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Dukovany

WWER 440/213 NPP Containment from the point of view of IAEA Requirements and Current European Practice

Prepared on the basis of data from
Dukovany, Bohunice and Mochovce NPPs
and Phare Project PH 2.13/95

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03/2000

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1. Introduction

A significant factor in design of complex technology of nuclear power plant (NPP) is minimisation of its impact on surrounding environment even in cases of extraordinary operational events.

In addition to several levels of protection which prevent from equipment damage there are three barriers introduced in the NPP system preventing from release of radioactive substances into surrounding environment. They are fuel cladding, primary circuit boundary and containment.

In summary these three barriers form an important item of the nuclear safety assurance system. The term "nuclear safety" means the state and capability of nuclear installation to prevent from an uncontrolled propagation of fission reaction as well as from an unallowable release of radioactive substances and ionising irradiation into environment both under normal operation and during accident conditions.

Presented document is focused on the 3rd barrier – containment and is aimed to explain the basic philosophy of management of maximum design accident in containment of WWER440/213 nuclear power plants. In addition it shall present that the WWER 440/213 containment provides protection of environment in way corresponding to IAEA requirements and to current European practice.

2. Brief description of the WWER 440/213-containment design

The NPP design shall take into account a set of requirements both for proper manufacturing equipment and for protection system as well as for protective barriers. The concept of WWER 440/213 has already certain attributes of enhanced reactor safety of new generation, in particular great reserve of water for active core cooling. This was accomplished by use of six horizontal steam generators connected by six detachable loops to reactor. Such configuration required, in particular based on spatial reasons, a specific structural solution of the 3rd. barrier – containment.

In particular the following basic functions has to be met by the containment:

1. Prevention from release of radioactive substances outside a hermetic area exceeding pre-set level, i.e. assurance of required tightness of biological protection under normal operation and during maximum design accident.
2. Management of impact of increased pressure and temperature inside hermetically sealed areas caused by failure of reactor cooling system.
3. Protection of reactor cooling system and plant equipment from external effects inside as well as outside the containment. Containment shall withstand effects of natural forces (earthquakes, winds) and human induced activities.

The system of vacuum bubbler condenser for restriction of maximum design accident consequences with break of main circulating pipeline was developed in late of seventies. This system is used not only in Russia (Kola NPP) but also in Ukraine (Rovno NPP), in the Czech Republic (Dukovany NPP), in the Slovak Republic (Bohunice, Mochovce NPPs) and in Hungary (Paks NPP).

Maximum design accident is an accident considered in design of nuclear power facility, which has the greatest radiation impact on environment. Probability of its occurrence is very low. Although its occurrence is hypothetical, the pre-set value of doses must not be exceeded for the most endangered individuals of public from surrounding of NPP. The Loss of Coolant Accident belongs among the most dangerous accidents. The failure of the first two barriers will occur during the LOCA - the fuel cladding and primary circuit integrity.

The WWER 440/213 containment presents the 3rd barrier against release of radioactive fission products into environment. It consists of the following main parts:

- Steam Generator Compartment
- Corridor
- Bubbler Condenser building with accident confinement shaft
- System of BC with air traps

- Spray system

The containment is sub-atmospheric with pressure suppression by bubbler condenser and spray system. It is designed for 150 kPa overpressure and for 20 kPa underpressure what together with safety coefficient cca 1,15 covers sufficiently assumed loading during maximum design accident – the rupture of the primary pipeline DN 500 with flow of coolant from both sides according to current IAEA requirements for the 3rd barrier.

The total free volume of containment is approximately 52 500 m^3. Reinforced concrete walls form boundary of containment with lining from steel sheets separating all hermetically sealed areas from surroundings as well as by other construction, technological and electrical items providing its tightness. They are in particular hermetically sealed doors, hatches, penetrations, and protective cover of reactor shaft and air-conditioning items. The steel lining with thickness of 6 mm connects all these items thus the tightness of reinforced concrete walls is provided.

There are quick acting isolating valves on the boundary of containment provided for quick isolation of systems inside containment in case of accident.

The quick acting isolating valves are doubled and they are located on both sides of containment in its close vicinity, thus during any accident event at least one barrier shall remain retained which will protect before spreading of radioactive substances towards to the NPP environment.

Under operation of unit the minimum underpressure of 50 Pa is kept inside the containment. Operation of containment under permanent underpresure allows for continued monitoring of its tightness, which is a significant safety aspect of this type of containment. The tightness of containment is verified also by periodical tests using an internal overpressure.

