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BWR 90 — THE ABB ADVANCED BWR DESIGN

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Abstract

ABB has two evolutionary advanced light water reactors available today - the BWR 90 boiling water reactor and the System 80+ pressurised water reactor. The BWR 90 is based on the design, construction, commissioning and operation of the BWR 75 plants. The operation experience of the six plants of this advanced design has been very good. The average annual energy availability is above 90%, and the total power generation costs have been low. In the development of BWR 90 specific changes were introduced to the reference design, to adapt to technological progress, new safety requirements and to achieve cost savings. The thermal power rating of BWR 90 is 3800 MWth (providing a nominal 1374 MWe net), slightly higher than that of the reference plant. ABB Atom has taken advantage of margins gained using a new generation of its SVEA fuel to attain this power rating without major design modifications. The BWR 90 design was completed and offered to the TVO utility in Finland in 1991, as one of the contenders for the fifth Finnish nuclear power plant project. Thus, the design is available today for deployment in new plant projects. Utility views were incorporated through co-operation with the Finnish utility TVO, owner and operator of the two Olkiluoto plants of BWR 75 design. A review against the European Utility Requirement (EUR) set of requirements has been performed, since the design, in 1997, was selected by the EUR Steering Committee to be the first BWR to be evaluated against the EUR documents. The work is scheduled for completion in 1998. It will be the subject of an *"EUR Volume 3 Subset for BWR 90"* document. ABB is continuing its BWR development work with the "evolutionary" design BWR 90+. The primary design goal is to develop the BWR as a competitive option for the anticipated revival of the market for new nuclear plants beyond the turn of the century, as well as feeding ideas and inputs to the continuous modernisation efforts at operating plants. The development is performed by ABB Atom together with TVO. Swedish BWR operators have also joined the project.

1. INTRODUCTION

Today, ABB has a modern BWR design, the BWR 90, that has already been offered commercially. This design was selected by the European Utility Requirements (EUR) group to be reviewed for compliance with its set of requirements. ABB is continuing its BWR development work, however, with focus on the 21st century, on a new design called BWR 90+ that offers reduced costs and significant safety improvements. The work aims at providing an economical alternative based on evolutionary development of the earlier advanced BWR design. The design goal is a 1500 MWe plant that can be built in less than 1500 days.

A second purpose of the development activities is to provide input to improvements and modernisation of earlier generations of nuclear power plants.

2. DEVELOPMENT BASED ON SUCCESSFUL OPERATION EXPERIENCE

ABB Atom has a long tradition of plant and system development activities related to nuclear power plants. Its first BWR unit, Oskarshamn 1 nuclear power plant in Sweden was taken into operation in 1972, - developed and built without reliance on licenses. This design incorporated a number of advanced features such as a pre-stressed concrete containment, fine-motion control rods and a passive isolation condenser. Subsequent plants were designed much along the same lines as Oskarshamn 1, with step-wise improvements.

A major step forward came with the advanced BWR 75 design, which is characterised by use of internal recirculation pumps, fine-motion control rod drives, four independent and physically separated trains of engineered safety systems, and a pre-stressed slip-formed containment. Six nuclear power plants of this design are in operation in Sweden and Finland. The accumulated successful operation experience of these plants amounts to almost 100 reactor-years, and demonstrates the capability of being operated at high energy availability factors (figure 1).

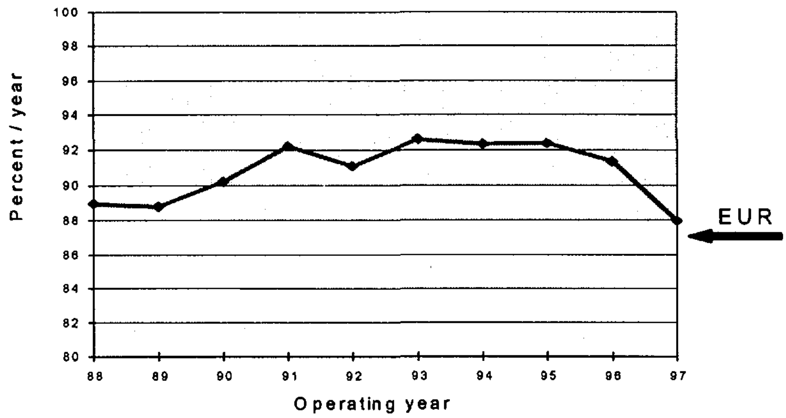

FIG. 1. Annual energy availability factors for the BWR 75 plants

The total electricity generation costs have been low, as demonstrated by the published production costs for the Forsmark 1, 2, and 3 plants during the last decade (figure 2).

