

Reactor Refurbishment and the Development of Improved Designs

Wulf Bürkle

Worldwide nuclear generating capacity of about 350 000 MWe represents an enormous challenge for plant operators and vendors of related services with respect to plant availability, safety and plant lifetime, as the cornerstones of economic power generation.

With, for example, steam generator replacements, power upratings, implementation of innovative digital instrumentation and control systems, reduced outage times, plant modernisation and backfitting measures, Siemens' expertise can contribute to plant operators' achievement of the goals mentioned above.

New projects such as the innovative boiling water reactor design SWR 1000 and the evolutionary design concept for the European Pressurised Water Reactor (EPR) – the latter jointly developed with Framatome and the French and German utilities – develop nuclear know-how and will further enhance the safety standard of nuclear power plants.

The upgrading of operating plants and the new projects both contribute to the availability of nuclear power plants with advanced design and safety standards for the coming decades.

Borssele Project “Modificaties”

As an outstanding example of a backfitting project, the safety design and engineering of the 24 year-old Borssele PWR in the Netherlands has been successfully brought up to the current state-of-the-art. This is probably the most extensive and complex backfitting project ever executed to date in an operating nuclear power plant, and this with

an extremely tight installation and commissioning schedule.¹

The single unit 450 MWe plant was built from 1969 to 1973 by Siemens/KWU and achieved a lifetime load factor of about 80% over its first 24 years of operation. The original financial investment for the plant was paid off in 1993, so plant operator EPZ decided to upgrade the power plant to today's state-of-the-art in order to run it competitively for another twenty years as a baseload station.

In 1989 an investigation was carried out to assess Borssele in the light of the latest regulations. Based on the results of studies and of a detailed probabilistic safety assessment, a comprehensive safety concept was developed in 1991 by EPZ in co-operation with Siemens/KWU, which was then approved by the Dutch nuclear authority. The turn-key contract was awarded to Siemens/KWU in 1992. From 1992 to 1994 an extensive licensing process, comparable with the procedure for new plants, was carried out. The hardware was ordered in 1995.

All present licensing requirements such as earthquake, gas cloud explosion, airplane crash, single failure criterion, high energy line break, ATWS, 30 minute criterion, internal fire and flooding, etc. had to be fulfilled. The major modifications executed in the frame of the project are summarised in Figure 1.

A large number and range of activities had to be carried out within limited space, a very tight schedule and with parts of the station still in operation. Work started at about 50 different locations at the same time.

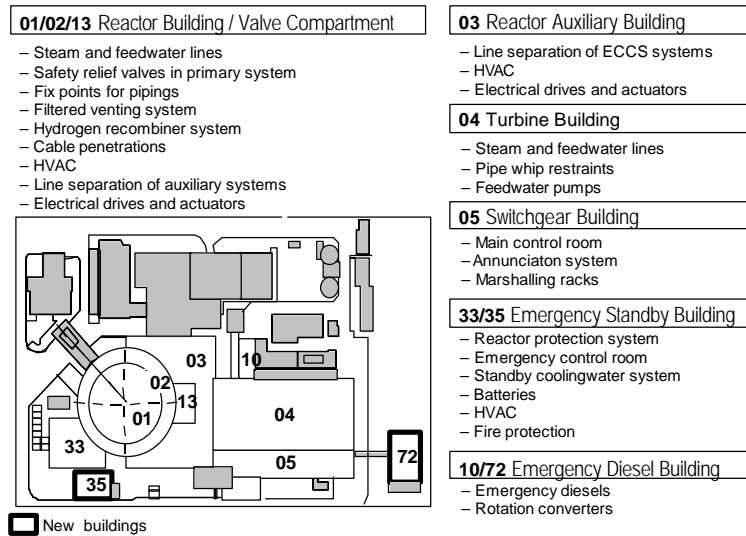


Figure 1. Modernisation of the Borssele PWR, major modifications.

