RESULTS FROM MODERNIZATION
OF THE CONTAINMENT LOCALIZATION SYSTEMS
OF THE KOZLODUY NPP UNITS 3 AND 4

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Summary

The improvements of the Accident Localization System (SLA) of units 3 and 4 systematically implemented by Kozloduy NPP shows an important direction for increasing the safety of NPP with VVER-440/V-230 containments. During the years Kozloduy NPP implemented a large scope of activities aimed in full resolution of all generic shortcomings identified in the original design of these containments. These activities allowed already in 2002 to justify that integrity of the containment is assured for all postulated events and the radiological consequences for all DBAs and BDBAs without core degradation are within the regulatory limits.

The last phase of this modernization was oriented toward achieving the same goals in case of severe accidents by installation of systems for avoiding long term pressurization of the SG compartments and by installation of a system for keeping of negative pressure (slight vacuum) during the late phases of development of the accidents thus minimizing significantly the uncontrolled radioactive releases from the containment and assured controlled purified release of radioactivity to environment, and for elimination of conditions for H2 deflagrations within the localization system.

This paper summarizes the results of the whole modernization process with an emphasis of the implementation of the latest phase successfully completed by KNPP in first quarter of 2005 which allowed the plant to demonstrate remarkable mitigation capability for a comprehensive set of very low probability severe accidents scenarios in line with the approach now being promoted for the modern design NPPs.

Plant approach toward modernization of the containment localization system

The overall approach of KNPP in resolution of the containment issues for WWER-440 reactors shows three different phases which are closely connected to the implementation of the different plant safety upgrading programs.

Nevertheless that the four WWER-440 units were built in two different stages more than 5 years difference all of them have been built with a containment system of the standard B-230 design. That is a low pressure containment (design pressure of 2 bars abs.) with relief valves to the atmosphere for protection from overpressure. The negative pressure during the normal operation is ensured by a two train filtered venting system and during accident by the spray system operation.

The systematic analyses for compliance of these Units with the current safety requirements and the internationally adopted codes and practices began in 1990and in 1991 the so called Short Term Program [1] for implementation of the safety upgrading measures on these units was developed.

The implementation of the program commenced in 1991 and was completed in 1996/1997 for the different units. This program was developed on the basis of expert judgement and was oriented to the short term activities on the high importance design and operational safety issues identified by various international missions and plant experience.

Continuation of the safety upgrading process initiated by the Short Term Program has been assured by parallel development of a new, Complex Program [2] based on the Periodic Safety Review methodology of IAEA. The goal of the programme was to address the issues identified trough a systematic in depth safety evaluation toward the current international safety requirements in the design and operational areas. Main basis and reference for these evaluations were the IAEA safety guides and requirements as well as the applicable Bulgarian and Russian current safety regulations.

Due to the fact that Units 1 and 2 of the plant were shut down in 2002 the full scope of the program [3] was concentrated on Units 3 and 4 which resulted in complete change of their design basis bringing these units in line with the level of safety of the other nuclear installations of the same vintage worldwide as confirmed by the international safety review missions [4]

On that basis the Nuclear Regulatory Agency of Bulgaria issued in 2003 new operational licenses to Units 3 and 4 which also specifies number of long term condition for further continuation of the safety enhancement process above the legislatively established basis.

Consequently the above presented safety upgrading process resulted in the following phases in upgrading of the Units 3 and 4 Containment Localization System (CLA):

- ✓ **Up to 1998** – Short term modernization program scope. During this stage the activities were oriented toward demonstration of the CLA adequacy on the extended list of DBA including containment tightness improvement measures and Containment Spray System improvement – mainly applicable to Units 1 and 2;
- ✓ **1998 to 2002** – Complex Modernization Program scope. Within this scope the plant activities were concentrated on demonstration of the CLA capability to meet not only the extended list of DBAs but also the BDBA thus completed the review of Containment response to all Postulated Initiating Events (PIEs) and on justification of meeting the regulatory requirements for radiological releases for both these classes of PIEs. The major step to achieve that goal was the installation of Jet Vortex Condenser (JVC);
- ✓ **After 2002** - Operational Licensee scope. The plant activities were organized in fulfillment of the long term programs (license conditions) for upgrading the containment toward management of Severe Accidents (SA) namely installation of two dedicated systems - Hydrogen Control System (HCS) and Filtered Venting System (FVS). In addition as separate activity Severe Accidents Management Guidelines (SAMGs) development was carried out with an aim to be implemented latter in 2005/2006

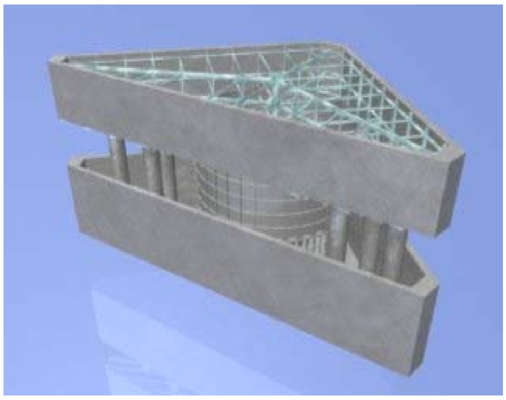
Although actually implemented in two different phases the major improvement of the CLS was guided and conducted within the last four years on the basis of an overall CLS modernization strategy [5] approved in 1999. The strategy was developed by KNPP in cooperation with ENPRO Consult Company and was aimed in full resolution of all known safety problems of these systems. To achieve that the strategy was oriented to the plant extended DBA basis, BDBAs and SAs. This strategy was firstly presented in the IAEA topical conference to discuss the WWER core cooling and containment improvements options [6] and subsequently on the specially organized follow-up IAEA design safety review mission in 2000 [7].