3. THE BWR 90 DESIGN FOR THE 1990s

The most recent BWR design of ABB, the BWR 90, was offered commercially to Finland in 1991, as one of the contenders for the fifth nuclear power plant project in Finland.

The BWR 90 design is based on the experience from design, construction, commissioning and operation of BWR 75 plants in Finland and Sweden. Specific changes were introduced to an established reference design, that of the Forsmark 3 and Oskarshamn 3 units. Modifications were made to adapt to technological progress, new safety requirements and to achieve cost savings. An efficient feedback of operation experience, and consideration of utility requirements, was provided by a co-operation with the Finnish utility Teollisuuden Voima Oy (TVO) that operates the Olkiluoto 1 and 2 plants of BWR 75 design in Finland. These units have operated extremely well, with an average capacity factor over the last ten years of 93,2 %.

The design is characterised by the use of internal recirculation pumps, fine-motion control rod drives, and comprehensive physical separation of the four-train safety systems, basically in the same way as in its predecessor. The thermal power rating of the base version is 3,800 MWth, supplemented by a smaller unit of 3,300 MWth.

In 1997, the Steering Committee of the European Utility Requirements (EUR) group, selected the BWR 90 to be the first BWR design to be evaluated and reviewed for compliance with the EUR document.

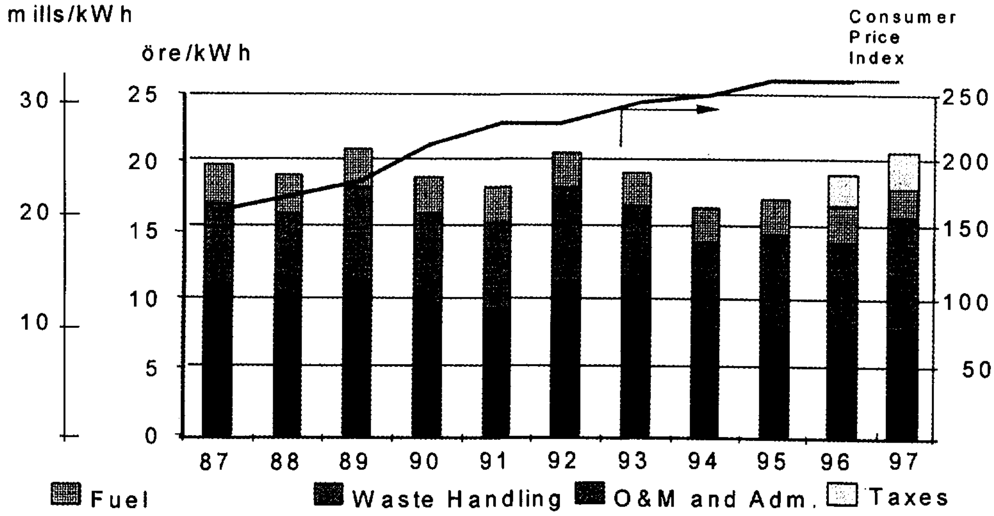

FIG. 2. Generation costs for the three BWR 75s at Forsmark

This work that is scheduled for completion by the end of 1998, has comprised a detailed assessment against the overall requirements - in Volumes 1 and 2 of the EUR document. The results will be incorporated into a "Volume 3 Subset for the BWR 90 design" document. As a matter of fact, the effort also serves to demonstrate the general applicability of the EUR document to BWR designs. The review has shown that BWR 90 meets most of the requirements; deviations mainly refer to technical details.

4. SOME BWR 90 HIGHLIGHTS

A main emphasis in the development work was to maintain "proven design" features, unless changes would yield improvements and simplifications. In line with this philosophy, the reactor design changed very little.

The reactor pressure vessel design was modified slightly; an enhanced use of large-section forgings has yielded a significant reduction in number and length of welds. This in turn reduces plant operation cost since it reduces the amount of in-service inspection to be carried out during the refuelling outage.

The recirculation system uses internal glandless pumps driven by wet asynchronous motors; this type of pump has been operating reliably in ABB BWR plants (for more than four million operating hours) since 1978. Such internal pumps have now been adopted also by other BWR vendors, in the ABWR plants.

The engineered safety systems are consistently divided into four redundant and physically separated subsystems, of which two suffice to meet the demands in any design basis accident situation. This BWR 75 concept has been reconfirmed as an optimal arrangement with respect to safety, layout and maintainability.