A few figures illustrate the volume of work: around 85 000 cable marshalling points had to be disconnected and reconnected; 1350 additional cables with a total length of 560 km had to be laid; some 450 new or modified 380 V drives and another 350 safety related components had to be put in place; 230 instrumentation and control (I&C) cabinets were mounted or modified, which meant roughly 15 300 new wiring connections; some 3600 welds had to be made in the piping systems and 2000 steel supports for earthquake protection attached to walls, ceilings and floors were installed; over 200 000 drawings were made.

The original schedule for the on-site work envisaged a six month interruption to plant operation. For economic reasons however EPZ and Siemens/KWU agreed to try to shorten the

time as much as possible. Site activities were therefore based on a so-called four-month working schedule (see Figure 2), the partners being fully aware that there was no “buffer” time for unforeseen repairs and events.

Work started on site on 8 February 1997. In the busiest period more than 1500 people were in the plant. After unloading the reactor core the control room was dismantled in one day. The new control room was already installed and completely connected by end of March. Most of the remaining dismantling and installation work on the electrical and I&C side was completed by mid April. Commissioning of the mechanical components followed in May, where some additional time was needed for testing of prototype components. Apart from some minor deviations, which were quickly

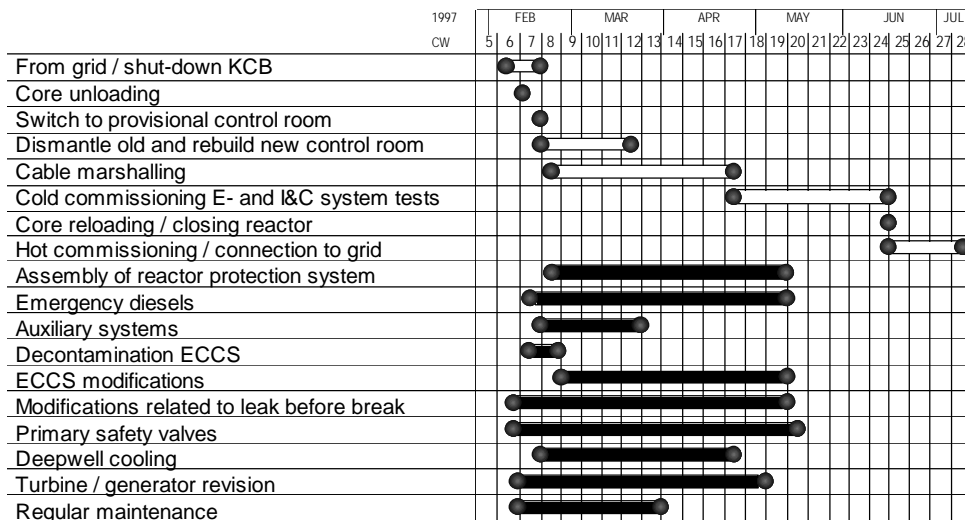


Figure 2. Modernisation of the Borssele PWR, the 151-day time schedule.

corrected, all equipment worked faultlessly.

The behaviour of the plant was successfully proven with a full load main coolant pump trip as well as a full load turbine trip. Borssele finally came back into commercial operation on 14 July 1997 – a very short shutdown in view of the complexity and large volume of modifications undertaken, including a full power test run of two weeks. The plant has operated without problems since then.

The success of the project can be mainly attributed to the following factors:

- Overall responsibility was passed to one supplier (turnkey contract with Siemens/KWU). Thus interfaces, which might cause mistakes and omissions, were minimised and consistency in approach to tasks was engendered.
- The scope of engineering and supply was clearly defined by the safety concept.
- The licensing procedure was mostly based on fixed regulations. The authorities did not ask for substantial additional requirements in the course of the project.
- Effective scheduling and thorough logistics preparation ensured that the right person with the right materials, right tools and right documents was at the right place at the right time. Progress was updated daily, and if necessary even hourly.
- Problems emerging in the course of the on-site work were immediately eliminated by so-called “problem solving teams”.
- Work was executed in shifts for four months practically uninterrupted, 24 hours a day, including weekends and holidays. The highly qualified and motivated crew of workers and engineers fully identified themselves with the goals of the work.
- Finally, a prerequisite for completing this large and ambitious project on budget and on time was the perfect teamwork of utility, supplier and licensing body.

