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Light Water Reactors for the Next Century

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Companies in the ABB group have supplied 29 light water reactors (LWRs) in operation worldwide; a further six are under construction in the Republic of Korea. ABB continues to develop both pressurised water reactor (PWR) and boiling water reactor (BWR) technologies. This paper describes the structure of this development and draws conclusions with respect to technology, economy and safety.

Table 1 identifies the 29 operating ABB LWRs as well as those under construction. The average capacity factor for the PWRs was 79.4% in 1996, and for the BWRs it was 82.4%. Both these results are above the average values for PWRs (76.1%) and BWRs (75.3%) worldwide given by *Nucleonics Week*.

Figure 1 shows the availability of the six latest BWRs delivered by ABB. They all have quite similar design, with four train safety systems and internal recirculation pumps. The figure illustrates the benefits of an evolutionary design — the latest two BWRs (Forsmark-3 and Oskarshamn-3) operated extremely well from the very beginning. The average availability for the six units during the last ten years is above 91%. This success is attributed to the characteristics of the original ABB BWR design and to the capable utilities operating these plants. Figure 2 shows the capacity factors of ABB PWRs during the last 20 years.

The total cost of producing power in the ABB reactors is low by international standards. For example, the production costs of power from the Forsmark-1, -2 and -3 plants are shown in the Figure 3.

There are generally substantial margins available for increasing the power of many LWRs. ABB BWRs have, for example, been uprated to generate another 600 MWe. Figure 4 shows the power uprates and stretches of ABB LWRs.

Net electricity generation increases in the range of 20 to 30 MWe per plant have also been achieved by efficiency improvements, most notably in the steam turbine. Excellent production economy ensures that continued investments can be made so that the production capability is retained or even improved, and so that safety improvements can be made to adjust to ever increasing demands. The excellent production records for LWRs originally designed by ABB make significant investments possible.

All BWRs originally designed by ABB have been retrofitted with systems which mitigate the consequences of core melt accidents. This includes diverse containment spray and flooding systems, and systems for filtered venting of the containment which practically eliminate the risk of ground contamination following a core melt-down accident. A large scale modernisation has been performed or is in progress at most of the plants.

Noteworthy is the modernisation of Oskarshamn-1, where all reactor internals were removed to inspect the pressure vessel and control rod nozzles in the bottom of the vessel. The main shroud, steam separators, core spray system and the moderator lid will be replaced early in 1998. Additional modernisation in the years to come will include improvements in the safety systems and replacements of control systems. The control room will also be modernised.

The reactor coolant pressure boundary has been

Table 1. ABB LWRs in operation or under construction worldwide.

Plant	Type	Operator	Year of operation
Oskarshamn-1	BWR	OKG, Sweden	1971
Palisades	PWR	Consumers Power, USA	1971
Maine Yankee	PWR	Maine Yankee Atomic Power Co, USA	1972
Fort Calhoun	PWR	Omaha Public Power District, USA	1974
Oskarshamn-2	BWR	OKG, Sweden	1974
Ringhals-1	BWR	Vattenfall, Sweden	1974
Barsebäck-1	BWR	Barsebäck Kraft, Sweden	1975
Calvert Cliffs-1	PWR	Baltimore Gas & Electric, USA	1975
Millstone-2	PWR	Northeast Utilities, USA	1975
St Lucie-1	PWR	Florida Power & Light, USA	1976
Barsebäck-2	BWR	Barsebäck Kraft, Sweden	1977
Calvert Cliffs-2	PWR	Baltimore Gas & Electric, USA	1977
Olkiluoto-1	BWR	TVO, Finland	1978
Olkiluoto-2	BWR	TVO, Finland	1980
Forsmark-1	BWR	FKA, Sweden	1980
Arkansas-2	PWR	Entergy, USA	1980
Forsmark-2	BWR	FKA, Sweden	1981
St Lucie-2	PWR	Florida Power & Light, USA	1983
San Onofre-2	PWR	Southern California Edison, USA	1983
San Onofre-3	PWR	Southern California Edison, USA	1984
Forsmark-3	BWR	FKA, Sweden	1985
Oskarshamn-3	BWR	OKG, Sweden	1985
Waterford-3	PWR	Entergy, USA	1985
Mühlheim-Kärlich	PWR	RWE, Germany	1986
Palo Verde-1	PWR	Arizona Public Service, USA	1986
Palo Verde-2	PWR	Arizona Public Service, USA	1986
Palo Verde-3	PWR	Arizona Public Service, USA	1988
Yonggwang-3	PWR	KEPCO, Republic of Korea	1995
Yonggwang-4	PWR	KEPCO, Republic of Korea	1996
Ulchin-3	PWR	KEPCO, Republic of Korea	1998
Ulchin-4	PWR	KEPCO, Republic of Korea	1999
Yongwang-5	PWR	KEPCO, Republic of Korea	2002
Yongwang-6	PWR	KEPCO, Republic of Korea	2002
Ulchin-5	PWR	KEPCO, Republic of Korea	2003
Ulchin-6	PWR	KEPCO, Republic of Korea	2004

NSSS	Nuclear steam supply system
NI	Nuclear island
TI	Turbine island
NSSS ES & CD	NSSS equipment supply and component design

improved in Ringhals-1, where all material susceptible to environmentally assisted cracking has been replaced. Electric cabling and cable penetrations have been replaced in the Oskarshamn-2 and Barsebäck reactors. Control systems are modernised to introduce digital, software-based systems. This includes implementation of digital equipment in safety protection systems.