As shown by the actual application of this strategy it allowed the plant to demonstrate feasibility and practicability of addressing issues of major importance for the future safety operation of units with WWER-440/230 CLA, which shall be recognized as an remarkable Bulgarian contribution to the overall process of their modernization.

Implementation of the activities up to 2002

In general as a result of the activities implemented during the first two phases the containment leakage was reduced more than 35 times. This achievement together with the installation of JVC allowed to justify that the radiological consequences will be managed well bellow the prescribed limits for all postulated events and even beyond.

A pressure suppression system based on JVC was successfully licensed and implemented in 2001-2002 for units 3 and 4. JVC reduces passively the containment pressure in case of an accident thus from one side preventing its over pressurization and from another significantly shortens the duration of the overpressure phase which may lead to uncontrolled releases to the environment. The fully passive operation principle (no moving parts) assures guaranteed re-closure of the condenser well before any fuel degradation process may occur



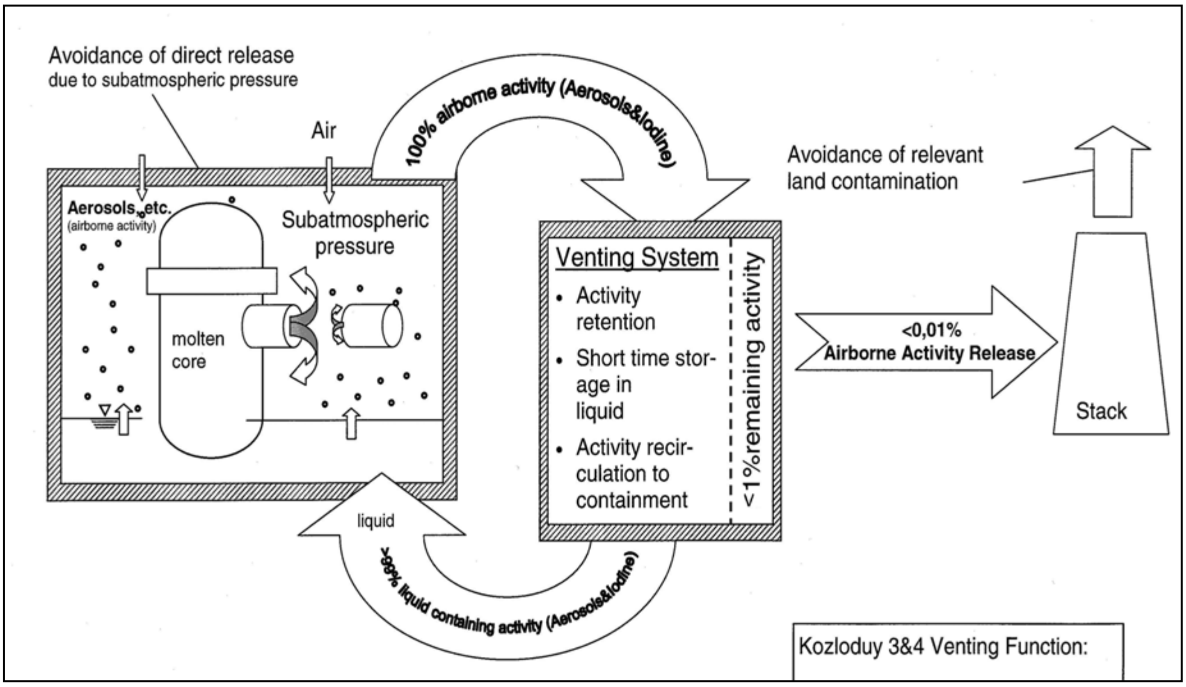
In addition the JVS allows passively to limit the negative pressure in the CLA whit a serious positive effect on the safety system performance. Another positive safety features are its installation inside containment and full elimination of the relief valves eliminating their potential “stuck open” type failure.

Design approach for CLA modernization toward Severe Accidents

In response to the licensing requirements of NRA between 2003 and 2005 Hydrogen Control Systems and a common Filtered Venting System were installed on units 3 and 4 specially dedicated for SA management purposes.

The systems were developed and installed in the framework of two parallel “turn-key” contracts with European Consortium Kozloduy within which Framatome ANP GmbH was the responsible Design, Supplier and Installation Company. Several Bulgarian engineering companies like ENPRO and Enemona companies were involved in all phases of the process for design, safety evaluation and installation of the systems.