Mochovce backfitting

The Mochovce units 1 and 2 in the Slovak Republic are an example of successfully upgrading Eastern European VVER-type nuclear power plants to Western European safety standards.

In 1990, Siemens/KWU performed the project work and supply of I&C (including the control rooms) for Mochovce-1 and -2. In order to train the plant operator’s personnel, Siemens/KWU successfully delivered and put a plant simulator

into operation. Following the supply of diagnostic systems for the primary loops and the preparation of a couple of safety engineering studies by Siemens/KWU, the EUCOM consortium – formed by Siemens/KWU and Framatome – received the order to plan and perform about 50% of the scope of safety improvements in the two units.

The complete set of measures for increasing safety resulted from close co-operation between Western institutes for nuclear safety, the IAEA, and the Slovak licensing authority, as well as from the collaboration of Western European, Russian, Czech and Slovak enterprises. French and German licensing experts stated in their joint final report, that Mochovce would achieve Western safety levels when this programme of safety related measures was realised.

The most recent highlights from Mochovce-1 were first criticality on 9 June 1998, and first connection to the grid on 4 July 1998. In late July 50% of maximum power was reached. Plant take-over was planned about one to two months later.

Mochovce is now a reference for how a competent and determined utility could swiftly complete a Russian-type nuclear power plant, aiming for ecologically beneficial power generation with sense of responsibility for its customers and neighbours, and by making use of all the technical resources available in Europe.

Advanced Reactor Projects

The belief in further development of nuclear power calls for the maintenance and further improvement of the already extensive overall knowledge base, including scientific know-how, application of tools and methods, and technological and industrial experience. Siemens has a long history as BWR and PWR supplier and is presently involved in two complementary nuclear plant development projects:

- The large (1500 to 1800 MWe) evolutionary European Pressurised Water Reactor (EPR) (see Figure 3), developed by Framatome, Siemens and their joint subsidiary Nuclear Power International (NPI), together with the major French and German utilities.
- The mid-size (1000 MWe) boiling water reactor SWR 1000 (see Figure 4), with a new passive safety system concept and an evolutionary operating system design developed by Siemens together with the major German utilities and with some support from other European utilities and research centres.

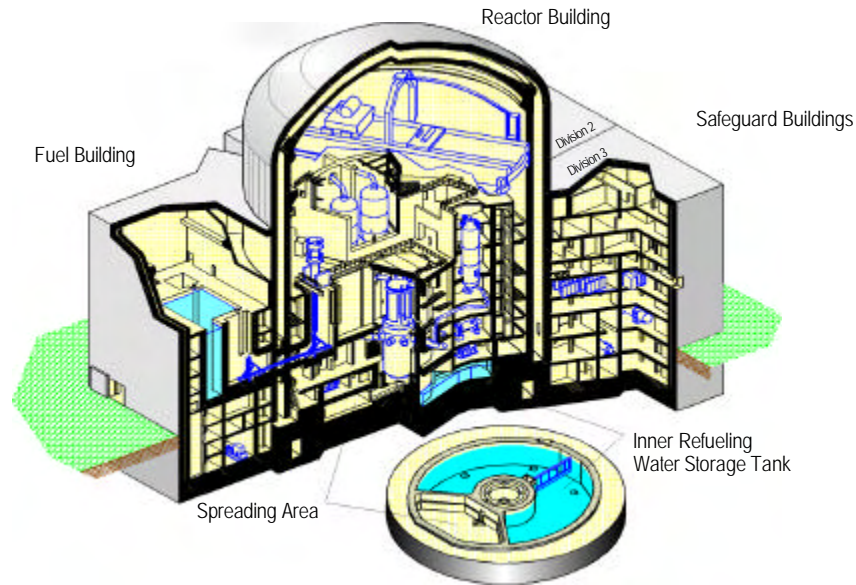


Figure 3. General arrangement of the nuclear island in the EPR design.

Safety Concept for Advanced Reactor Projects

For existing LWRs, in general a three-level defence-in-depth approach is implemented, consisting of:

- First level: high quality in design, construction and operation for prevention of disturbances and accidents.
- Second level: control and limitation of operational occurrences.
- Third level: use of engineered safety systems for control of accident conditions.