The scheme of containment is shown in the Fig. No. 1

The containment consists of hermetically sealed compartments (2) housing reactor equipment (1) and equipment of air-conditioning systems, spray system (5) a bubbler condenser building which is connected to hermetically sealed compartments by corridor (7). The bubbler condenser building contains 12 staggered floors of passive condenser with bubbling of steam (8) and air traps (9) equipped by check valves (10). The gas volumes above the water level (beyond the water sealing) are through dual check valves connected to the air traps. There are four air traps to which uncondensed gases from containment are forced each connected to three floors of bubbler condenser trays. Between volume beyond water sealing and shaft of bubbler condenser are two self-closing check valves on each floor whose function is to prevent a reverse flow of water from trays in case of small accident.

3. Course of maximum design accident confinement in WWER 440/213 containment

The BC system is operated only in accident conditions in conjunction with loss of coolant of either primary or secondary circuit resulting in pressure and temperature increase in hermetically sealed area. It is put under operation automatically by arising pressure difference between hermetically sealed (2,3 – Fig. 1) and retaining areas. Operation of bubbler condenser is clearly passive. General scheme of hermetically sealed volumes with confinement system is shown on the Fig. 1; the detail of bubbler condenser building with several floors of trays is in Fig. 2.

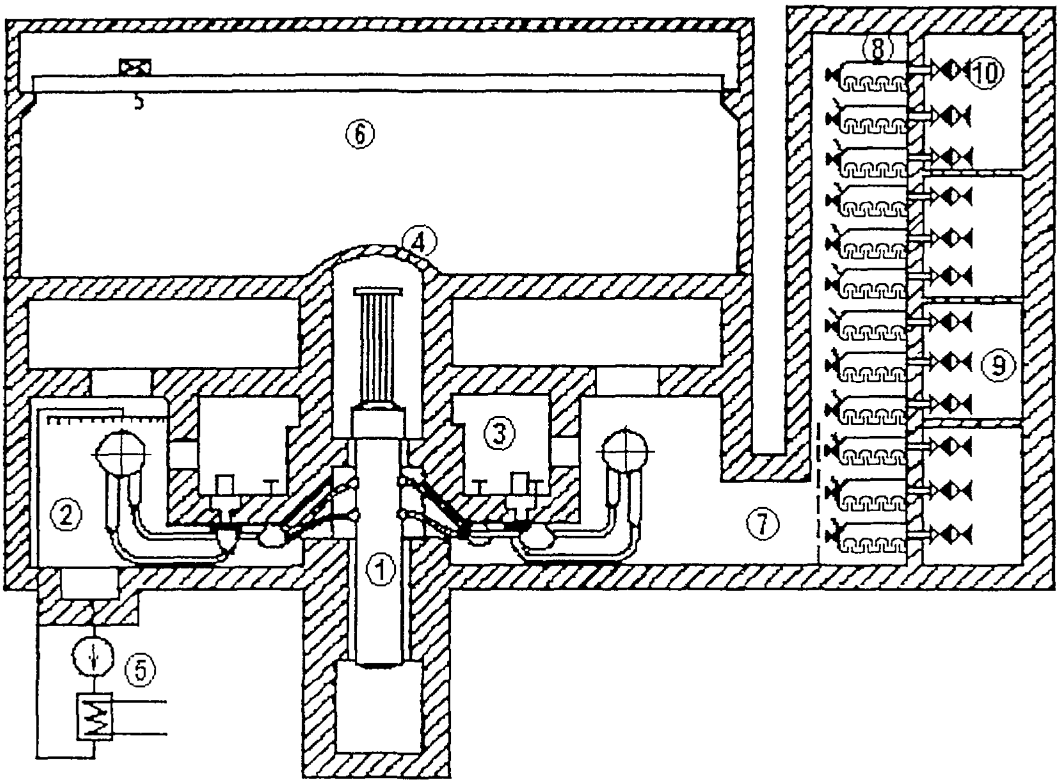
Principle of passive pressure reduction

Passive reduction of quick pressure increase in hermetically sealed areas in maximum design accident is enabled by two basic function of bubbler condenser:

a) steam condensation through bubbling of steam in 12 floors of trays with water (2 – Fig. 2)
b) capture and retention of air and uncondensed gases in four air traps (5 – Fig. 5)

The bubbler condenser is arranged in such way that air-steam mixture is passed through corridor to the bubbler condenser where the flow is distributed in bubbler condenser shaft (1- Fig.2) to individual floor and through volumes between ceilings and bottoms of floors the mixture enters in 1806 gas-cap water seals (2 – Fig. 2). After expulsion of water column in inlet cap of seals (3- Fig. 2) the mixture shall bubble through water layer where steam condenses with transfer of part of its thermal energy and concurrently reduces its volume in significant way.
Air and uncondensed gases are then cumulated above water level and due to arising overpressure this mixture flows through dual check valve DN 500 (4 – Fig. 2) to the air traps (5 - Fig. 2).
The time history of presented process is governed by pressure difference arising between bubbler condenser shaft (1 – Fig.2) and air traps (5 – Fig. 2). In case of maximum design accident it means very quick process (see graph in Fig. 3) attended by significant dynamic impacts of jetting flow on all technological devices as well as on structure of bubble condenser and hermetically sealed area. Dynamic effects of flow of steam-air mixture are at the inlet to bubbler condenser captured by special reflexive wall anchored to bearing structure of bubbler condenser trays and this way to the reinforced concrete building.