The following diagram presents the genera idea for assurance of the localization functions during systems operation:



During a hypothetical event of a beyond design basis accident with core melting, the pressure in the containment will increase. This increased pressure will cause uncontrolled release of radioactive products to the environment through the leaks of the accident localization system.

Filtered venting system could reduce significantly such uncontrolled releases of fission products from the localization system to the environment through preventing containment operation at overpressure and maintaining a slight vacuum inside SLA during the majority of the late phase of an accident with core degradation.

Filtered venting system is designed to decrease the radiological consequences of beyond design based accident through:

- Providing a slight vacuum in the hermetic zone to minimize unfiltered releases to the environment during the majority of the accident progression;
- Post accident treatment of airborne radioactive releases from the localization system;
- Retention of airborne activity inside a filter device housing and transfer back of the majority of the retained radioactivity to the containment or waste treatment systems of the plant after operation of the venting device.

In order to perform these functions, the system is sized to cope with the phenomena that lead to increase of the containment pressure for different SA scenarios of core degradation and in this way, to reduce significantly the release of radioactive fission products to the environment. The pressure increase may be a consequence of accumulation of non-condensable gases, unremoved heat, generated in the hermetic zone for a long period of time due to decay heat release, pressure spikes due to relocation of hot materials inside RPV during core degradation, etc. For this purpose the filtered venting system includes an active element – gas blower designed to suck steam-air mixture from SLA through the filter.

Design criteria for the system were established in three specific areas:

- ✓ Design Criteria with regard to the containment venting:
  - The system shall keep short and long-term (at least 100 days) slight sub-atmospheric pressure in the containment with the purpose to minimize the uncontrolled release to the environment.
  - The system shall be designed to suck steam, air and mixtures of both from the containment through the filter stages from the beginning of the core degradation phase
  - The achieved purification of the controlled releases should allow limitation of the environmental impact:
    - individual doze at the border of the emergency planning area bellow the limits of 5 mSv for the whole body and 50 mGy for the thyroid within the first year after the accident.
  - The retained activity in the water separator and in the Venturi scrubber unit shall be returned back to the containment periodically
  - The radiation doses in the plant compartments shall allow post accident actions to be performed by the staff
- ✓ Design Criteria with regard to control of the steam-gas mixture overall burnability:
  - The possibility of deflagration should be excluded:
    - by maintaining of combustible gas concentration bellow 8% of the volume during all phases of the evaluated SAs

    - by inertization of the containment atmosphere in case the buildup of the hydrogen above the limit can not be prevented by other means
  - Conditions for effective operation of the hydrogen recombiners should be assured
  - Specific technical means required:
    - Steam injection into the containment with a high speed nozzle to increase the steam content inside the containment
    - Supply of air to the containment atmosphere to enhance catalytic hydrogen oxidation rate
    - Measurement of the steam and hydrogen concentration inside the containment at three different locations by a new measurement system
- ✓ Plant systems availability and control considerations:
  - Total black-out for the affected unit is assumed
  - The electrical supply is assured from the emergency power supply (diesel generators) of the not affected unit for which loss of off site power is assumed
  - The status of FVS is displayed on in the main control rooms (MCR), the emergency control rooms (ECR) of both units
  - After initialization of the system operation by the operator the system is controlled fully automatically for the desired period of at least 100 days
  - The system do not need any media (water or gas supply) at least for the first 24 hours after which supply of the water may be needed
  - The supply of the additional make up water is assured by variety of means

With regard to the systems purposes HCS and FVS are classified as systems for beyond design based accident management. In addition HCS justification is provided for meeting design requirements for DBA LOCAs from the point of view of hydrogen volumetric concentrations (less than 4%). With regard to seismic qualification the systems are designed for earthquake SSE before operation of the FVS and for “functional capability after earthquake” OBE.

From the point of view of the applicable regulatory basis classification was proposed on the basis of Russian regulations as follows:

- according to OPB 88/97:
  - Safety Class 4 (“elements used for accident management”)
- according to PNAEG 07-008-089:
  - Quality Class NC – M
- according to PNAEG-5-006-87:
  - Seismic Class 1
  - Power supply Category 1

From the point of view of the system basis large scope analysis conducted for systems sizing. More than 35 different scenarios were analyzed including all potential important SA scenarios. Different scenarios of “in vessel” and “ex vessel” SA sequences were evaluated to size required throughput:

- “dry” case when there is no external coolability of the RPV, resulting with penetration of the bottom head of the reactor vessel and generation of non-condensable gases as a result of MCCI;

- “wet” case with flooding of the reactor cavity as possible AM measure that precludes penetration of the RPV and MCCI, however generates significant amount of steam, evaporated in the reactor cavity and results in increase of the containment pressure.

The operation of the spray system was taken into account, considering its possibility to remove heat from SLA and the associated steam condensation that leads to not inert conditions inside the localization system. Each of the cases above have been considered for sizing of the corresponding parts of the FVS and the H2 recombination system.

In fact the design of the systems was performed in parallel with development of the KNPP units 3 and 4 Severe Accident Management Guidelines which was conducted as a separate activity within a PHARE financed project. Both projects were adjusted accordingly and the specifics arising from their development were reflected on both projects final documentation.