As the EPR relies on the proven designs and technologies implemented in the German Konvoi and French N4 PWR plants, and the SWR 1000 similarly relies on the German Advanced Boiling Water Reactor design implemented in Gundremmingen, both new plant designs are based on an improved version of this defence-in-depth concept, in order to further decrease the core melt probability.

Beyond that, the safety authorities in Germany and France have required that measures have to be taken at the design stage to limit the consequences of even a postulated full core melt down. There must not be a need for evacuation of the surrounding population except in the immediate vicinity of the NPP site, nor for long term restrictions with regard to the consumption of locally grown food.

Thus EPR and SWR 1000 both feature a fourth level of defence-in-depth: mitigation of severe core damage consequences.

The EPR features a dry corium spreading area beneath the reactor vessel with later flooding of the corium layer for cooling. The SWR 1000 keeps the melt inside the vessel and cools it by flooding the outside.

EPR Basic Design

The main goal of the basic design phase of the evolutionary EPR was to create a clearly defined set of technical features.² In particular, the objectives were:

- to enable the French and German licensing authorities to assess the safety level of the EPR nuclear island and its licensability in France and Germany,
- to enable the utilities and the vendors to perform a cost estimate,
- to serve as the basis for the performance of subsequent phases.

It must be noted that the good results of the basic design phase were attained through close co-operation between the vendors and the utilities, bearing in mind that both the licensing requirements and the experience and practice are different in both countries.

The technical advisors of the safety authorities in France (GPR, IPSN) and Germany (RSK, GRS) received the relevant information during the whole design process. Most of the technical features of the EPR have been commented on and accepted, and most of these comments were already considered in the basic design. The process will continue in the basic design optimisation phase, and is scheduled to be completed with a set of common Franco–German guidelines in 1999.

From the vendors' point of view, the harmonised requirements from the utilities as well as from the regulatory bodies will lead to a situation previously considered unlikely to be achieved. This will allow the same design to be offered in both countries

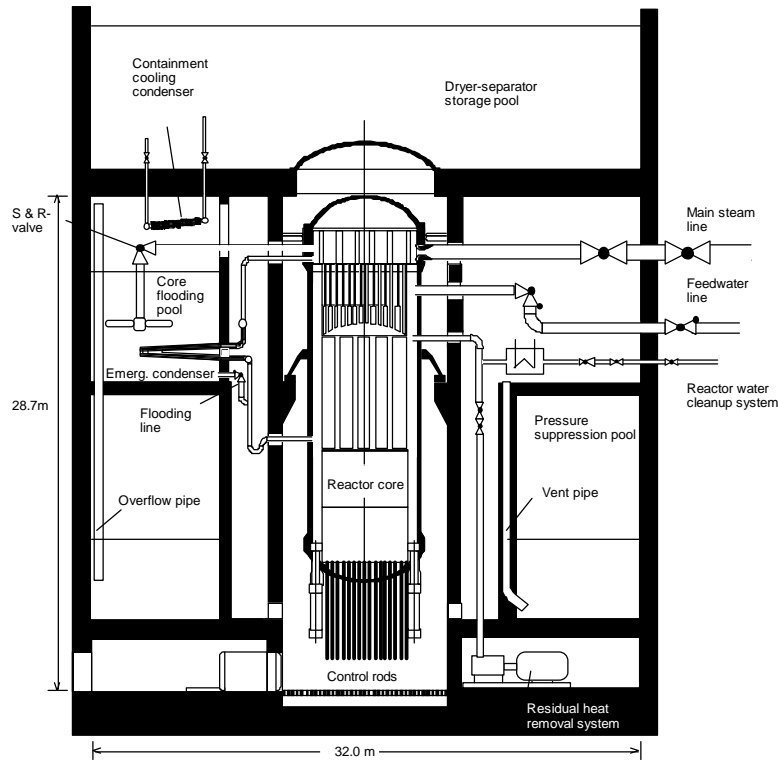


Figure 4. The containment and internal of the SWR 1000 design.

and thus simplify the design work and licensing procedures, and reduce overall costs.