Fig. 1: **WWER 440/213-containment scheme**



1 Reactor Pressure Vessel
2 Steam Generator Compartment (SG)
3 MCPs room
4 Removable hatch in the reactor hall
5 Emergency core cooling system and spray system

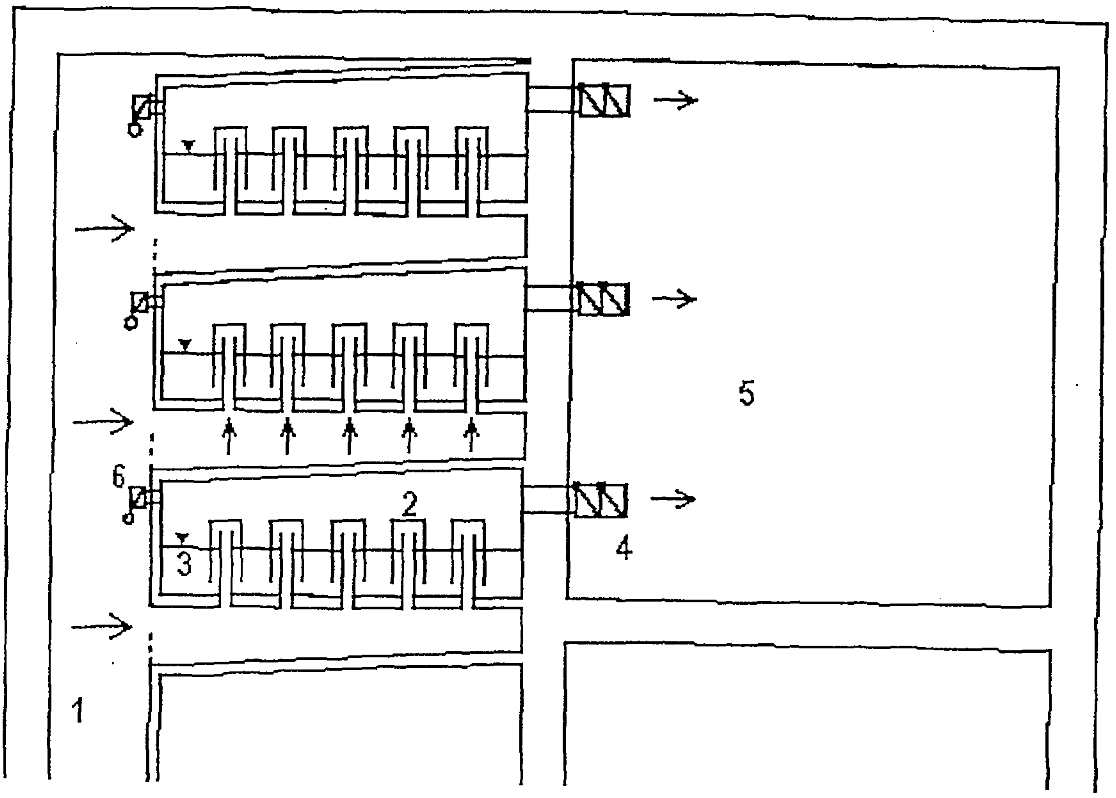
6 Reactor hall
7 Corridor
8 BC unit
9 Air trap
10 Check valve

In the course of accident localisation the pressures above water level (3 – Fig. 2) and in air traps (5-Fig.2) are equalised while check valves DN 500 (4- Fig. 2) are automatically closed retaining compressed air in chambers. Flow of hot water and steam from primary circuit continuously decreases and pressure in hermetically sealed area begins to fall due to steam condensation and heat transfer to the walls possibly also due to operation of an active spray system. Reverse pressure difference, when the pressure above water seal (2 – Fig. 2) is greater than the pressure in bubbler condenser shaft (1 – Fig. 2), causes a reverse water flow from trays to bubbler condenser shaft. Water flows through the same path where the steam – air mixture flowed up, along the ceiling of the lower floor flows to perforated collectors on the face wall of bubbler condenser and sprays the volume of shaft. This passive spraying causes further reduction of pressure in hermetically sealed volumes. Spilled water from trays is collected on the bottom of bubbler condenser shaft and spontaneously flows through corridor to the SG and MCP compartments. From this room the water is together with used sprinkling water transferred by flow net to suction of emergency system pumps.