The choice of the design scenarios and the degree of improvement of the units safety is based on the PSA results for units 3 and 4, and cover all possible BDBA scenarios with extremely low cut-off frequency of 2.0^{-12} 1/reactor-year. This means that the design of the systems considers all possible scenarios that may happen once in $5x10^{11}$ years may be mitigated by the system, ensuring conditions that containment integrity is preserved.

This demonstrates that the installation of the system will improve the nuclear safety of “Kozloduy” NPP and will decrease significantly the risk of unacceptably high radioactive contamination of the environment in case of beyond design based accident.

Main features of the systems

In order to allow performance of the main function of the Filtered Venting System a turbo blower unit is used to suck out the gas mixture from the containment atmosphere and therewith to establish a slight sub-atmospheric pressure inside the containment. This generates an additional pressure barrier to minimize the activity releases to the environment via existing leak of the containment. During the system operation the sub-atmospheric pressure is maintained automatically by the FVS process controller based on TELEPERM system trough controlling the position of the system bypass line. Because this by-pass the TBU works in his design point with respect to volume flow for varying volume flows discharged from the containment which also is important to preserve the best scrubbing regime for the system wet filtered stages.

To control the hydrogen concentration inside the containment 15 hydrogen Passive Autocatalytic Recombiners (PAR) are installed in different locations of three different elevation of the containment structure. To allow the required conditions for their operation the FVS controller operates specially installed system for delivering of additional air to the containment with the purpose of assurance of the oxygen concentration needed for effective recombination of the generated hydrogen.

Overall control of the gas mixture burnability is achieved by injection of live steam into the containment when necessary by means of specially installed pipeworks and nozzles. The source of the steam is the NSSS of the affected unit but arrangements of the connections allows this to be done also by the not affected unit. After the initial inertization of the system which is done with the full steam supply line capacity the Operator will controls the time and amount of steam to be delivered.

For this purpose he is supported by additionally designed and installed hydrogen and steam concentrations measurement system. Measurement of the steam and hydrogen concentration inside the confinement at three locations by a discontinuously operating sampling system. The measuring equipment itself is installed outside the containment as common system to be used for both units.

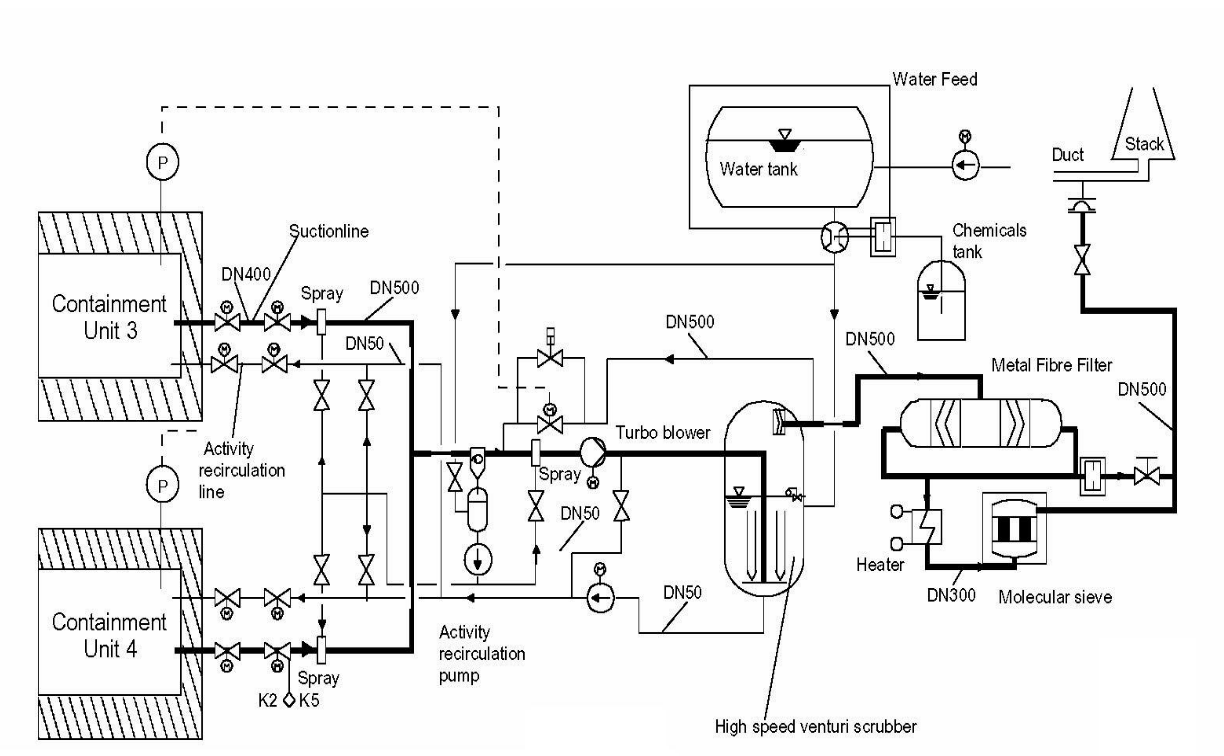
FVS consists of two different filtered stages - wet and dry. Wet filtering stages includes purification by spraying of water in the pipelines and separation of the water droplets in the Separator and a Venturi scrubber unit used for aerosol and iodine retention.