The results of the basic design phase, documented in the nine volumes of the Basic Design Report (equivalent to a PSAR) and in more than 1000 supporting documents and drawings, show that the EPR is in a considerable number of its features establishing a new state-of-the-art, mainly in the fields of safety system design, instrumentation and control, and layout.

The main technical data of the EPR, before and after a 15% uprating, are summarised in Table 1.

Improved safety is not a contradiction to improved economics. The EPR design at the end of the basic design phase proved to be fully competitive with fossil power plants for imported hard coal, and in the current optimisation phase further cost reductions are being investigated, with the objective of achieving competitiveness also with modern gas-fired combined cycle plants.

Figure 5 shows an evaluation by German utilities based on plant lifetimes of 30 years corresponding to 50% of the EPR design lifetime. The necessary refurbishment of the gas plant to reach a 30 year

Table 1. The main technical data for the EPR design.

		basic design	basic design optimization phase
☐ Rated thermal power (NSSS)	MW	4272	4925
☐ Rated electrical power (gross)	MW	1609	1850
○ house load	MW	~ 80	~ 100
☐ Reactor coolant system:			
○ number of loops		4	4
○ operating pressure	bar _{abs}	155	155
○ RPV inlet / outlet temperature	°C	291.3 / 326.3	292.5 / 330
○ total flow rate	kg/s	21050	22240
☐ Main steam pressure at full load	bar _{abs}	72.5	74.6
☐ Main steam pressure at hot standby	bar _{abs}	84	86
☐ Core:			
○ number of fuel assemblies		241	241
○ number of control rod assemblies		89	89
○ fuel assembly array		17x17-25	17x17-25
○ active height	cm	420	420
○ average linear heat rate	W/cm	155	178
○ max. enrichment	% U ₂₃₅	5	5
○ Total inventory of fuel	Mg	141	141
○ Batch discharge burnup	MWd/kg	60	60

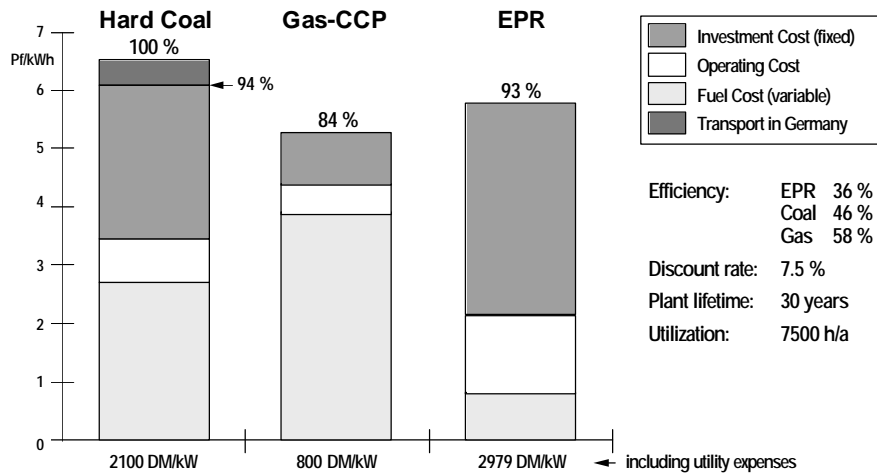


Figure 5. A comparison of specific power generation costs for hard coal, gas combined cycle and nuclear plants, as evaluated by German utilities.

lifetime is included in the specific investment cost.

SWR 1000 Basic Design

The operating concept of the SWR 1000 is based on the extensive range of experience which has been gained from BWR plants currently in service. It makes use of system and component designs which have proven themselves in operation at these plants, with certain systems having been simplified on the basis of operating experience.³

In the frame of the SWR 1000 basic design work, which is expected to be finished in mid 1999, the safety requirements have been defined and documented, and the safety concept as a combination of active and passive systems for accident control has been successfully tested. Passive systems were given preference over active systems whenever it was of benefit to safety and was economically

justifiable. The investigation on core melt retention inside the reactor pressure vessel is not yet fully completed, but looks promising. The same specific investment cost as with the EPR seems to be feasible.