Accidents with small release of coolant have similar but slower course with lower achieved pressure also. In order to prevent an undesired outflow of water in case of small accident (small accident could become step by step large accident) there are two special check valves DN 250 equipped on each floor (6- Fig. 2) which allow pressure equalisation before and behind the water seal. These check valves are fitted with special blocking system which depending on pressure value in volume before a hydraulic seal automatically locks or unlocks the valve. The blocking system is set to value of 165 ± 5 kPa of absolute pressure. Reaching this value the valve is automatically locked and does not allow pressure to be equalised. In case of lower pressure before water seal the reverse flow occurs. If during an accident localisation the pressure in the shaft does not exceed a limit value of 165 kPa the valves remain unlocked and in case of pressure drop before water seal the pressure will be equalised before and behind seal thus water remains in trays.

Presented passive function of bubbler condenser system causes spontaneous decrease of pressure in hermetically sealed areas with continuous cumulating of significant amount of released thermal energy. Full localisation of accident is accomplished by active spraying of SG and MCPs compartments which gradually reduces pressure in sealed compartments down to the minimum value of 80 kPa (underpressure) when the spraying system is automatically switched off. Achievement of moderate vacuum in sealed area will prevent release of radioactive substances; underpressure is maintained by controlled actuation of active spray systems. Violation of minimum values of vacuum with possible consequent violation of system tightness is prevented by deactivation of active spray systems.

Fig. 2: Detail of part of containment – bubbler condenser system



1 Bubbler condenser shaft

2 BC units with water siphon seals

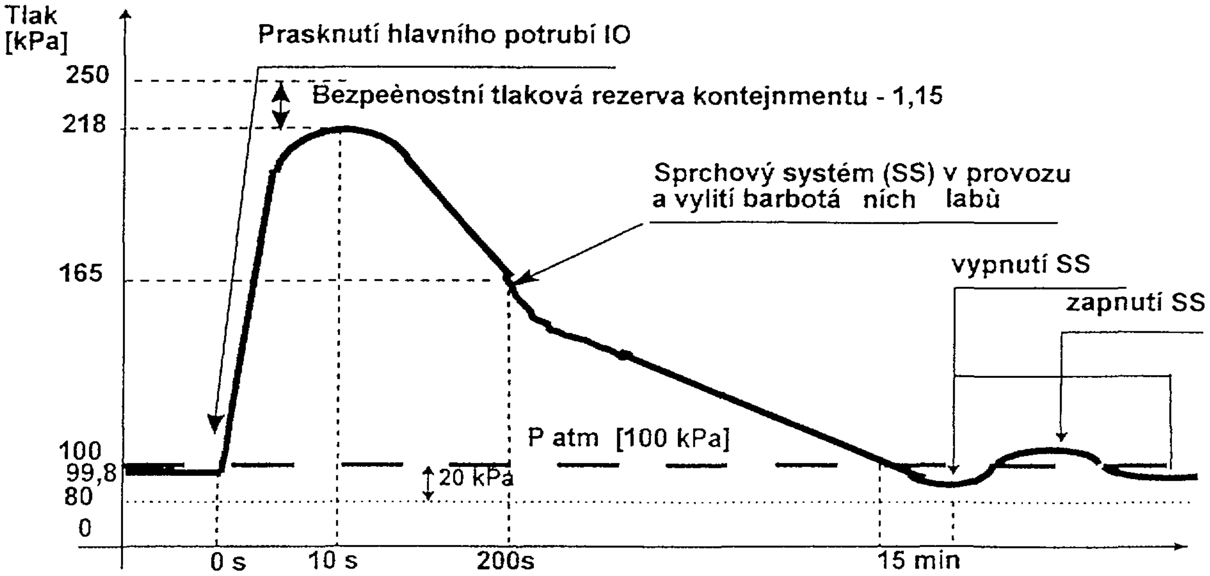
3 Level of water solution (H_3BO_3)

4 Dual check valve DN 500

5 Air trap

6 Lockable check valve DN 250

Fig. 3: Pressure history in WWER 440/213 containment in maximum design accident



Tlak = Pressure; Prasknutí hlavního potrubí IO = Rupture of main pipeline of primary circuit; Bezpečnostní tlaková rezerva kontejnmentu –1,15 = Safety pressure margin of containment-1,15; Sprchový systém v provozu a vylití barbotážních žlabů = Spraying system under operation and bubbler condenser trays emptied; vypnutí SS = deactivation of spraying system; zapnutí SS = actuation of spraying system

4. Comparison of course of localisation of maximum design accident for WWER 440/213 and for selected types of BWR containment

Similar type of containment is used for western boiling reactors BWR. In full-pressure protective shell – containment the large deep pool was located to which steam released during accident from primary circuit was brought. This type of containment developed by general Electric in the seventies and known as MARK was subjected to certain technical development in several modifications (from type I to type III)