The Ventury scrubber consists of several vertical long Ventury nozzles submerged in the scrubber water amount. In the convergent part of the Venturi nozzles the steam / gas mixture is accelerated to high velocities of more than 100 m/s which is favorable for high retention rates for airborne activity. As already mentioned. These high flow velocities are preserved regardless the operating conditions of the system via the by-pass control valve. Because entrained particles stay suspended in the scrubbing liquid they can be returned with the scrubbing liquid from the Venturi scrubber unit to the affected containment which is done periodically by designed drainage pump and pipe line to the containment.

First FVS dry filtering stage is the metal fibre filter which has four vertical metal fibre filter elements of several fine layers of metal fibre with increasing density (up to micro meter size). These filter elements provides a high retention efficiency especially for the small fraction of micro aerosols penetrating the venturi scrubber unit.

After the metal fibre filter the filtered gas is transferred trough the molecular sieve to the plant stuck. The molecular sieve is substantially used for retention of organic iodine during long-term ventilation because generation of organic iodine will increase with prolonged duration of the accident.

The general flow chart of the system is presented in the following diagram:

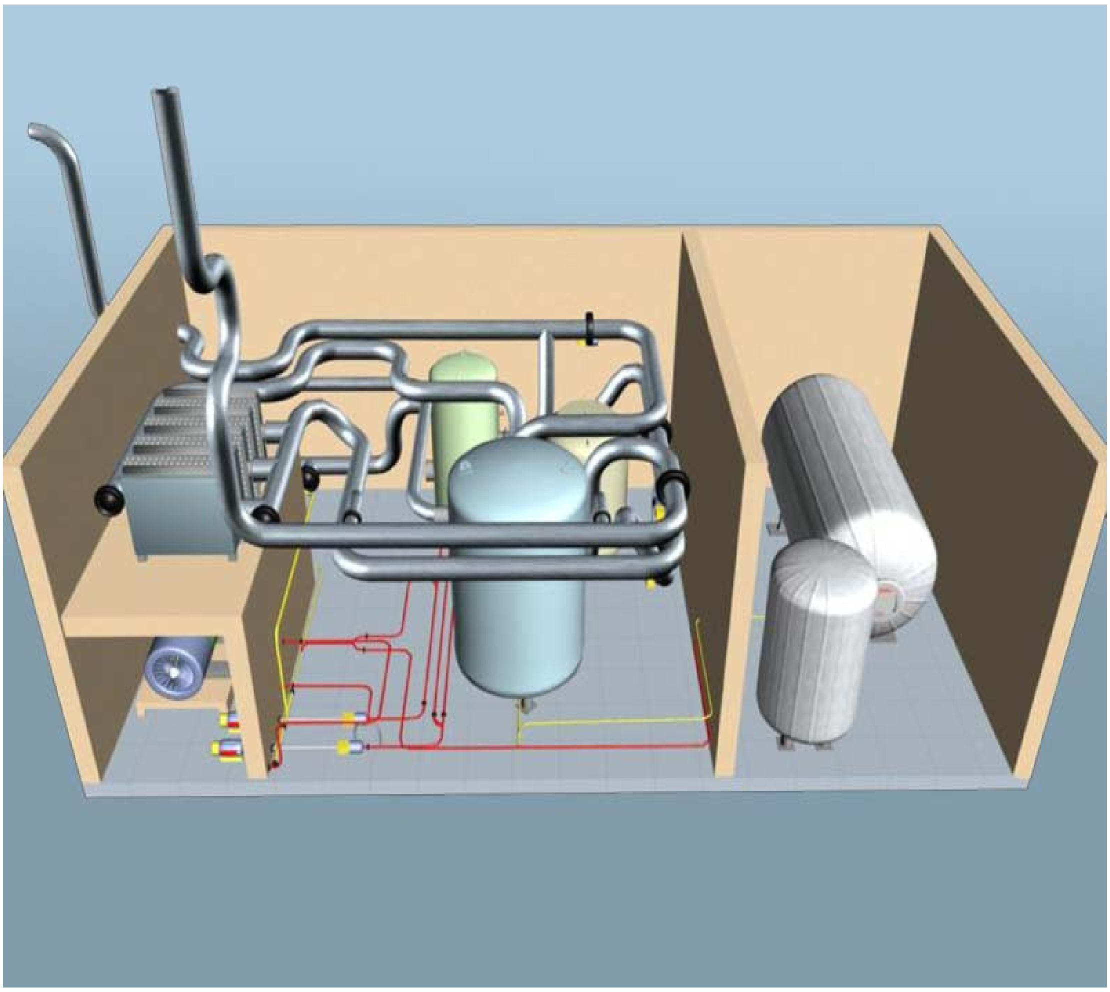


The connection of the Containment Leakage Control and Venting System to the containment is done by containment isolation flaps and suction lines with integrated spray nozzles, arranged in the Reactor Building. The main system components are installed in a special compartments inside the reactor building on an elevation which is even to the containment bottom elevation.