The safety-related electrical power supply and I&C systems are divided into four sub-divisions in the same way; the reactor protection system operates in a 2-out-of-4 logic for signal transmission and actuation.

With respect to diversity, it may be noted that the traditional ABB BWR control rod drives system incorporates diversified means of control rod actuation and insertion, by hydraulic pressure and by electrical motor. Together with a generous reactor pressure relief capacity, and combined with a capability of rapid recirculation flow rate reduction (by pump runback), it provides an efficient ATWS (Anticipated Transient Without Scram) countermeasure.

The general arrangement of the buildings *(cf. Figure 3)* is characterised by a division into a nuclear, safety-related part of the plant, containing the reactor building, the diesel buildings and the control building, and a more "conventional" part that is "separated" from the former by a wide communication area. The "conventional" part contains the turbo-generator and auxiliary systems of the plant. This arrangement is advantageous when building the plant as well as during plant operation, since the conventional part does not interfere with the nuclear part.

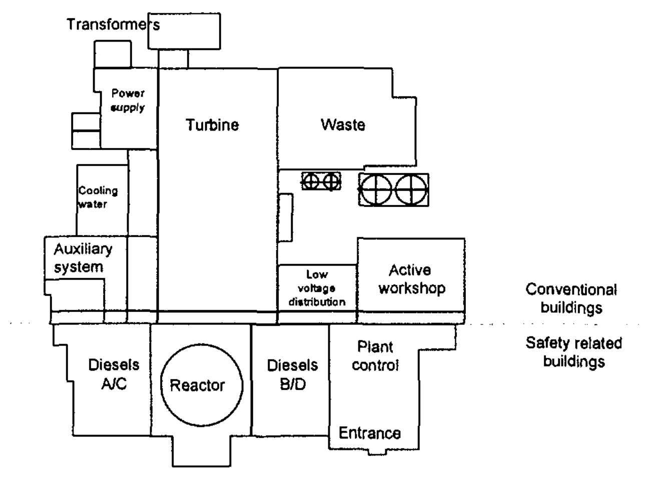

FIG. 3. BWR 90 General building Arrangement

Compared with previous plants, building volumes have been substantially reduced, yielding a significant cost reduction. Nevertheless, BWR 90, like previous plants, is characterised by a fairly spacious layout. This facilitates access to components and is a key to low occupational exposure.

The pressure-suppression containment consists of a cylindrical pre-stressed concrete structure with an embedded steel liner - as in all previous ABB BWR plants. The containment vessel, including the pressure-suppression system and other internal structural parts as well as the pools above the containment, forms a monolithic unit and is statically free from the surrounding reactor building.

At the time of the BWR 90 design, regulatory developments indicated a need to strengthen the capability of the reactor containment to withstand the effects of a core melt accident. Today, such requirements are codified in several countries, e.g., Finland and Sweden. The essential features of the BWR 90 containment to achieve enhanced environmental safety including protection during a degraded core accident are:

- The blow-down of steam to the suppression pool passes through vertical concrete pathways to horizontal openings between drywell and wetwell.
- The relief pipes from the safety/relief valves are drawn into the suppression pool via the lower drywell rather than penetrating the drywell-wetwell intermediate floor.
- A pool is provided at the bottom section of the lower drywell for the purpose of collecting and confining fuel melt debris. The pool is permanently filled with water to enhance passive safety.

In addition, the containment vessel can be vented to the stack through a filter system, installed in the reactor building, similar to the filtered venting systems installed at all nuclear power plants in Sweden. These arrangements improve the reliability of the pressure-suppression system and reduce the probability of containment leakage during a severe accident.

A simplification of the auxiliary power supply configuration is easily distinguished; the number of distribution voltage levels have been reduced. As an example, it can be noted that DC distributions at several voltage levels for power supply to control equipment has been replaced by power supply from the battery-backed AC-distribution, using distributed AC/DC converters for the supply to the various types of equipment, when needed. The simplifications of the electric power systems will of course have a significant influence on the amount of maintenance work; a substantial reduction is anticipated.

A key to modern process control and communication applied to the BWR 90 is the use of control and instrumentation systems based on micro-computers. Process communication with the control room is realised by means of distributed functional processors. These in turn interact via serial communication links with a number of object-oriented process interface units. Thus, the protection and control system configuration is characterised by decentralisation and the use of object-oriented intelligence. The arrangement satisfies the requirements of redundancy and physical separation. It includes intelligent self-monitoring of protective circuits.

