The SWR 1000: A Nuclear Power Plant Concept with Boiling Water Reactor for Maximum Safety and Economy of Operation

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Introduction

Although the construction of new nuclear power plants has been stagnating for some time now, reactor vendors all over the world have nevertheless been working on further developing their reactor design concepts. What is the motivation behind these development efforts? The answer is: a conviction that the growing demand for electricity both in the industrialized nations and, above all, in countries that are on the threshold of industrialization – due to their dramatically expanding populations – will only be able to be met if nuclear power plants are used for base-load power generation. Nuclear power is the only environmentally friendly and economically efficient alternative in the long term, for any corresponding increase in the number of fossil-fired power plants would have a catastrophic impact on our environment by producing more greenhouse gases. Renewable energy sources that do not produce carbon dioxide (CO2) are all – with the exception of hydropower – uneconomical, and are also unpredictable as far as their generating capacities are concerned since they are heavily dependent on local weather conditions. Renewable energy sources that are "CO2-neutral" will in no way be capable of providing the amount of power that is needed. Since power generation from nuclear fusion will probably take another few decades to reach maturity, it is a widely acknowledged fact that nuclear power will experience a renaissance; the first signs of this are already to be seen in the USA where operating licenses for some nuclear plants have now been extended to up to 60 years. For these reasons – as well as to ensure that valuable know-how is not lost – work has also been continuing in Germany on further developing light water reactor technology, despite the government's decision to phase out nuclear energy. In addition to the European Pressurized Water Reactor (EPR), which is being developed by Nuclear Power International (NPI) and its parent companies Framatome and Siemens Nuclear Power in cooperation with EDF and Germany's electric utilities, Siemens Nuclear Power is continuing to develop its boiling water reactor (BWR) product line – on behalf of the German utilities and in collaboration with international partners – by designing a new BWR plant called the SWR 1000. The international partners involved in the SWR 1000 project are: TVO and VTT (Finland), NRG (Netherlands), PSI (Switzerland) and EDF (France).

Goals Pursued in Developing the SWR 1000

The goals pursued in developing the SWR 1000 can be summarized as follows:

- To increase nuclear plant safety – in other words, protection against accident-induced releases of radioactivity – even further compared to existing plants, and

- To achieve power generating costs competitive with those of larger-capacity nuclear plants as well as fossil-fired (including combined-cycle) power plants.

To meet the goal related to safety, the probability of occurrence of core damage states must be further reduced and the plant must be designed to restrict the effects of a postulated core melt accident to the plant itself so that emergency response actions such as evacuation or relocation of the population do not become necessary. Steps taken to meet the economic goal must focus above all on reducing plant capital cost, although the two other main contributors to power generating cost – namely, plant operating cost and fuel cycle costs – must also be given due consideration.

These two main development goals have also served as a basis for defining other technical and commercial objectives and requirements to be met by the design concept of the plant:

<u>Plant Operation and Plant Economics</u>

- Application of operating experience from existing BWR plants to simplify system engineering and use of their component and system designs as far as reasonably possible

- High service reliability and short refueling outages, leading in turn to high plant availability (> 87%/a)

- Flexible fuel cycle lengths (12 to 24 months)

- Low-maintenance and maintenance-friendly plant design

- Design service life of 60 years

- High fuel discharge burnups (up to 65 GWd/tU)

- Reduction in the number of operating personnel to match the simplified plant design

- Collective personnel dose of < 0.5 manSv/a

- Minimization of process waste.

Safety

- The integral frequency of core damage states resulting from plant-internal events occurring during power operation and after plant shutdown should be < 10-6/a.
- The integral frequency of core damage states resulting from plant-internal events leading to large releases of radioactivity should be < 10-7/a.
- A well-balanced safety concept with largely passive safety features should be pur-sued. Passive systems should be given preference over active systems whenever this is of benefit to safety and economically justifiable.
- After the occurrence of a design basis accident, intervention by operating person-nel should not be necessary within the first 72 hours.
- The integrity of the reactor pressure vessel (RPV) should be maintained by means of passive heat removal for 72 hours without manual intervention after a postu-lated loss of all active systems following reactor scram and should continue to be assured for an indefinite period thereafter by means of simple actions.
- The integrity of the containment should also be maintained after the occurrence of a severe accident by means of passive heat removal for 72 hours without manual intervention and for an indefinite period thereafter by means of simple actions.

Licensing

The plant must be licensable according to German laws, codes and standards and must also meet the requirements specified in the IAEA guidelines, the Finnish YVL guides and the European Utility Requirements.

		SWR 1000	
Power plant	Thermal power	2778	MW
	Gross power output	1013	MW
	Net power output	977	MW
	Net power efficiency	35.2	%
Reactor core	Number of fuel assemblies	648 (12x12)	
	Number of control rods	157	
	Length of active core	2.80	m
	Average power density	47	kW/l
	Average enrichment	4.95	%
	Discharge burnup	65000	MWd/t
Reactor pressure vessel	Inner height	22.70	m
	Inner diameter	7.00	m
	Design pressure	88	bar
	No. of recirculation pumps	6	
Containment	Inner diameter	32	m
	Inner height	28.7	m

Fig. 1: Principal design data

Design Concept

The above development goals and the resulting requirements to be met by the plant design have led to a concept that is less expensive than that of existing BWR plants but is nevertheless based on service-proven technology:

- Reactor Core and Fuel Assemblies
  The active core height has been reduced to 2.8 m. As a result, the core can be positioned lower down inside the RPV which – since the overall height of the RPV stays the same and the main steam and feedwater nozzles are positioned at a higher elevation on the RPV shell – provides a much larger water inventory above the core for accident control purposes.