Recently, the introduction of a digital system for neutron measurement and supervision was approved for Olkiluoto-1 and -2. Swedish utilities are investing about 500 man-years in design

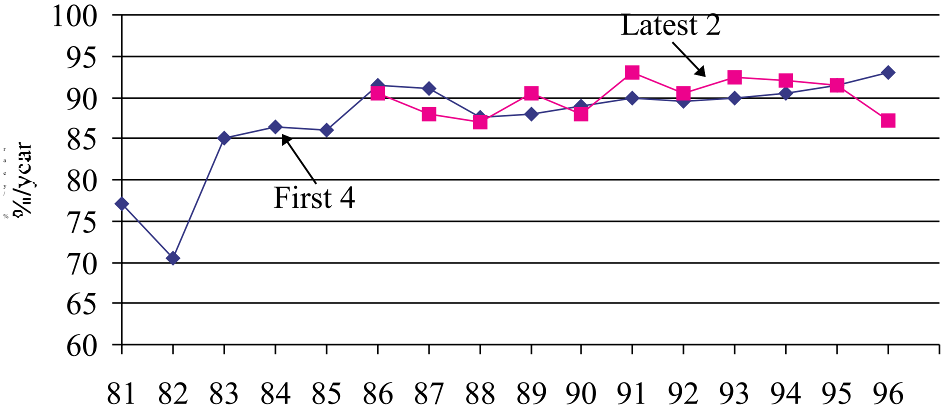

Figure 1. Average energy availability for the six latest ABB BWRs with internal recirculation pumps, with annual refuelling for all plants. (Source: Kärnkraftsäkerhet och Utbildning, KSU, Sweden.)

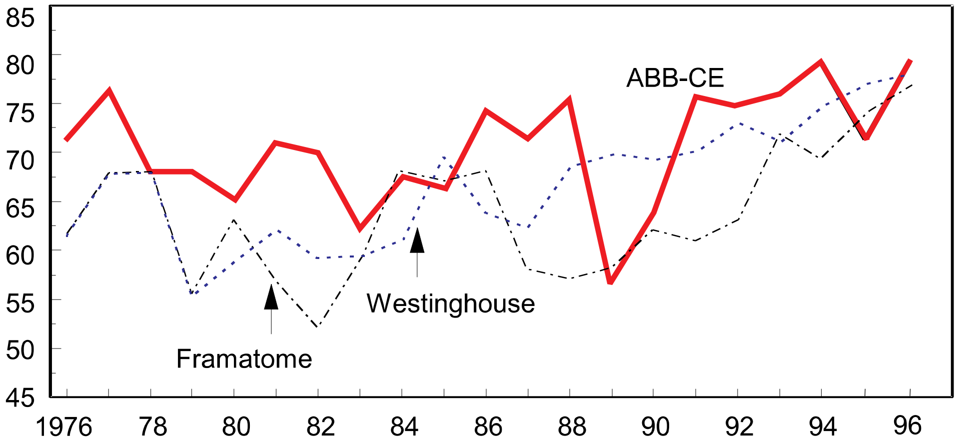

Figure 2. Capacity factors for System 80 PWRs. (Source: Utility Data Institute, USA.)

reconstitutions which will re-engineer all licensing documentation and safety evaluations. The results of this work will be used in continuous improvement of the plants.

These were a few examples of the investments made in existing reactors in Sweden and Finland. The excellent operational economy of the plants ensures a long prosperous life for these plants.

In the 1970s, ABB Combustion Engineering committed to the development of a standardised nuclear steam supply system (NSSS) design that would be a step beyond the industry standard and would meet customers' needs in the 1980s and beyond. The primary design objectives were:

- improved power generation economics;
- greater safety margins;
- improved operating and maintenance performance.

These objectives led to the development of the System 80 NSSS, with a higher power level, higher operating temperatures, and economiser steam generators to reduce the overall cost of nuclear power. The design also included a unique reactor vessel upper guide structure and control rod configuration to provide significantly increased safety margins for both uranium and mixed oxide (MOX) fuel loadings.

In addition, bottom entry in-core instrumentation, with both fixed and movable in-core detectors, was added to allow a more precise and continuous mapping of the core power distribution, providing increased accuracy in monitoring core behaviour and contributing to increased operating efficiencies. Finally, a solid state digital protection system was included to maximise core power output while minimising the uncertainty on safety para-meters, thus maintaining required safety margins. The three 1300 MWe System 80 units in operation at

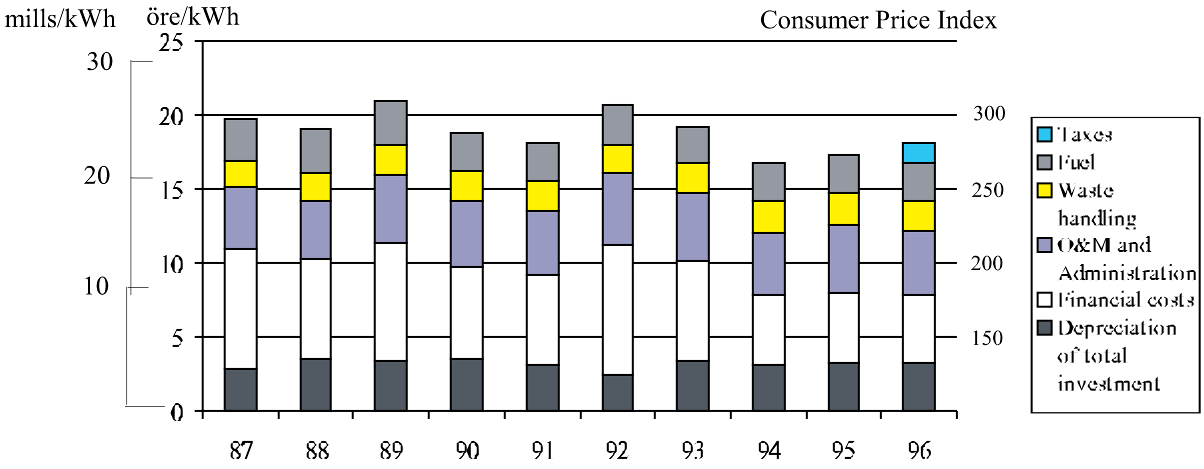

Figure 3. Total production costs for Forsmark-1, -2 and -3, without inflation adjustment, US mills and Swedish öre (US$1 = 770 öre). (Source: 15 year review by Forsmarks Kraftgrupp AB.)