The use of serial communication links guarantees interference-free performance and reduces cabling. Standardisation of the object-oriented circuits minimises maintenance and the necessary stock of spare parts. The arrangement will also tend to improve availability, since components can be replaced quickly and simply. An important aspect is that the software is also standardised to simple program functions. This makes it easy even for non-computer specialists to handle the systems, and it facilitates implementation of new micro-computer generations.

Video display units (VDUs), keyboards, and display maps are used consistently to facilitate the man-machine communication in the control room. The main control room *(cf. Figure 4)* contains several work positions, each equipped with a number of VDUs. Typically, one VDU will display a total view of the process in interest, another will provide a list of alarms, and a third VDU will display a diagram with sufficient detail to facilitate operator action. This arrangement is supplemented with a special overview panel, visible to all operators in the control room. The overview shows the main process in the form of a flow diagram and indicates the status (normal, disturbed or failed) of various plant functions by conventional instruments and computer-based displays.

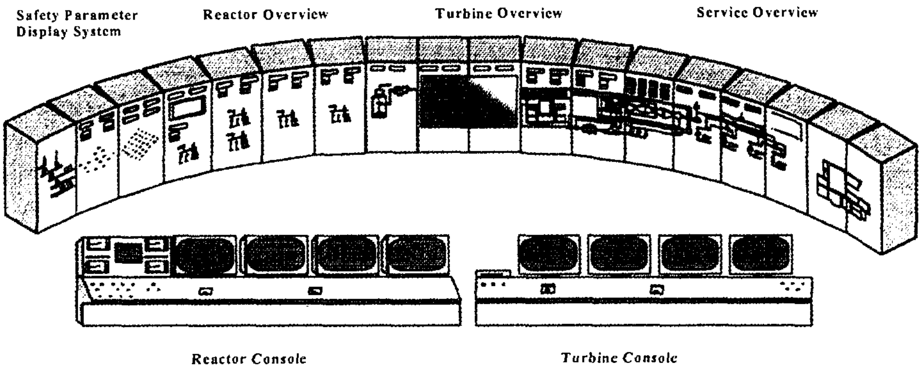

FIG. 4. BWR 90 Control Room Arrangement

The main computer has the task of collecting information from the process control systems, and it communicates with the distributed micro-computers via serial links. The main computer compiles information and generates reports, such as daily/weekly operation reports, reports of periodic testing, actual status reports, and disturbance reports.

5. THE BWR 90+ DESIGN

ABB is continuing its BWR development with work on a new advanced design, the BWR 90+. The aim of the continued programme is to maintain and develop the BWR as a competitive option for a reviving market, primarily in Europe, beyond the turn of the century, as well as feeding ideas and inputs to the continuous modernisation efforts at operating plants. In essence, the programme is firmly based on evolutionary development of the company's previous, advanced BWR designs.

The main objectives of the project focus on anticipated utility needs in the 21st century; the new design should offer reliable power generation at reduced construction and operation costs and incorporate significant safety improvements. The on-going review of the BWR 90 against the EUR is of importance for the BWR 90+ development work, and observed findings are specifically addressed in the design.

The development work is conducted in co-operation with TVO, which feeds adequate operation experiences into the project and performs analyses of different design alternatives regarding safety aspects, including mitigation of severe accidents. Swedish BWR operators have also recently joined the project with focus on getting ideas and inputs for modernisation and improvement works at their existing nuclear power plants.

5.1 Design and performance goals

Economic competitiveness is of paramount importance for a new nuclear power plant design. The BWR 90+ design work aims at developing a plant with: - reduced investment cost, - short construction time, - high energy availability, - short refuelling outages, - low operation and maintenance costs, - low fuel cycle cost, as well as - low waste management and decommissioning costs.

With respect to flexibility and reliability the governing design guideline again is: "Proven system design and components are to be adopted to ensure reliable electricity production, and moderate development steps are introduced only when bringing improvements." As a result, most of the fundamental design features from the previous designs with respect to the energy production capability and reliability will be incorporated also in the BWR 90+ design.

Some specific design and performance goals of the BWR 90+ development project are:

(a) Plant nominal power output; 1500 MWe
(b) Construction time; less than 1500 days
(c) Energy availability; higher than 90 %
(d) Refuelling outage; 15-20 days/year.