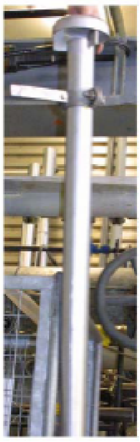
As seen by the system flow chart in addition to the main equipment described above the system includes also make-up water storage tank chemical storage tank recirculation, drainage and make-up pumps. The discharge line to the stack is arranged also trough the reactor building compartments.

Regarding the expected high radiation in the main system compartment during operation of the system in case of a severe accident, the main electrical consumers (e.g. motor of turbo blower, valve motors) are arranged in cubicles which are separated and shielded from that room.

The layout of the realized Filtered Venting System composition in these rooms is as follows:



In the process of development and production the systems components were subject of an extensive qualification programme. Venturi nozzles manufactured for KNPP unit 3&4 were tested in the JAVA facility in Karlstain, Germany within the factory acceptance program. The test results proved retention efficiencies more than 99 % which allowed the assignment of results to the national and international verification process.

Venturi nozzle	Venturi nozzle in operation (installed within test vessel)
	

Retention efficiency of metal fibre filters was verified by the German independent inspection authority TÜV by using the test aerosol called Uranin. Mean diameter of the test aerosol was bellow 0.20 µm. The test procedure and the test bed which were set up according to French industrial standards and the results confirmed the achievements of the test criteria.

Removal efficiency for gaseous organic iodide (CH3I) was tested again by the German TÜV at a testing facility at the Research Centre Karlsruhe, Germany. To achieve a very high measuring accuracy even in case of very low concentrations I 131 was used as tracer material because of its longer half-life period Tests were conducted for different carrier gas compositions, different temperatures and varying residence times and confirmed the retention efficiency required.

The following table summarizes the results from purification values verified as a result of different national and international tests:

Parameters verified	**Verified values %**
For retention of aerosols	
Macro aerosols cleaning level (≈1 µm MMD)	> 99.999
Macro aerosols cleaning level (≈0.5 µm MMD)	> 99.99
For retention of elemental iodine and organic iodide	
Elemental iodine cleaning level in short term ventilation (approx. 1 h)	> 99.5
Elemental iodine cleaning level in long term ventilation (several weeks)	> 99.9
Rate of retaining of organic iodide in short term ventilation	>> 80
Cleaning level for organic iodide in long-term	> 99.9

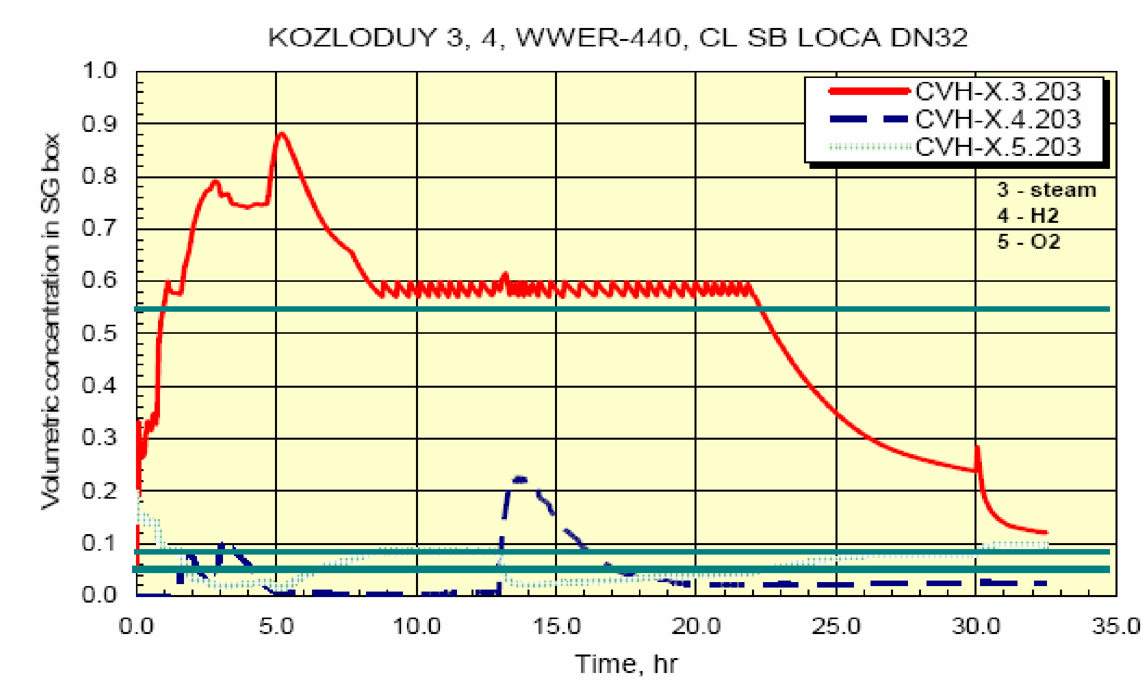
Analytical justification of the systems efficiency

The design and performance of the system were systematically justified by preparation of a comprehensive Safety Analysis Reports [8] and [9] which combined results from the extensive assessment during the different stages of the systems development and design. It reflected also the important results from the analysis to evaluate the response of the upgraded CLA, the achieved effect on mitigation of the consequences from a SA to the environment and to the population.