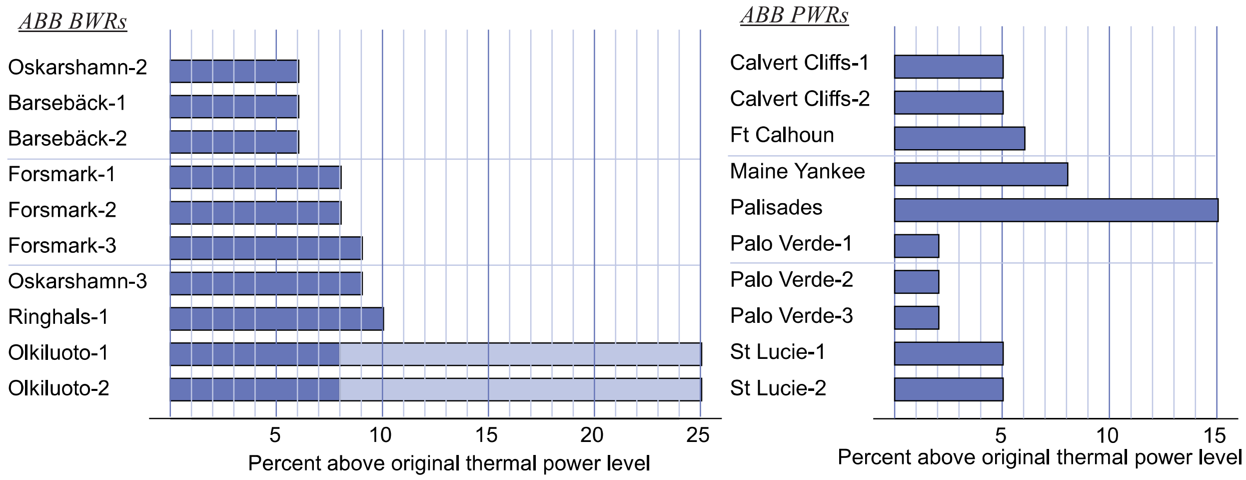

Figure 4. Power uprates or stretches of ABB BWRs and PWRs. (Note: TVO is in the process of increasing the thermal power of Olkiluto-1 and -2 by another 15% to reach 25% above the orginal design power level.)

the Palo Verde Nuclear Generating Station have set numerous US and world performance records.

Development of LWR Technology

ABB continues to develop both PWR and the BWR technology. Recently, the System 80+ advanced PWR design was certified by the US Nuclear Regulatory Commission through formal rulemaking. BWR development continues in cooperation with utilities, with the new BWR 90 design being the first BWR to be reviewed by European utilities for compliance with the European Utility Requirements (EUR).

BWR 90 Development

The development of the BWR 90 started in 1986 when the latest two BWR 75 designs, Forsmark-3 and Oskarshamn-3, had been put into operation. Since 1988 the development work has been conducted in cooperation with the Finnish utility Teollisuuden Voima Oy (TVO) which operates the Olkiluoto-1 and -2 BWRs, which are the first of the BWR 75 design.

This cooperation has provided efficient feedback of operating experience. In 1991 the BWR 90 design was offered as the fifth nuclear power plant in Finland. Detailed evaluations were performed in 1990–93, including discussions with the Finnish nuclear power regulator body. However, due to a decision by the Finnish parliament, the fifth NPP in Finland was put on hold in September 1993.

The BWR 90 design includes some carefully evaluated improvements to the reference design, which is the successful BWR 75 design used at Forsmark-3 and Oskarshamn-3. Changes have been introduced to:

- reduce construction costs;
- improve the operability and energy production

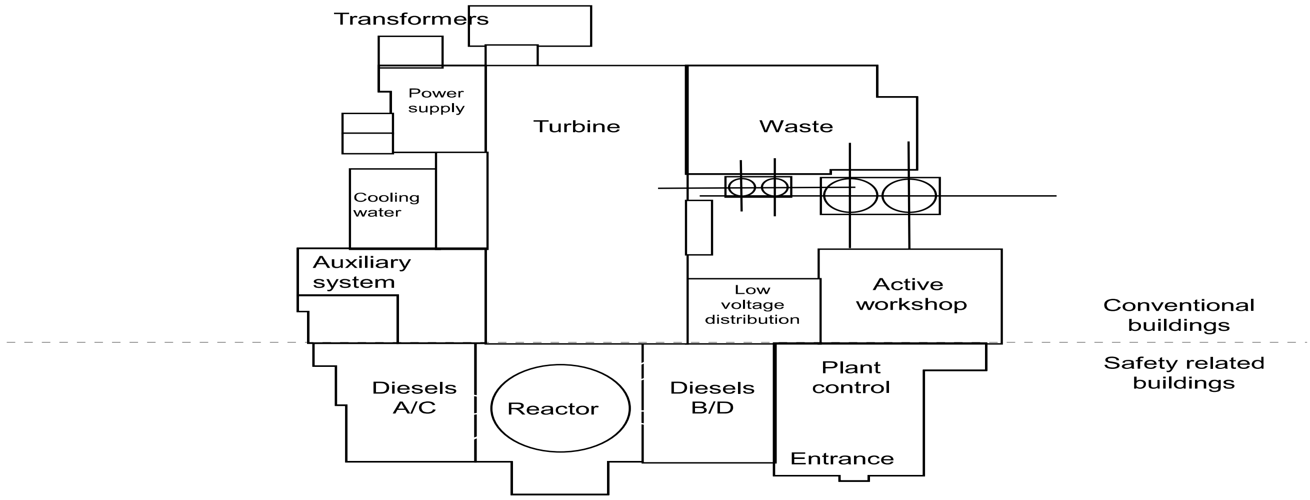

Figure 5. General layout of the BWR 90 design.

capability of the plant even further;

- reduce the radiation doses to plant personnel;
- improve the safety of the plant.

The general layout of the plant is shown in Figure 5.

The plant is designed for 3800 MW thermal power, corresponding to approximately 1350 MW electrical power. It is designed for a minimum of 40 years of operation, with 60 years as a design requirement for large structures and components. The average availability during 40 years of operation is expected to be better than 90%. The average refuelling outage will be less than 20 days / year. The doses to plant personnel are expected to be less than 0.75 man-Sievert per year of operation. The plant is designed to be built significantly faster than the BWR 75 plants, for which the shortest building time was 50 months (from start of civil construction work to fuel loading).

Extensive life-cycle cost evaluations have been made in order to address all the important parameters affecting the total cost of each kWh produced. All design goals have been verified against design, construction and operating experience from the BWR 75 designs in operation. The operating experience from the six BWRs of that type is now close to 100 reactor-years.

The reactor pressure vessel (RPV) has been redesigned to reduce the number and lengths of welds. The welding length in the larger BWR 90 vessel will be almost half the length in the smaller RPV of Olkiluoto-1 or -2. The basic design of the RPV internals is kept from BWR 75, which means that they are not welded to the RPV and can be easily removed.

The designs of the steam separators and steam dryer units have been improved to reduce the carry-over of liquid droplets to the turbine. The internal recirculation pumps are basically the same as those operating in the BWR 75 reactors. The accumulated operating experience since 1978 for these pumps of more than 4 million hours has demonstrated the benefits of the design.

The safety and maintenance benefits of a systematic division of each engineered safety system into four independent and physically separated sub-systems (trains) are kept from the previous BWR 75 design. Two out of four trains in the safety systems always provide the safety function that is required. In most cases, only one train is necessary to provide the safety function.

The safety-related auxiliary electric power supply equipment is also divided into four independent and separated parts (divisions) which each feed one of the trains in the engineered safety systems. The reactor protection system also consists of four completely independent and separated sub-systems and operates on a two-out-of-four logic for signal transmission and actuation.

The reactor auxiliary systems have been optimised using the operating experience from existing BWR 75 reactors. The reactor water clean-up system has, for example, been redesigned so that the flow through the system's filters is determined by the operating conditions. This reduces the heat losses from the system.

Strict specifications for materials and material treatments have been set for BWR 90 to increase the lifetime of components and to reduce radiation

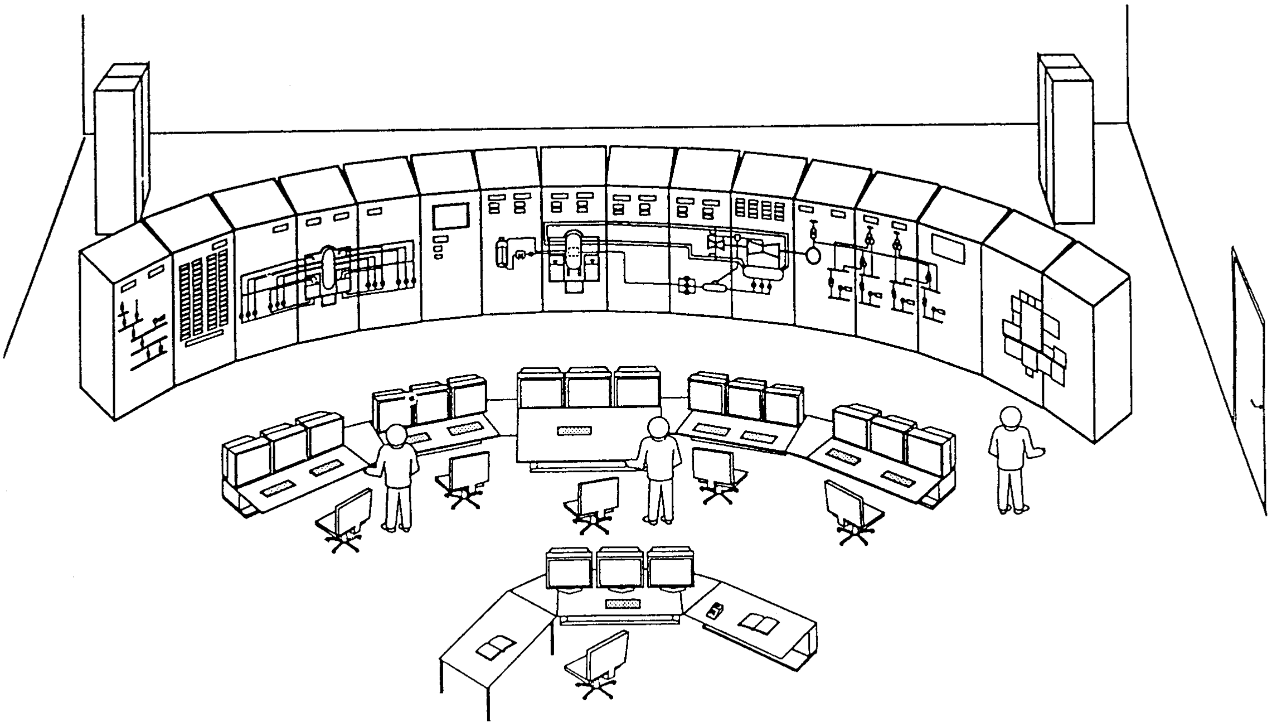

Figure 6. Schematic view of the BWR 90 control room.