5.2 New evolution and safety requirements

The BWR 90+ design builds firmly on proven design, but considers and adopts new developments including new technology, digitised control equipment, and passive features and functions, as well as features that yield improved severe accident mitigation.

The design principles of BWR 90+ are based on generally established international codes and standards. In addition, specific attention is paid to the requirements of STUK, the regulatory body of Finland. The EUR documents and the EPRI URD[1] are also considered.

The safety requirements applied in the design lead to use of redundancy and diversification in addition to physical separation to ensure independence. The diversification includes use of passive systems. The design follows the "defence-in-depth" principles, aiming at ensuring:

(1) low frequency of disturbances;
(2) that disturbances are controlled and do not develop into more severe events;
(3) that accidents are mitigated and do not develop into a core melt accident; and
(4) that the effects on the surroundings of a core melt accident remain acceptable.

The most recent edition of the STUK guides[2] addresses the need for a very high safety level and calls for improved severe accident mitigation, and limited accident consequences. Some examples are:

(a) The plant shall be designed so that no release of radioactivity will occur during the first period after a severe accident, even if all easily oxidising materials in the reactor core react with water.
(b) The design should include a containment venting system, but containment venting shall not be the primary way to reduce a containment overpressure in a severe accident situation.
(c) The relief valves shall be activated only temporarily (for brief discharges) during an anticipated transient to control the reactor pressure.
(d) The plant shall be designed to prevent release of radioactive matter in case of a possible accident, including a LOCA, during shutdown conditions, e.g., resulting from human errors during refuelling.
(e) Provisions shall be made to ensure decay heat removal in the event of loss of the ultimate heat sink normally used.

In order to meet these demands, a number of changes are introduced in the BWR 90+ design, compared with previous designs, including an improved containment design, introduction of passive systems and ECCS modifications. Design measures to cope with a "degraded core" accident have been incorporated in the containment design by provision of a core catcher arrangement and filtered venting for the containment.

5.3 Improved containment design

The containment design (*cf. Figure 5*) is characterised by robust design principles. During normal operation, the containment is inerted by nitrogen gas, thereby eliminating the risk of fires during operation and the risk for hydrogen explosions in case of postulated core melt accidents.

Except for vacuum breakers, all pipe connections between drywell and wetwell have been eliminated. The number and size of the vacuum breakers have been reduced. The wetwell, including the partitioning floor, is provided with a leak-tight liner in stainless steel. This design minimises the potential for drywell - wetwell bypasses.

A dry core catcher is arranged beneath the reactor pressure vessel; its steel structure is submerged into the containment pool. In case of a severe accident, involving core melt and penetration of the reactor pressure vessel, the molten core will be collected in the core catcher, which will be cooled by the surrounding water. The containment structure is protected against the direct impacts of the molten material and does not serve as the primary barrier for a core melt. The containment proper will serve as an inherently passive system ensuring that no releases of radioactivity to the environment will occur during the first period after a severe accident

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[1] EPRI URD – Utility Requirements Document of Electric Power Research Institute, USA
[2] Guide YVL 1.0 – Safety Criteria for Design of Nuclear Power Plants

with a molten core. The improved design implies a reduced risk for steam explosions, and a released molten core will be cooled in a passive way by the containment pool water.

The wetwell gas compression chamber volume and the pool water volume have been increased compared with previous designs. The improved design will accommodate the pressure build-up that may occur from hydrogen generation from all zirconium in the core for one day without activation of the cooling, overpressure protection, and support systems. Activation of active cooling systems, as well as spraying water into the drywell, will cool the containment structure, reduce the containment pressure and, in turn, prevent releases to the surrounding. The filtered venting system can be used to reduce the containment pressure in the long term without concerns for significant off-site consequences.

In the BWR 90+ design, there are no openings or pipe and cable penetrations from the lowest part of the drywell. The top of the core is located below the level of the upper drywell (or partitioning) floor. In the hypothetical case of a LOCA induced by human errors during plant shut-down and refuelling operations, the *water volume in the pools above the reactor will suffice for filling the drywell volume to above the partitioning* floor, and consequently, this design implies that the core will remain flooded without human action or safety system actuation.

The improved containment design – with the pools on its top - is fully adapted to construction by means of slip-forming methods; the peripheral walls of the pools are made as integral parts of the containment wall structure. Combined with an extensive use of modular building technique, this reduces the construction time and costs.