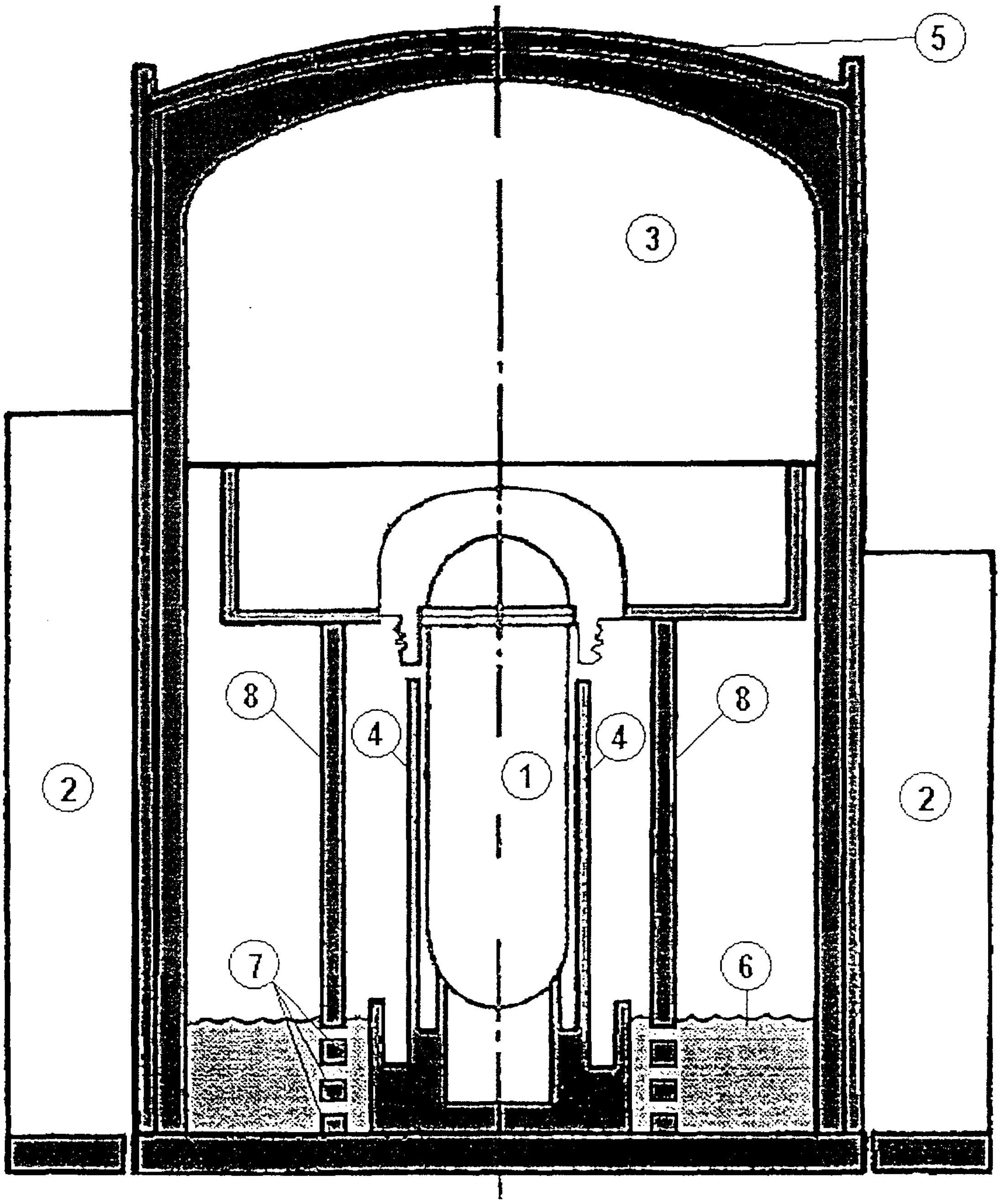
Comparison of main parameters of individual systems is given in the Table I.

Table No. 1: Characteristics of different type of containment

Type of Containment		GE-MARK I	GE-MARK II	GE-MARK III	KWU-BL69	KWU-BL72	VVER-440/V213
NPP		PEACH BOTTOM	LIMERICK	GRAND GULF	KRÜMMEL	GUND-REMMINGEN	MOCHOVCE
Overpressure	kPa	390	385	105	350	330	150
Thermal Power	MWt	3293	3293	3833	3800	3800	1375
Free Containment Volume	m^3	8100	11400	44300	7600	14500	48210
Free Volume/ Thermal Power	m^3/MWt	2,46	3,46	11,3	2	3,82	35
Water Volume	m^3	3480	3530	3850	3700	3100	1360
Water volume/Thermal Power	m^3/MWt	1,06	1,07	1,01	0,97	0,818	0,99
Number of pipes		74	106	78 (horiz.)	72	64	1800 (siphon)

From this comparison it follows that the free volume of containment is the greatest for WWER type what in conjunction with lower output leads to lower maximum pressure achievable in design accident. The share of water used for steam condensation in relation to power is similar for all compared power plants.