in the plant. Cobalt content is set to below 0.05% and limits on impurities like silicon, sulphur and phosphor are also specified. Weldings and other material treatment processes are strictly controlled. Grinding and cold worked materials are, for example, not allowed. In addition to all these measures, the BWR 90 is designed so that it should be easy to replace components during the lifetime of the plant.

The simplifications which have been introduced for the ordinary power distribution within the plant are expected to reduce maintenance work considerably. The use of modern switchgear components together with careful design of the process systems have made it possible to significantly reduce the requirements for the size and characteristics of the emergency diesel power generators. The number of distribution voltage levels has also been reduced to three levels. All distribution is by alternating current and local alternating / direct current converters are used where needed.

BWR 90 is designed to use digital systems for plant control, including reactor protection systems. This improves the control of the plant, eases the burdens on the operator, and facilitates operation and maintenance. Significant savings also result since less space and cabling are needed. 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 multiplexing with serial communication links reduces cabling. Standardisation of the object-oriented circuits minimises maintenance and the necessary stock of spare parts. The arrangement also tends to improve availability, since components can be replaced quickly and simply.

Man–machine communication in the control room is facilitated by the consistent use of video display units, keyboards, and display maps (see Figure 6). This arrangement is supplemented with an overview panel, visible to all operators in the control room. The operating experience from the use of the ABB Advant Power systems, already implemented in replacement and modernisation projects for operating nuclear power plants, forms an excellent basis for introduction of the system as a proven design in BWR 90. This includes the design of the control room where, for example, the utility OKG in Sweden has decided to modernise

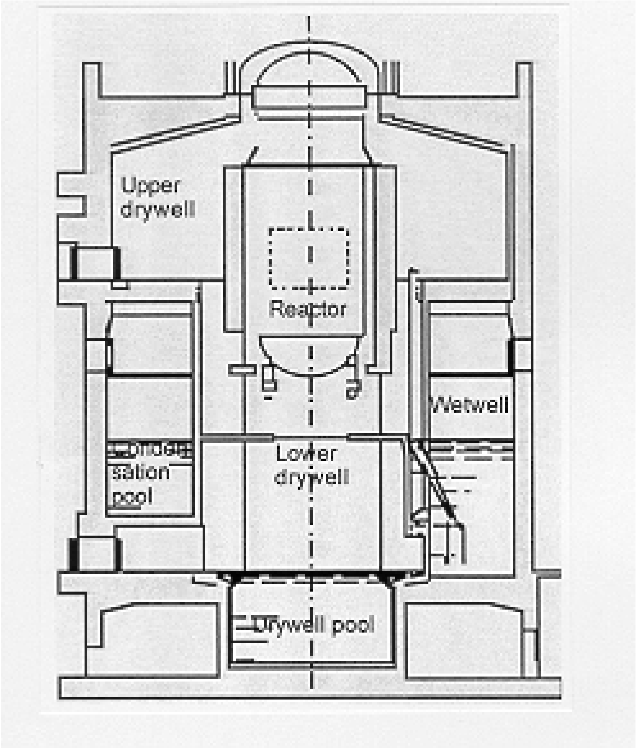

Figure 7. BWR 90 containment design.

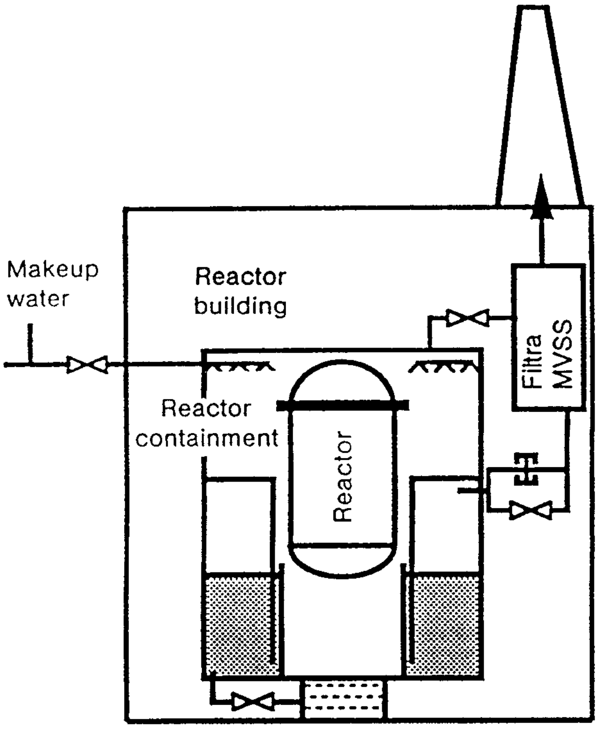

Figure 8. Containment venting system in the BWR 90 design.

the Oskarshamn-1 control room.

