

1. 10 CFR part 50.55a and the GDC 1 as they relate to concrete containment being designed, fabricated, erected and tested to quality standards commensurate with the importance of the safety function to be performed.

2. GDC 2... withstand the most severe natural phenomena such as winds, tornadoes, floods and earthquakes and the appropriate combination of all loads,

3. GDC 4... withstand the dynamic effects of equipment failures including missiles and blowdown loads associated with LOCA

14 Equivalent assumptions are made

15 the precise wording of requirements is different
GDC 13 Instrumentation and Control

... shall be provided to monitor... the containment and its associated systems parameters.

GDC 16 Containment Design

... shall provide an essentially leak-tight barrier against the uncontrolled release of radioactivity to the environment...

GDC 38 Containment Heat Removal

A system to remove heat from the reactor compartments shall be provided...

to reduce rapidly...the containment pressure and temperature...

Suitable redundancy ...and interconnections, leak detection, isolation and containment capabilities shall be provided to assure that for either electric power system operation the system safety function can be accomplished assuming a single failure

GDC 50 Containment Design Basis

...containment and its internal compartments shall be able to accommodate without exceeding the design rate and calculated pressure and temperature the conditions resulting from any LOCA.

GDC 51

Fracture Prevention of Containment Pressure Boundary

... ferritic pressure retaining components behave in a nonbrittle manner, and probability of rapidly propagating fracture is minimized.

---

16 for DBA conditions

17 degree of leak-tightness not specified
### GDC 52 Capability for Containment Leakage Rate Testing

... periodic integrated leakage rate testing can be conducted at containment design pressure.

<table>
<thead>
<tr>
<th></th>
<th>Yes</th>
</tr>
</thead>
</table>

### GDC 53 Provisions for Containment Testing and Inspection

<table>
<thead>
<tr>
<th></th>
<th>Yes</th>
</tr>
</thead>
</table>

### GDC 54 Piping Systems Penetrating Containments

...shall be provided with leak detection, isolation, and containment capabilities having redundancy, reliability and performance capabilities that reflect importance to safety of isolating these piping systems. Periodical testing required.

<table>
<thead>
<tr>
<th></th>
<th>Yes</th>
</tr>
</thead>
</table>

### GDC 55 Reactor Coolant Pressure Boundary Penetration Containment

...isolation valves, at least two, one inside and one outside the containment, of which one locked closed, or two automatic valves.

<table>
<thead>
<tr>
<th></th>
<th>Yes</th>
</tr>
</thead>
</table>

### GDC 56 Primary containment Isolation

Each line that connects directly to the containment atmosphere and penetrates primary reactor containment shall be provided with two containment isolation valves, of which one locked closed, or two automatic isolation valves.

<table>
<thead>
<tr>
<th></th>
<th>Yes</th>
</tr>
</thead>
</table>

### The loads normally applicable to concrete containments

The loads normally applicable to concrete containments include the following

<table>
<thead>
<tr>
<th></th>
<th>Yes</th>
</tr>
</thead>
</table>

a) loads encountered during preoperational testing,
b) loads encountered during normal plant startup, operation and shutdown, including dead loads, live loads, thermal loads and hydrostatic loads,
c) loads induced by the design wind and the operating basis earthquake,
d) loads induced by the design basis tornado and the safe shutdown earthquake,
e) loads due to LOCA, including elevated temperatures and pressures, localized loads such as jet impingement and associated missile impact. For BWR containments hydrodynamic loads...
in suppression pools manifested as jet loads and/or pressure loads. [6, section 3.8.1.-3]

Loading combinations

1. Testing conditions
2. Design conditions (including design pressure, design temperature and design mechanical loads generated by the DBA.)
3. Service conditions
   A. Level A Service Limits (including LOCA)
   B. Level B Service Limits (Level A + natural phenomena during which NPP must remain operational, e.g. LOCA + Operating Basis Earthquake (OBE))
   C. Level C Service Limits (Level A + natural phenomena for which safe shutdown of the plant is required, e.g. LOCA + Safe Shutdown earthquake (SSE))
   D. Level D Service Limits (include Level C + loadings of a local dynamic nature for which the containment function is required, e.g. LOCA + SSE + local dynamic loading) [6, section 3.8.2-10]

Transient and localized loads

In a PWR ice-condenser containment and in a BWR pressure suppression containment nonaxisymmetric and transient pressure loads will develop after LOCA and should be considered. For the effect of such localized and transient loads, the overall behaviour of the containment structure should be first determined. A portion of the containment shell, within which the localized or transient load is located, should then be analyzed, using the results obtained from the analysis of the overall vessel behaviour as boundary conditions. [6, section 3.8.1.-9]

The loads applicable to steel containments include those hydrodynamic loads which are associated with BWR suppression pool swell phenomena and are produced as a result of the purging of air and steam in the drywall and vent system into the subversion pool during a postulated LOCA. Such loads include bubble pressure, bulk swell, and froth swell loads, drag pressure pool boundary chugging loads and other pool well loads associated with these phenomena. Also those loads which are resulting from fluid-structure interaction due to seismic

\[\text{No}^{18}\]

\[\text{No}^{19}\]

\[18\] No such gradation of loads and of allowable stresses exists for WWERs.

\[19\] So far there is no express analysis of these effects for bubbler condenser structure available in Safety Analysis Reports of WWER units.
and/or pool swell should be considered" [6, section 3.8.2-4].