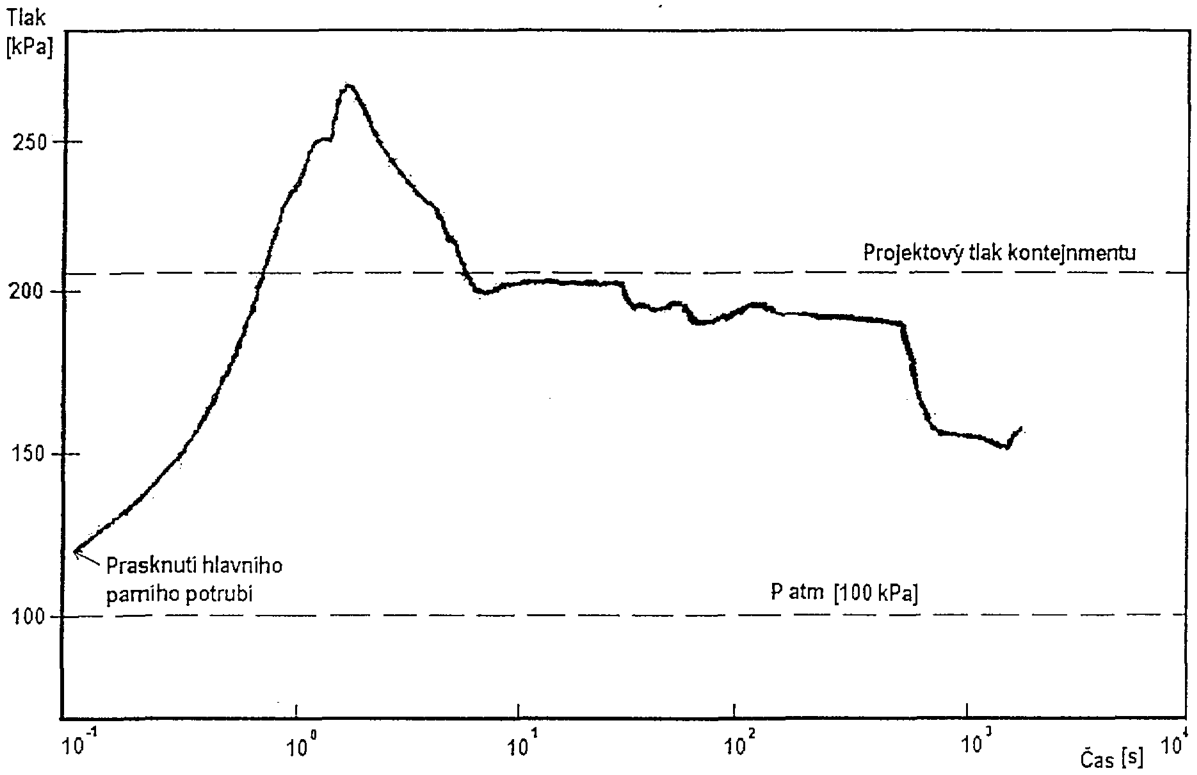
Fig. No. 4: The scheme of bubbler condenser MARK III



1	Reactor pressure vessel	5	Containment
2	Auxiliary buildings	6	Bubble condenser pool
3	Reactor hall	7	Horizontal channels
4	Reactor shielding	8	Separating walls

Large difference is in structural arrangement of bubbler condenser system. The scheme of the MARK type of containment is shown on the Fig. No. 4. Large protective shell (5) contain primary circuit with reactor pressure vessel (1) and deep ample pool for steam bubbler condenser (6) in its bottom part. In case of rupture of primary circuit pipeline the released steam is forced through siphon seal and horizontal channels (7) to bubbler condenser pool for condensation. Air and uncondensed gases then remain in protective shell (3). Pressure history for the case of maximum design accident is shown in figure 5.

Fig. No. 5: Pressure history in MARK III containment during accident localisation



Tlak = Pressure; Projektový tlak kontejnmentu = Design pressure in containment; Prasknutí hlavního parního potrubí = Rupture of main steam pipeline; Čas = Time

Pressure suppression by bubbler condenser leads also in this case to the lower pressure peak, however containment remains under long-term pressure loading. Generally, utilisation of bubbler condenser leads to effective reduction of pressure peak in both cases (MARK III and WWER 440/213). The MARK system is more compact as for its structure, it uses smaller number of active items but it must withstand to long-term internal overpressure, while the WWER system is more complex, it contains larger number of active items but reduction of pressure is more effective and containment may not withstand to long-term pressure loading.