Analysis of the upgraded CLA together with the installed JVC, HCS and FVS were conducted for the all leading scenarios of SA with MELCOR-1.8.4 with the purpose of determination of the primary and secondary systems response as well as the containment response under severe accident conditions. The MELCOR analyses are mainly related to determination of the release of gases from the containment atmosphere to the environment through the 3 possible release paths – FVS, JVC and leaks through untightness of the containment. In addition the analyses with MELCOR code provide information for the source term of the fission products, aerosols and for the noble gases.

The analysis proved the concept and the design of the FVS and HCS based on low oxygen concentration (below 5 vol. %) or low hydrogen concentration (below 8 vol. %) and/or significant margin above inert containment conditions (steam concentration above 55 vol. %). The concept was based on analyses with accommodation of all uncertainties of the analyses. The following diagram gives an example of the results from the application of this strategy to one of the most probable scenario of SA sequencing from a small LOCA progressing to a ex-vessel release scenario.

As seen from the diagram despite of the serious rate of hydrogen generation after the core melt and even more after the beginning of the molten core concrete interaction (around 12th hour) first 22 hours no condition for deflagration of hydrogen exists due to maintained steam concentration above 55%. The effective operation of the hydrogen PARs reduce the hydrogen concentrations bellow 4% even before the 24 hours which allows the steam inertization to be terminated with a consequent restoration of the containment spray system operation around 30 hours after the incident.



The modeling of the complex iodine chemistry and its behavior has been performed with COCOSYS V 1.2 code. The evaluation of the source term of molecular and organic iodine is done based on the results from COCOSYS for I2 and CH3I airborne concentrations and the gas releases through FVS and JVC – from results obtained with MELCOR code.

The determination of the source term was based on analysis for a bounding SA scenario that leads to maximal release of radioactivity to the environment without consideration of application of particular SAM strategies for mitigation of the consequences. The analyses are performed with moderate conservatism - e.g. retention of radioactive iodine in JVC not considered.

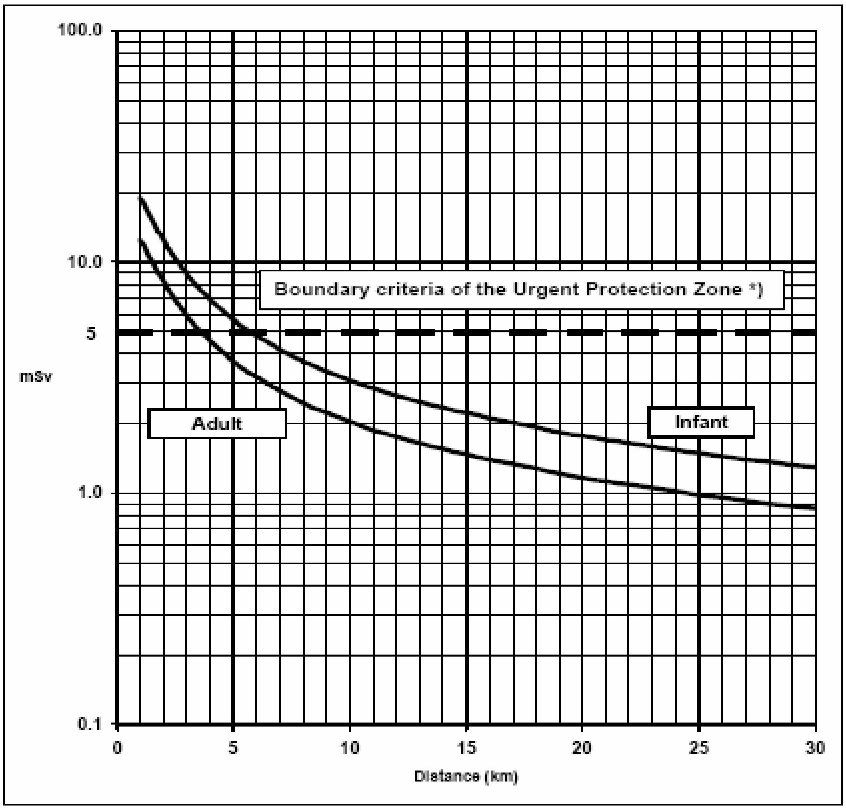
The scope of analyses performed and the results, obtained provide sufficient information for evaluation of the predicted doses for the population and also for determination of the expected dose rates in the rooms surrounding the containment as well as the dose rates in the vicinity of the pipeline connecting the containment with the scrubber of the filter.

According to the source term analysis results the released iodine fraction within 3 days after the accident is 0.0002 % (2.0E-6) which is equivalent to about 63.4 Ci (2.346E12 Bq) for I-131. The released cesium fraction is 0.00029 % (2.9E-6) which is equivalent to 7.8 Ci Cs-137 (2.89E11 Bq). The obtained results for the source terms demonstrate the high efficiency of the elaborated systems. The fractions released to the environment are very low and are in line with the expected source terms for the contemporary large dry containments. Exception are the noble gases which are extracted almost entirely to the environment by the blower of the filter.