As a result, on the one hand the safety level was significantly increased, and on the other hand a simplification of systems was achieved, which subsequently led to a cost reduction. The use and improvement of proven concepts for plant operation are the basis for high plant availability. In this sense, the SWR 1000 represents an essential stage of development in creating the prerequisites for the nuclear power generation option in the future. The main technical data of the SWR 1000, compared to a conventional BWR, are summarised in Table 2.

An accelerated detailed design is being considered in order to participate in potential bidding for a fifth unit in Finland in 2000.

Table 2. The main technical data for the SWR 1000 design.

		SWR 1000	1300MW GUN	
Power plant	Thermal power	2778	3840	MW
	Gross power output	1013	1344	MW
	Net power output	977	1284	MW
	Net power efficiency	35.2	33.4	%
Reactor core	Number of fuel assemblies	648 (12x12)	784 (9x9)	
	Number of control rods	157	193	
	Length of active core	2.80	3.71	m
	Average power density	48	56.8	kW/l
	Average enrichment	5.3	3.14	%
	Discharge burnup	65000	35000	MW d/t
Reactor pressure vessel	Inner height	22.70	22.35	m
	Inner diameter	7.00	6.62	m
	Design pressure	88	87.3	bar
	No of recirculation pumps	6	8	
Containment	Inner diameter	34	29	m
	Inner height	28.7	32.5	m

Advanced Fuel Assemblies

The core of the EPR consists of 241 fuel assemblies with a 17x17 array, as used in most operating PWRs. The core is designed to provide high flexibility with respect to cycle length, low leakage loading schemes, and capacity for recycling high quantities of plutonium. The main goal is to reach very low fuel cycle costs. For this purpose, the enrichment limit of 5% U-235 in fuel fabrication has to be fully used.

Criticality requirements for the 17x17-type fuel assemblies with respect to transport and storage can be fulfilled up to this 5% limit without using burnable absorbers. Using this enrichment, a reload batch burnup of 65 MWd/kgU can be achieved for annual cycles in the EPR. The fuel technology, especially the cladding material and the pellet structure needed for this high burnup, is already under development and has been inserted for qualification in existing PWRs.

The ATRIUM design, characterised by an internal square water channel, will be the basis for the SWR 1000 fuel assembly, implemented with a 10x10 array. Main design features of the already proven ATRIUM 10 design, such as fuel rod diameter, rod pitch, and type of spacers, will be maintained. However, due to the significant reduction of handling time, due to fewer fuel assemblies and fewer control blades and associated drives, the SWR 1000 fuel assembly will be a 13x13 or 12x12 ATRIUM with an internal water channel replacing 5x5 or 4x4 rods, respectively.

At the current enrichment limit of 5% U-235, an average reload batch burnup of 60 MWd/kgU is

achievable with this fuel assembly for annual cycles in the SWR 1000. The fuel technology, especially the cladding material and the pellet structure needed for this high burnup, is already under development and will be inserted for qualification into an operating BWR in 1999.

Outlook

It is Siemens' conviction that nuclear energy will regain its competitive position and will be recognised as the true answer to environmental concerns such as the greenhouse effect and acid rain.

Investments in upgrading plants, such as those made at the Borssele and Mochovce units, contribute to this aim by making sure that the originally planned lifetime can be exceeded, or that the safety standard is upgraded to Western standard, respectively. In addition, new reactor projects give the opportunity to adjust designs to state-of-the-art low-cost energy production requirements. And finally, through the experience from complex backfitting projects, the skills of our staff are improved and secured, whereas through the new reactor developments innovative safety technology is developed.

References

1. Gruhl H & Kalverboer C, *Backfitting Borssele*. Nuclear Engineering International, December 1997.
2. Bürkle W & Charbonneau S, *The EPR – the Vendor's View*. EPR Conference, Cologne, October 1997.
3. Brettschuh W & Fuchs M, *Stand der SWR 1000 Planung*, Jahrestagung Kerntechnik, Munich, May 1998.