The BWR 90 safety-related systems are based on a well-balanced mixture of redundancy and diversification. As mentioned above, safety systems are strictly divided into four completely independent sub-systems to provide redundant equipment. Examples of diversified designs provided in the BWR 90 include the RPV overpressurisation protection, where the safety relief valves are actuated by electric signals as well as by an increase in RPV pressure, and the reactivity control function, where the control rods can be inserted into the core by a hydraulic scram as well as by electric motors. Furthermore, rapid run-back of the main recirculation pumps provides fast negative reactivity feedback. Finally, there is an automatic and high capacity liquid boron injection system which is activated if core shut-down should not be achieved by these other means.

Environmental impact from a postulated core melt accident has practically been eliminated. The basic strategy for severe accident mitigation in BWR 90 is to design a robust containment which provides an effective safety barrier (see Figure 7). There is also a highly reliable system to depressurise the reactor pressure vessel after a severe accident to avoid the risk of a high pressure melt-through. There are means to quench and effectively cool the core material after a melt-through of the reactor pressure vessel. This is done by introducing a lower drywell which is permanently filled with water. The design of the lower drywell focuses on minimising the risk of basemat melt-through or other effects of molten core material.

A highly reliable containment spray system would partially fill up the containment with water to above the core level to ensure a safe and stable final state after a severe accident. The containment must then be vented to relieve non-condensable gas pressure. Filtered venting limits the release of radioactive matter so that long-term ground contamination or other significant environmental effects are avoided (see Figure 8).

The risk of core damage has been evaluated using probabilistic methods and is lower than limits set by authorities and utilities. A considerable margin is available for design purposes. The off-site consequences of postulated core melt accidents have been practically eliminated by limiting the release of caesium-137 to less than 100 TBq. Other isotopes which are relevant with respect to ground contamination would be limited so as not to cause a hazard greater than that which would arise from caesium-137.

Development of the BWR 90 design continues with the BWR 90+ project, which is being performed in cooperation with utilities. Additional optimisations of the containment design are being introduced

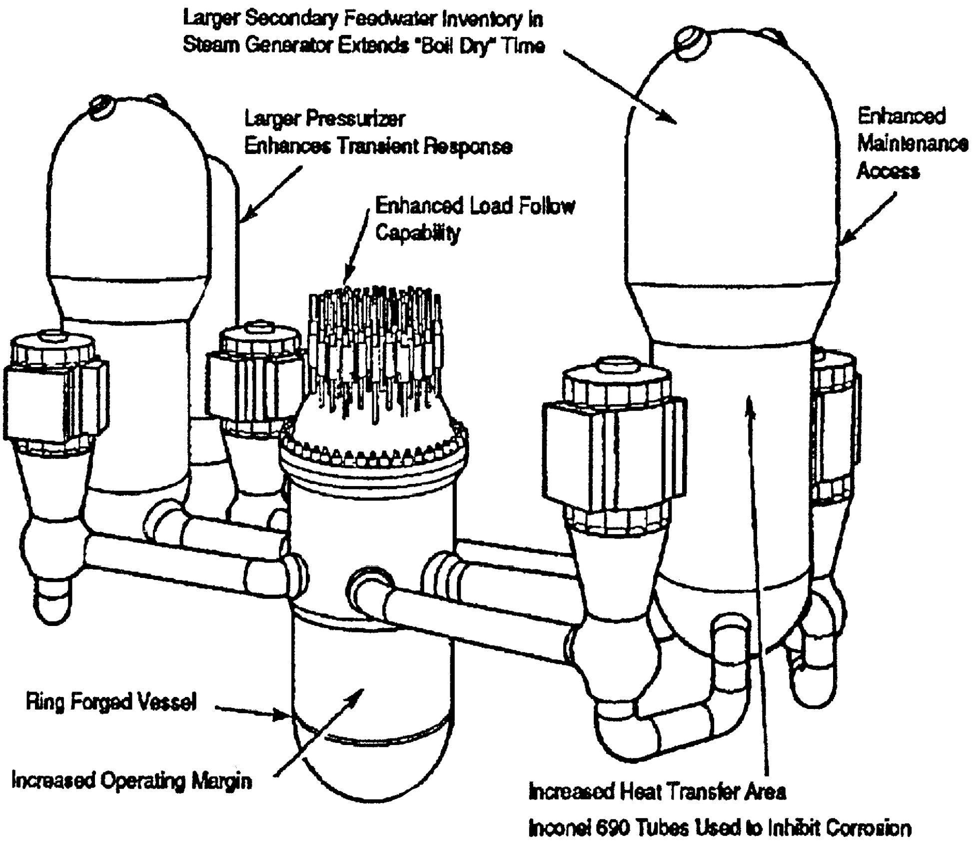

Figure 9. Improvements in the System 80+ reactor coolant system.

to improve even further the capability to cope with core melt-down accidents, and to reduce the costs of construction. We are also studying passive means of removing the heat generation from the primary system as well as from the containment in emergency situations.

System 80+ Development

The System 80+ standard plant design incorporates improvements which have evolved from lessons learned during thousands of reactor-years of nuclear plant operating experience. It builds upon the very successful System 80 NSSS design, construction and operating experience.

It also conforms to the US Electric Power Research Institute (EPRI) Advanced LWR Utility Requirements Document (URD) in almost all respects, since the design was being developed essentially at the same time that the URD was being developed. The design enhancements meet virtually all of the URD goals of simplicity, improved reliability, improved accident prevention and mitigation, improved economics, and better man–machine interfaces.