The following specific codes were used also for evaluation of the source term and radiological consequences formed from it:

- KORIGEN code - extension of the Oak Ridge Isotope Generation and Depletion Code ORIGEN-2 based on the UK WIMS code. KORIGEN calculates the nuclear inventory - isotope and/or element concentrations, radio activities, heat, radiation from given initial compositions, irradiation history and decay times.
- ACARE – (Activity in interrelated Compartments And Release into the Environment) is a computer code developed by FRAMATOME-ANP to predict the transport of radioactive material between interrelated compartments of a building and finally the release to the nvironment. The data output of ACARE are used as input information for the computer code PRODOS.
- PRODOS – (PRObabilistic DOSe calculation) is a computer code developed by FRAMATOME-ANP to make prediction of radiological environmental impact resulting from accidental releases into the air and for the assessment of emergency countermeasures after postulated severe accidents inside nuclear power plants. The program fulfills the German requirements of accidental calculation methods, which correspond to the European requirements. PRODOS calculates probability distributions of consequences to the environment of a plant due to a time depending release of radioactive substances out of this plant using a weather course of a large time span.

The results from the probabilistic dose calculation for the first year after the accident (see the diagram bellow) shows that already within the first 6 km from the plant the estimated doses for 95% of the possible atmospheric conditions are bellow the boundary criteria established by the regulations as the intervention level for the 30 km. zone which shows that due to the extreme efficiency of the developed systems the units are demonstrating significant capabilities in minimizing the environment impact even in case of very hypothetic sequences of core gradation accidents.



Extensive evaluations were conducted to assess the dose distribution in the plant rooms in order to assure that the control over the system by the plant staff, including radiation conditions in the Main Control Room, Refuelling and other main rooms, FVS compartments and their surrounding. The following codes were used in the evaluations:

- RANKERN – (Point Kernel Integration Code for Complicated Geometry Problems) for assessment of dose distribution in the plant rooms. RANKERN has been described as the most powerful gamma-ray shielding code available. It has been verified and validated via literally hundreds of comparisons with Monte-Carlo methods, with the results of experimental benchmarking and actual measurements in nuclear installations. Its developers, Serco Assurance, Winfrith, United Kingdom have gained certification against ISO 9001 quality assurance standard.
- SKETCH – (code for checking geometry models used in RANKERN) Version 2D dose distribution in the rooms Serco Assurance, Winfrith, UK

As a result of calculation it was demonstrated that the dose distribution pattern in the compartments of the affected unit and around the pipework and equipment of the system allows performance of the necessary control from the staff. Particularly the conditions in the Main Control Room and the local control room from where the system status is controlled.

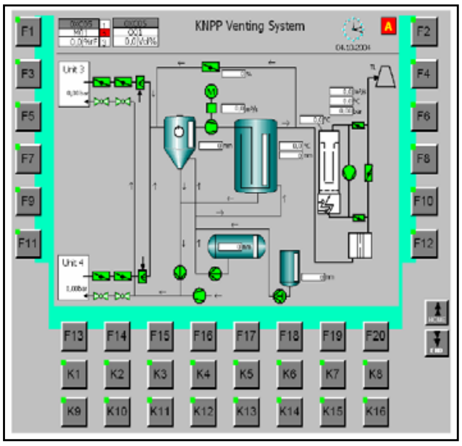
The effect of periodical transfer of the retained activity back to the containment is seen very clearly leading to significant reduction of the dose rate in the later phases of the SA management. As an example it my allow within first 72 hours the doses around the most loaded FVS components to be reduced more than 10 times.

Current status of the FVS and HCS

Presently all systems described in the paper are installed and commissioned on Units 3 and 4 of Kozloduy NPP thus finalizing the implementation of the strategy developed in 1999, the plant programs developed for its application and the licensing conditions issued by the NRA.

All components of HCS inside containment were installed during 2004 outages of Units 3 and 4 with a subsequent completion of the installations outside the containment in parallel with FVS implementation. FVS and relevant part of HCS are controlled by a special SIMATIC S7 based computer control system by control boards installed in the Main and Auxiliary Control rooms of the both Units.

The use of the systems is coordinated with the Severe Accident Management Guidelines for Units 3 and 4 which were developed in parallel as a separate activity



Full functional testing of the FVS was conducted in the end of March 2005 to demonstrate the system capability to performed the designed modes of operation and the operability of the control system developed.

Conclusions

The following conclusions can be made about the overall CLA modernization result:

- ✓ The modernization of the localization systems of units 3 and 4 with installation of Hydrogen Control System and Filtered Venting System ensure effective management of the highly improbable severe accidents.
- ✓ These systems ensure containment integrity and reduce by some orders of magnitude the radiological consequences in case of severe accidents
- ✓ With this last stage of upgrading of the localization systems of units 3 and 4 their performance in SA scenarios is not worse than the large dry containments
- ✓ The upgrading puts these units in the small group of NPPs that are prepared to withstand severe accident

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