The main features of the improved containment design are:

(a) Reduced construction time and costs.
(b) Minimised probability for drywell - wetwell bypass.
(c) Core remains covered by water if loss of coolant accident occurs during refuelling.
(d) Passive core melt retention and cooling inside containment; no releases within one day in the event of a core melt accident.
(e) Containment structure is protected against core melt impact by core catcher arrangement.
(f) A dry core catcher reduces the probability for steam explosions.
(g) Core concrete interaction is negligible.
(h) Increased volumes cope with pressure build-up from hydrogen generation at core melt accident.
(i) Nitrogen gas inertion allows cooling and pressure reduction by water spraying without risk for hydrogen explosions.
(j) Ultimate overpressure protection by filtered containment venting.

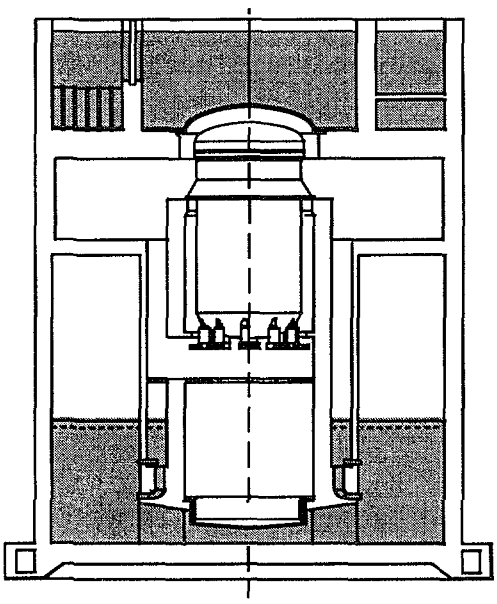

FIG. 5. Containment design for the BWR 90+

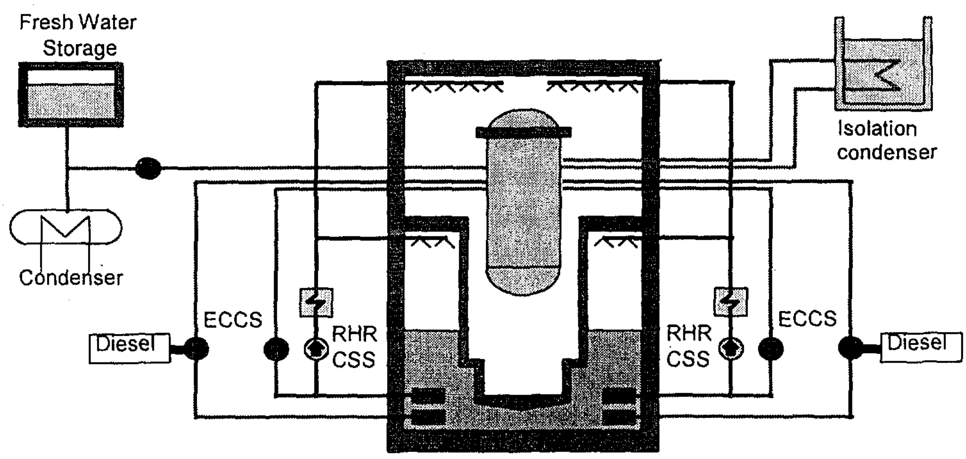

FIG. 6. Decay heat removal and coolant make-up systems.

5.4 Decay heat removal and safety systems

A number of diversified components and system functions have been introduced, in line with the new safety requirements from the Finnish safety authority STUK, which demand diversity and provisions, in particular against loss of the final heat sink normally used, and that relief valves be actuated only temporarily. To this end, a passive heat removal system similar to the isolation condenser in the first ABB Atom NPP, Oskarshamn 1, will be incorporated in the design. The principles for the decay heat removal and coolant makeup systems are outlined in figure 6.

6. CONCLUSIONS

ABB is convinced that there will be a reviving market for new nuclear power capacity in the near future. ABB is determined to be in a position to be able to compete for the new orders and therefore has continued its development efforts.

The BWR 90 design is available today for deployment in new plant projects and has been offered commercially. The design has, with a positive outcome, been subjected to a review by European utilities to evaluate how it compares with the requirements established by the EUR group.

The development of the BWR 90+ design is based on its 'forerunners' and can be referred to as a 'proven design', in line with power utilities' preferences. The 1500 MWe design incorporates considerations of new safety requirements, including severe accident impacts, and it will be marketed by the turn of the century. The development work on the BWR 90+ design will also serve as input for modernisation, uprating and improvements of earlier generations of nuclear power plants.

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