5. IAEA and EU standpoints for structural solution of WWER 440/213 containment

The chapter 3.2.1 of the IAEA- EBP-WWER-03 publication presents for the WWER 440/213 type "Utilisation of the bubbler condenser for steam condensation and for restriction of maximum overpressure inside containment are conceptually equivalent to design of PWR with condensers or to BWR containment with pressure suppression pools in particular type MARK III". Requirements for analytical and experimental support of bubbler condenser design are therefore the same as in the case of other containment where the items of unit protection systems (ESFAS) are used which ensure restriction of maximum overpressure and serve for suppression of time of this overpressure inside containment"

The positive features of containment with bubbler condenser rely on fast reduction of internal pressure down to the sub-atmospheric value. In compliance with design calculations in case of accident with large release of coolant (LOCA) the time of overpressure does not exceed 15 minutes that means that small releases occur even for permitted design leakage of containment.

However, sufficiently amount of evidence was not available for the IAEA whether design of the bubbler condenser is mechanically adequate enough in order to withstand the pressure differences which occur in an early stage after immediate rupture of primary circuit with medium release from both sides. In order to solve this problem the OECD Support Group on "WWER 440/213 Bubbler Condenser Containment Research Work" was established in 1992. Based on initiation of the EU the "WWER 440/213 Bubbler Condenser Containment Feasibility Study" was carried out. The Study confirmed the need for additional research in this field and the necessity for an experimental verification of Bubbler Condenser function within framework of TACIS /PHARE assistance by Programme named "Bubbler Condenser Experimental Qualification". One part of this Programme deals with course of thermal – hydraulic processes, resistance and integrity of bubbler condenser steel structure under the conditions of design accidents was verified by the other part.

The first IAEA Experts mission was held in the Dukovany NPP with following objectives:

- To review technical design of structure in the Dukovany NPP documentation
- To check "as built" status of the bubbler condenser steel structure
- To evaluate feasibility of proposed enhancement

Following recommendations were drawn from this IAEA mission:

- To continue in detailed calculations of structural nodes using more accurate methods
- To support an experimental verification of function on models in full scale.

These recommendations are included in above-mentioned Project PHARE/TACIS (see chapter 7). In case that the publication will be used also by the Bohunice and Mochovce NPPs it could be better to rewrite paragraph concerning the Dukovany NPP in such way that it will generally reflect also results from similar IAEA missions held on other NPPs.

6. Impact of maximum design accident localisation in WWER 440/213 containment on environment.

The release of radioactive substances to environment and its radiological effects for public in case of NPP accident presents the most serious problem. Influence of released radioactive substances on radiological burdening of public is reviewed according to the WHO and ICRP recommendations, Decrees of regulatory bodies and national legislature.

The third barrier - containment is formed by a sophisticated system of technical means serving at first for reliable protection of public against consequences of reactor accident.

Under normal operation the containment is underpressurised in regard to ambient atmosphere what prevents an uncontrolled release of radioactive substances to environment.

After rupture of primary circuit (violation of the 2nd barrier) the release of coolant occurs. All radioactive substances contained in coolant are released to volume of containment but regarding to the total activity contained in coolant such release is not significant for influence on radiation burden of public in NPP surroundings. Due to insufficient cooling of core the temperature of fuel increases what leads to untightness of the 1st barrier – fuel cladding. This phenomena causes more significant release of radioactive substances which is confined by the containment. Part of released radioactive substances is captured by structures of the primary circuit; part of them is captured in air traps of bubbler condenser system. Passive as well as active spray systems provide flushing of radioactive substances from containment atmosphere thus they contribute to reduction of released amount to environment.

Quick achievement of underpressure in the containment will minimise NPP impacts on surrounding also in cases of extraordinary events.

7. Conclusions resulting from common PHARE/TACIS Project

In 1995 the common PHARE / TACIS Project on "WWER 440/213 Bubbler Condenser Experimental Qualification" was approved. This Project followed after previous Project (PH 4.2.8/92) by which current status of knowledge and feasibility of experiments on full-scale equipment directed towards to functionality of confinement systems was evaluated. This serve to refute of fears arising in the community of western experts on the late of eighties.

Responsible solver of this Project became Consortium BCEQ grounded by Siemens, EdF and Empresarios Agrupados. Work within framework of this Project was commenced in the October 1997 and it was subdivided to four tasks:

Task 1:
Project leadership;
Inception, planning, administrative

Task 2:

Performance of thermal-hydraulic tests and fluid-structure interaction tests on the experimental facility presenting the bubbler condenser of Paks NPP in scale 1:100

Task 3:

Performance of static structural test for internal structure of bubbler condenser of Bohunice NPP a Dukovany NPP subjected to stresses in an early stage of accident.