"Those loads which are generated as a result of the LOCA in the ice condenser. These loads are categorized as nonsymmetric dynamic transient pressure loads which in the first few seconds might produce compressive stresses in the containment due to the differential pressure across the containment" [6, section 3.8.2-4]

For internal structures

In the PWR ice-condenser system which utilizes the pressure suppression concept, the divider barrier surrounds the RCS. In the event of LOCA, the divider barrier will contain steam released from the RCS and temporarily acting as a pressure retaining envelope, will channel the steam through the venting doors and into the ice-containment.

The divider barrier will be subjected to differential pressure and possibly jet forces and any structural failure in its boundary may result in steam bypassing the ice condenser and flowing directly into the containment, possibly generating a containment pressure higher than that for which it has been designed.

With this functional requirement in mind the general arrangement and principal features of the divider barrier are reviewed with emphasis on structural framing and expected behaviour when subjected to the design loads. [6, section 3.8.3-3] The same formulations concern the drywall surrounding the RCS in the BWR Mark III containment system.[6, section 3.8.3-4]

Weir wall

The weir wall forms the inner boundary of the suppression pool and is located inside the drywall. It completely surrounds the lower portion of the RCS. The general arrangement and principal features of the weir wall are reviewed with emphasis on structural framing and behaviour under loads. [6, section 3.8.3-4]

---

20 The bubbler condenser walls are equivalent to the divider barrier described for ice condenser

21 caps in bubbler condenser trays are equivalent to weir walls in BWR suppression pools
Since the divider barrier has to maintain a certain degree of leak-tightness during a LOCA and is thus a critical structure with respect to the proper functioning of the containment, it is treated on the same basis as the containment. [6, section 3.8.3-9]

Elastic analysis is usually used for the ice-condenser and its components. However, **plastic analysis may also by used** as an alternate. Accordingly, the load factors that are applied to each of the applicable loads and the basis and justification of these loads are reviewed. [6, section 3.8.3-9]

Where experimental verification of the design using simulated load conditions is used, the procedures used to account for similitude relationships which exist between the actual component and the test model are reviewed to assure that the results obtained from the test are a conservative representation of the load carrying capability of the actual component under the postulated loading. [6, section 3.8.3-9]

**Structural acceptance criteria**

The containment shall be designed to resist the loads and load combinations given below [7, CC-3200]

**Service loads.** Service loads include normal loads encountered during normal plant operation and shutdown, construction loads - applied to the containment from start to completion of construction, and test loads.

**Factored loads,** namely severe environmental loads, extreme environmental loads and abnormal loads generated by DBA.

**Structural members designed to resists impulse loads and dynamic effects** in the abnormal, extreme environmental and abnormal and extreme environmental categories are allowed to exceed yield strain and displacement values. Design adequacy is controlled by limiting the ductility assumed in evaluating the energy absorption capability or resistance function of the structure (ductility is defined as the ratio of maximum deformation or strain of the member at the point of collapse to the maximum elastic deformation or strain). [7, CC-3921]

---

22 No expressly formulated acceptance criteria are available
According to SRP, section 3.8.1-12, an additional limitation in comparison to [7] is imposed, namely that the tangential shear stress carried by the concrete must not under any conditions exceed 40 psi for abnormal/severe environmental condition combination and 60 psi for abnormal/extreme environmental conditions.[6, section 3.8.12-12]

In the case of steel containments and their elements, in particular for BWR units, pressure suppression systems are reviewed with special attention on those piping which channel steam and air, and are necessary for the containment function. Such items include, but are not limited to, the torus, the vent header, the equalizing ring header and the downcomers. Also, the drywall/vent header junction, the vent header/downcomers junctions and the penetrations are reviewed to determine the expected behavior of the structure when subjected to the design loads.

[6, section 3.8.2-3].

Allowable design pressures depend on the level of Service Limits and are graded differently for different components. For example, in the case of valves the service pressure for Level B may be 110% of the value for Level A,

- for Level C - 120 % of the value for level A, and
- for Level D a separate set of guidelines is provided. [9, NB-3520, Design considerations]
- for Pressure Relief Valve design, the primary membrane stress intensity for level A and B shall not exceed $S_m$, for Level C may be 50% higher and for level D a different set of guidelines is provided [9, NB 3592]

For piping the permissible pressure under Level B conditions is by 20%, for Level C by 50% and for Level D by 100% higher than for Level A conditions. [9, section NB - 3600]

**For BWR Containment internal structures**

The drywall...is critical with respect to the proper functioning of the containment. The design and an analysis procedure utilized for the drywall are reviewed on a basis similar to those of containments.