The main emphasis in the reactor area has been to maintain the proven design of System†80; therefore, changes are very limited. The System 80+ steam generators include tubes made from Inconel 690 alloy, improved steam dryers, and a 17% increase in overall heat transfer area, including a 10% margin for potential tube plugging (Figure 9). The steam generators have a 25% larger secondary feedwater inventory to extend the “boil-dry” time and improve response to upset conditions. Steam generator improvements have also been made to facilitate maintenance and long term integrity, eg. larger and repositioned manways, a standby recirculation nozzle, and a redesigned flow distribution for the economiser.

The System 80+ safety systems have been enhanced to produce additional safety margins and to offer more flexibility to recover from accidents and transients. Changes include:

- A safety injection system, which doubles the high pressure injection flow capacity of current plants and can keep the core covered (and cooler) for larger size pipe breaks.
- A shutdown cooling system, with increased design pressure to minimise inter-system loss-of-coolant accidents.

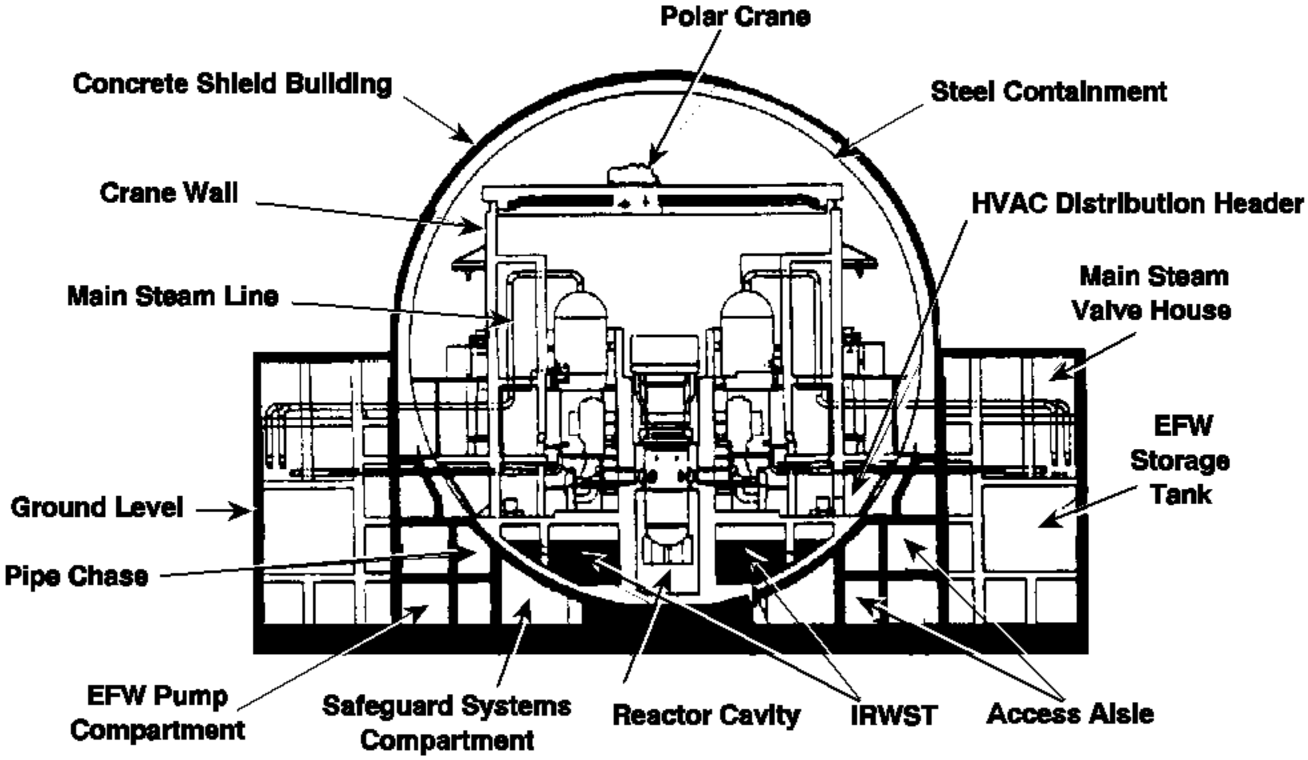

Figure 10. The System 80+ spherical steel containment.

- A containment spray system, with increased heat removal capacity to reduce post-accident containment peak pressures and temperatures.
- A higher capacity reactor coolant gas vent system, which removes the non-condensable gases and assists in depressurising the reactor coolant system.

These safety system enhancements are, in essence, improvements to those already in the System 80 design. In addition, the System 80+ design incorporates entirely new safety systems which further increase the safety margins and address new licensing requirements.

The System 80+ design specifically addresses the severe accident issues arising as a result of the Three Mile Island accident. The containment structure is a steel sphere designed to ASME code requirements, which is enclosed in a cylindrical concrete shield building (Figure 10). The containment structure is specifically designed to mitigate the consequences of severe core damage accidents. The dual containment reduces the potential for radioactive release to the environment by retaining any releases from the steel containment inside the shield building.

The size and design of the containment, along with hydrogen ignitors, enhances mixing, dilution, and control of hydrogen gas which could conceivably be released during a severe accident, thus preventing a deflagration or detonation that could challenge containment integrity. The configuration of the reactor vessel cavity and its support system (the cavity flood system) is such that any molten core material would be collected and cooled in the lower cavity area, which prevents it from migrating into the containment atmosphere and ultimately contributing to containment failure.

Another very significant feature of the System 80+ design is the Nuplex 80+ Advanced Control Complex (ACC) . The objectives of the ACC are to:

- improve the man–machine interface between the operator and the plant;
- improve plant safety by providing the operator with important information in an uncluttered and direct manner;
- reduce the cost of plant construction.