Task 4:

Analytical support and tests on equipment in small scale for development of task 2 experiments

The Consortium awarded contracts with local Subcontractors: EREC (Electrogorsk, Russia) for task 2, VUEZ (Levice, The Slovak Republic) for task 3 and SVUSS (Prague, the Czech Republic) for task 4.

Within framework of the Project two large and one small experimental facilities were constructed. The first experimental facility (EREC – in scale 1:100 for volumes and flow sections) modelled all essential parts of actual accident localisation system including simulation of outflow from damaged part of primary circuit which was reproduced by the system of five tanks in order to enable modelling of different kinds of accidents. Individual parts of hermetically sealed area were modelled by three interconnected chambers and by own model of bubbler condenser (structure according to the Paks NPP). Its main part was a section of one floor of condenser with two sections in full scale each containing nine "gap-cap" units and an additional volume for air trap modelling. Also dual check valve DN 500 between bubbler condenser and air traps and lockable check valve DN 250 connecting volumes before and behind water seal were modelled.

In the course of analytical phase the parameters of experimental facility were more specified and its anticipated behaviour during different types of accidents were compared with calculated courses for Paks NPP. In order to increase reliability the analysis of bubbler condenser was carried out by two computation programmes – DRASYS and CONTAIN; for calculation of outlet from the source part the programme ATHLET was used. Results of analyses showed that:

- The most loading of system occurs in case of design basis accident (LOCA)
- For modelling of an early phase of accident localisation it is necessary to perform two different tests with different margin conditions, directed towards to accident initiation (pressure loading of internal structure of bubbler condenser) and towards the middle term phase (maximum pressure in system)
- Conditions can be established and modelled which cover expected loads of system and its parts (different floors of bubbler condenser) in case of maximum load in an initial phase of accident
- Deviations in course of accident localisation for individual NPPs are small (up to 10%)

Test equipment were fitted with measuring system allowing to determine course of main parameters in its main parts. Courses of pressure and pressure differences, temperatures of air-steam mixtures, temperature of water and walls, flows and roughly also mixture concentration, stresses and displacements and water level were measured. Process and check valves behaviour was also visually monitored. Selected methods including visualisation were verified before test on equipment for small-scale test (SVUSS).

Three experiments presenting design accident LOCA were carried out in September and October 1999. The first one was focused on integrity of system in middle term phase of accident, remaining two experiments were focused on an initial phase and effect of break location (far from and close to bubbler condenser)

Concurrently with these tests the strength analyses and test of internal structures of bubbler condenser reproducing the Dukovany and Bohunice NPPs were carried out in order to verify integrity of steel structure in assumed pressure loads (pressure difference up to 30 kPa).

The tests were prepared and carried out both with dynamic load for different rate of pressure increase (small model with three sizes of gap-cap units) and for step by step increased static loading up to expected maximum (model with two sections each containing nine "gap-cap" units in full scale).

Test results

Bubbler condenser had worked during all thermal – hydraulic tests in expected manner and after tests neither damage nor mechanical failure were detected. Test evaluation and their analysis showed that:

- Results of measurement of main quantities (pressures, temperatures and pressure differences on bubble condenser) are representative
- There is relatively significant non-uniformity in water warm up in bubbler condenser pool
- No significant tear off of water to air traps occurs.
- During flow through corridor to the bubbler condenser complex thermal-hydraulic conditions occur
- Conservative results were predicted by computation programme (little conservative for maximum pressure, more conservative for initial pressure difference)
- Measured initial pressure difference did not exceed the value of 20 kPa for conditions reproducing the Paks NPP, for other NPPs it will be smaller than 22 kPa.
- According to measurements the maximum pressure should not exceed the value of 210 kPa for any NPP
- The test results should be further analysed and should serve for validation and further development of computation programmes.

The strength and integrity of internal structure of bubbler condenser was successfully proven by strength tests with following conclusions:

- Even in maximum pressure the structural integrity and tightness of bubbler condenser remained intact.
- Partial strains of some parts of internal structure were identified at 24 kPa overpressure however they did not affect proper function of facility
- Methods used for strength analysis showed that they are sufficiently representative and calculated results were in well compliance with measured values
- Several provisions and small reinforcing were recommended for structure of the 1st and the last floor of bubbler condenser.

8. Conclusion

The containment in WWER 440/213 NPPs is an original and fully functional technical solution. Due to utilisation of large reserve of H3BO3 solution and due to activity of active spray systems an underpressure can be quickly created and this way any impact of accident on environment is minimised. The capability of the bubbler condenser system for maximum design accident has been proven by analyses and tests carried out within framework of PHARE PH 2.13/95. It was proven that bubbler condenser system could reduce pressure in containment in an effective way. The majority of up to now arising questions and comment was answered and some so far existing concern resulting from insufficient verification of this system according to western standards were refuted.
The WWER 440/213 containment is fully valuable choice of worldwide used design solutions of NPP containment and it fulfils appropriate requirements.