The weir wall should not deform to an extent that might impair or degrade the pressure suppression performance.[6, section 3.8.3-10]

---

23 Plastic deformation is allowed for bubbler condenser elements, provided that they do not deform to an extent degrading the bubbler condenser performance.
For steel portions of the ice condenser divider, of drywall and of weir wall, that resist pressure but are not backed up by structural concrete, the design and analysis procedures are acceptable if found in accordance with the applicable provisions of Subsection NE of the ASME Code, Section III, Division 1. [6, section 3.8.3-22]
# COMPARISON OF DESIGN CRITERIA FOR NPPs CONTAINMENTS OF BUBBLER CONDENSER AND LARGE DRY CONTAINMENT TYPE

<table>
<thead>
<tr>
<th>PLANT CONDITION</th>
<th>PWR (US)</th>
<th>PWR(FRG)</th>
<th>WWER 440/213</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power level</td>
<td>102%</td>
<td>nominal(100%)</td>
<td>102%</td>
</tr>
<tr>
<td>Containment atmosphere</td>
<td>normal operating conditions</td>
<td>&quot;conservatively specified&quot;</td>
<td>normal operating conditions</td>
</tr>
<tr>
<td>Break Size equivalent to</td>
<td>spectrum up to double ended instantaneous guillotine break of RCS and main steam pipe</td>
<td>ibid</td>
<td>LB LOCA</td>
</tr>
<tr>
<td>Mass and Energy</td>
<td>RCS mass and energy secondary side energy</td>
<td>RCS + 1 secondary side SG coolant inventory</td>
<td>RCS mass and energy</td>
</tr>
<tr>
<td>Decay Heat Release</td>
<td>120% ANS 5.1 Standard Rates</td>
<td>idem [1]</td>
<td>idem</td>
</tr>
<tr>
<td>Stored energy from core and coolant system structures</td>
<td>according to transient blowdown calculations</td>
<td>as in US [1]</td>
<td>as in US</td>
</tr>
<tr>
<td>Reaction heat from metal-water reaction</td>
<td>according to Baker-Just curve</td>
<td>according to experimental evidence [1]</td>
<td>as in US</td>
</tr>
<tr>
<td>Heat exchange with secondary system</td>
<td>via analyses of DBAs</td>
<td>idem</td>
<td>idem</td>
</tr>
<tr>
<td>PLANT CONDITION</td>
<td>PWR (US)</td>
<td>PWR (FRG)</td>
<td>WWER 440/213</td>
</tr>
<tr>
<td>-----------------------------------------------------</td>
<td>-----------------------------------------------</td>
<td>----------------------------------------------</td>
<td>--------------</td>
</tr>
<tr>
<td>Heat transfer to containment structures</td>
<td>Tagami or Uchida correlations</td>
<td>experimentally proven correlations acceptable [1]</td>
<td>as in FRG</td>
</tr>
<tr>
<td>Safety addition to released energy</td>
<td>conservatism of App.K to 10 CFR 50</td>
<td>1.02 (defined as [1] RCS volume tolerance)</td>
<td>none</td>
</tr>
<tr>
<td>Safety margin in design pressure</td>
<td>15% for Mark III plants [6, Section 6.2.1.1.C-3]</td>
<td>15% above calculated incident pressure [1]</td>
<td>not specified</td>
</tr>
<tr>
<td>Design temp. of containment steel</td>
<td>maximum calculated value</td>
<td>maximum equilibrium temp. of the containment atmosphere [1]</td>
<td>not specified</td>
</tr>
<tr>
<td>Safety margin to the maximum differential pressure</td>
<td>For BWR Mark III containment the design differential pressure between drywell and containment should provide at least a 30% margin above the peak calculated differential pressure [6, section 6.2.1.1.C-3]</td>
<td>15%, but not less than 0.1 bar [1]</td>
<td>not specified</td>
</tr>
</tbody>
</table>
**SPECIFIC REQUIREMENTS FOR THE GLOBAL CONTAINMENT MAXIMUM PRESSURE PREDICTION**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermodynamic nonequilibrium in cont. atmosph.</td>
<td>not addressed</td>
</tr>
<tr>
<td>Nodalisation</td>
<td>none</td>
</tr>
<tr>
<td>Containment volume construction tolerances</td>
<td>not addressed</td>
</tr>
<tr>
<td>Requested safety factors on load predictions</td>
<td>1.1 (C.P.stage), 1.0 (O.L.stage)</td>
</tr>
<tr>
<td>Possible locations of ruptures</td>
<td>not explicitly addressed</td>
</tr>
<tr>
<td>Leak Size related to cross-section of broken pipe</td>
<td>guillotine type fracture</td>
</tr>
<tr>
<td>Energy discharge rates determined</td>
<td>models acceptable to App. K. to 10 CFR 50</td>
</tr>
<tr>
<td>Break opening time</td>
<td>not addressed</td>
</tr>
</tbody>
</table>

Overall pressure to be increased by 0.3 bar in each compartment [1]

2% reduction of available free volume [1]

Most unfavourable break location as in FRG

200% as in US

Possible maximum, based on experimental evidence or blowdown calculations as in FRG

Break opening time 15 ms instantaneous

---

*The tables partly based on the report of Prof. H. Karwat: Practices applied for the design of large dry PWR-containments within EC countries, Commission of European Communities, EUR 12251E (1989)*