The Nuplex 80+ ACC utilises a unique combination of currently available, proven instrumentation and control technologies to facilitate an orderly transition from an analogue to an all-digital software-based control complex. Key design features include:

- advanced information processing and display which has man–machine interface features that significantly improve operator awareness during both normal and abnormal conditions;
- utilisation of field-proven commercial products qualified for nuclear service;
- avoidance of unproven technologies or

incorporation of unique, special hardware items that could hinder licensing, training, operations or maintenance;

- utilisation of distributed architecture to minimise the effects of equipment failures.

In operations and maintenance of the System 80+ design, cost savings will result from:

- use of advanced fuel cycles with power manoeuvring capabilities;
- increased diversity and redundancy, eg alternating current power sources, which can be credited to relax operability requirements in the technical specifications for a plant;
- advanced materials and fabrication techniques that extend design lifetimes of components and provide a basis for relaxing surveillance inspection and testing;
- selection of components with high reliability, demonstrated by extensive use in the nuclear industry;
- maintenance-friendly layouts that anticipate needs for access, removal of equipment, and workspace;
- use of digital balance of plant control systems that have higher reliability and availability;
- increased steam generator tube plugging margins and increased steam generator manway diameters for easier maintenance access.

The System 80+ design includes other advanced features to further reduce operations and maintenance costs, simplify operations, and reduce surveillance and maintenance. Advanced electronics with self-testing and equipment diagnostic features, full flow testing capabilities for fluid safety systems, advanced controls, alarms and displays, and refuelling systems and procedures to minimise refuelling times are just a few examples.

The development of System 80+ continues in cooperation with the Korea Electric Power Corporation (KEPCO). ABB and KEPCO have extended their technology cooperation agreement for an additional ten years and are working together to develop the Korea Next Generation Reactor, which is based on System 80+ technology. Construction is expected to start at the turn of the century.

Fuel Developments

ABB has introduced BWR fuel with internal water structures, which has led to considerable savings in fuel cycle costs. This design feature has also been used in a 10x10 fuel assembly to increase burnup capability and thus to reduce back-end costs. Improvements in the heat transfer capability of the fuel assembly can be used in existing reactors for fuel cycle cost reductions or power uprates. They are also credited for continued reactor design developments.

PWR fuel design developments include items like improved spacer designs to increase thermal margins, use of advanced burnable absorbers, and advanced cladding alloys to achieve burnup well beyond present limits.

These fuel development results are fully incorporated in the development of the advanced light water reactors. ABB fuel development is described in more detail in Reference 1.

Evolutionary Development & Harmonisation

ABB believes that a carefully planned and evaluated development of mature and well-proven LWR technology will provide the largest benefits for owners of new plants. The operating records and costs of electricity production of the latest ABB LWRs support this strategy.

The cost of energy production in LWRs depends on several factors as described in Reference 2. Large power output, standardisation, short construction time, low cost design features, and proper project and information management are all important factors for the initial costs. Recent experience supports the conclusion that a competitive initial cost of around US$1500–2000 per kWe should be achievable, depending on various factors including the country that the plant is located in, the degree of local sourcing, the type of financing, and whether the plant is the first-of-a-kind or the nth-of-a-kind.

Life-cycle profit evaluations should, however, be done to fully acknowledge the benefits of nuclear power. Total production costs are low in modern LWRs, as illustrated in Figure 3. Pre-requisites for low production costs — in addition to low initial investment costs — are low unplanned capability loss factor, short refuelling outage duration, low operation and maintenance costs, low fuel cycle costs, and low waste management and decommissioning costs. An excellent example is provided in Reference 3 to illustrate the importance of good performance: the fixed part of the overall generating costs was reduced by 33% by increasing the capacity factor from 70% to 93% at the two Olkiluoto reactors in Finland over the last ten years.

The full benefits from the evolutionary development of LWRs can be drawn if utility, as well as regulatory, requirements are harmonised. Major progress has been achieved in this area.

Utility requirements have now been formulated in the US (in the EPRI ALWR Utility Requirements Document, URD) and in Western Europe (the European Utility Requirements, EUR). There are significant similarities between these requirements.

The design certification of the System 80+ advanced plant design by the US NRC is based on licensing requirements which are similar to those in the URD. It is expected that the System 80+ design will be evaluated against the EUR in the next round of evaluations. This will provide an excellent comparison between the requirements set in the USA and in Western Europe.

Harmonisation of regulatory requirements in Europe is also stimulated by the development of the European Pressurised Water Reactor (EPR). The progress is encouraging. We also hope that the establishment of the International Nuclear Regulators Association (INRA) will promote harmonisation of regulatory views between North America and Western Europe. The experience of ABB is that adaptation to requirements in one country provides significant benefits when compliance to requirements in other countries is evaluated. All in all, harmonisation of design and licensing requirements will make nuclear power more competitive.

Summary

Modern LWRs of ABB design continue to operate well and provide significant benefits to their owners and their customers. We believe that proactive investments in these plants will ensure that they operate well throughout their lifetime, which can exceed the 40 years design criteria.

The benefits from evolutionary plant development are mainly that development costs are reduced and that past experience can be applied in design, construction, operation and maintenance. New designs are adjusted to utility requirements as well as to requirements set by regulatory bodies. Experience demonstrates that this can be achieved within the framework of an evolutionary development.

The ABB strategy for LWR development is to successively improve the designs to meet new requirements for low-cost energy production and increased safety. Both the BWR 90 and the System 80+ developments follow this strategy. The System 80+ design and ABB technology will be applied for the Korean Next Generation Reactor, which will provide additional input for future improvements.

ABB is confident that the System 80+ and BWR 90 advanced light water reactors are designs that provide attractive options for nuclear energy now and for the next century.

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