  The fuel assemblies have been enlarged to a 12 x 12 rod array (type 12 x 12-16Q) which is based on Siemens' ATRIUM 10 x 10-9Q fuel assembly. This reduces the total number of fuel assemblies in the core and thus also the number of control rods and control rod drives as well as in-core neutron flux monitors. This is an ef-fective way of lowering both capital cost and operating costs, the latter due to the shorter time required for refueling and the smaller maintenance effort.

- Reactor Pressure Vessel (RPV)
  In terms of its overall height, the RPV is comparable to that of a 1300-MW plant. It has an inside diameter of 7 m, a size which is still covered by sufficient manufac-turing experience. The volume of water above the core is such that, during post-accident reactor depressurization, no active supply of makeup feedwater to the RPV is needed to maintain water level inside the RPV. To

increase the effective water inventory even further, a chimney is provided above the core in which the steam-water mixture is routed through pipes.

- Reactor Water Recirculation Pumps
  Because of the benefits afforded in connection with fuel utilization and operational flexibility, and since there were no economic reasons opposing such a choice, the method of forced coolant circulation was selected. This is performed by six internal recirculation pumps that are so-called canned-rotor motor pumps without me-chanical seals or an oil supply, a feature that yields interesting benefits in terms of operation.

- Control Rod Drives (CRDs)
  The CRDs familiar from existing plants have only been modified in one area which, however, has a particularly beneficial effect on plant design and CRD mainte-nance. The long internal drive components of the CRDs can be installed and re-moved from above through the RPV. Only the electric-motor drives and the seal housing still have to be installed and dismantled from down inside the CRD com-partment. This eliminates the space previously needed in the CRD compartment for removing the hollow piston and the threaded spindle, and reduces the overall height of the building by about 3 m, resulting in a considerable reduction in cost.

- Reactor Water Cleanup (RWCU) System
  The section of the RWCU system in which the reactor water is purified is designed as a low-pressure system and is installed outside the containment, while the high-pressure and high-temperature sections of the system are located inside the con-tainment. The purified reactor water is returned to the RPV by high-pressure return pumps that are also used to supply seal water for the reactor water recirculation pumps and cooling water for the CRDs. Existing BWR plants have a separate system for each of these three functions.

- Electrical Systems
  The auxiliary power supply system is of two-train design. Thanks to the simplifica-tions in plant design, fewer drives have to be supplied with power.

  The emergency power supply system with its emergency diesels and batteries is likewise of two-train design. Thus the scope of the system is much smaller than that of a three-train configuration requiring two diesels for each train (i.e. a total of six). The provision of only two emergency power supply trains is permissible since the plant's passive systems effectively represent more than a third redundant train.

- Instrumentation and Control (I&C) Equipment
  Both the operational (non-safety-related) and the safety-related I&C systems are configured using state-of-the-art digital programmable I&C equipment. Critical safety functions such as reactivity control, containment isolation at the main steam line penetrations and automatic depressurization of the reactor in the event of a loss-of-coolant accident (LOCA) can all likewise be actuated by passive pressure pulse transmitters which are of entirely diverse design.

- Containment

  As in all contemporary BWR plants, a reinforced-concrete containment with steel liner and pressure suppression system has been chosen. However, contrary to previous practices, use of a concrete reinforced with steel fibers as well as reinforcing bars is under consideration. Inside the containment – which like all pressure suppression type containments is subdivided into a pressure suppression chamber and a drywell – there are additionally four large core flooding pools that technically belong to the drywell. The core flooding pools serve on the one hand as a heat sink for passive heat removal from the RPV by emergency condensers as well as for the safety-relief valves and, on the other, as a water reservoir for gravity-driven flooding of the core at reduced reactor pressures following a LOCA. Apart from ventilation systems, the containment also houses the systems which communicate directly with the RPV, such as the high-pressure section of the RWCU system and parts of the two-train residual heat removal (RHR) system. The RHR pumps and heat exchangers are installed in separate compartments under-neath the pressure suppression chamber which are isolated from the containment atmosphere in the event of an accident. This arrangement ensures that the redun-dant RHR pumps are installed with physical separation and structural protection but nevertheless remain accessible after the occurrence of an accident.

  The containment also accommodates the new equipment provided for passive ac-cident control. This comprises the safety-relief valves with their additional passive pilot valves, the emergency condensers for passive removal of heat from the RPV to the water of the core flooding pools, the containment cooling condensers for passive heat removal from the containment to the shielding/storage pool situated above it, the passive flooding lines and the passive pressure pulse transmitters provided for safety function actuation.

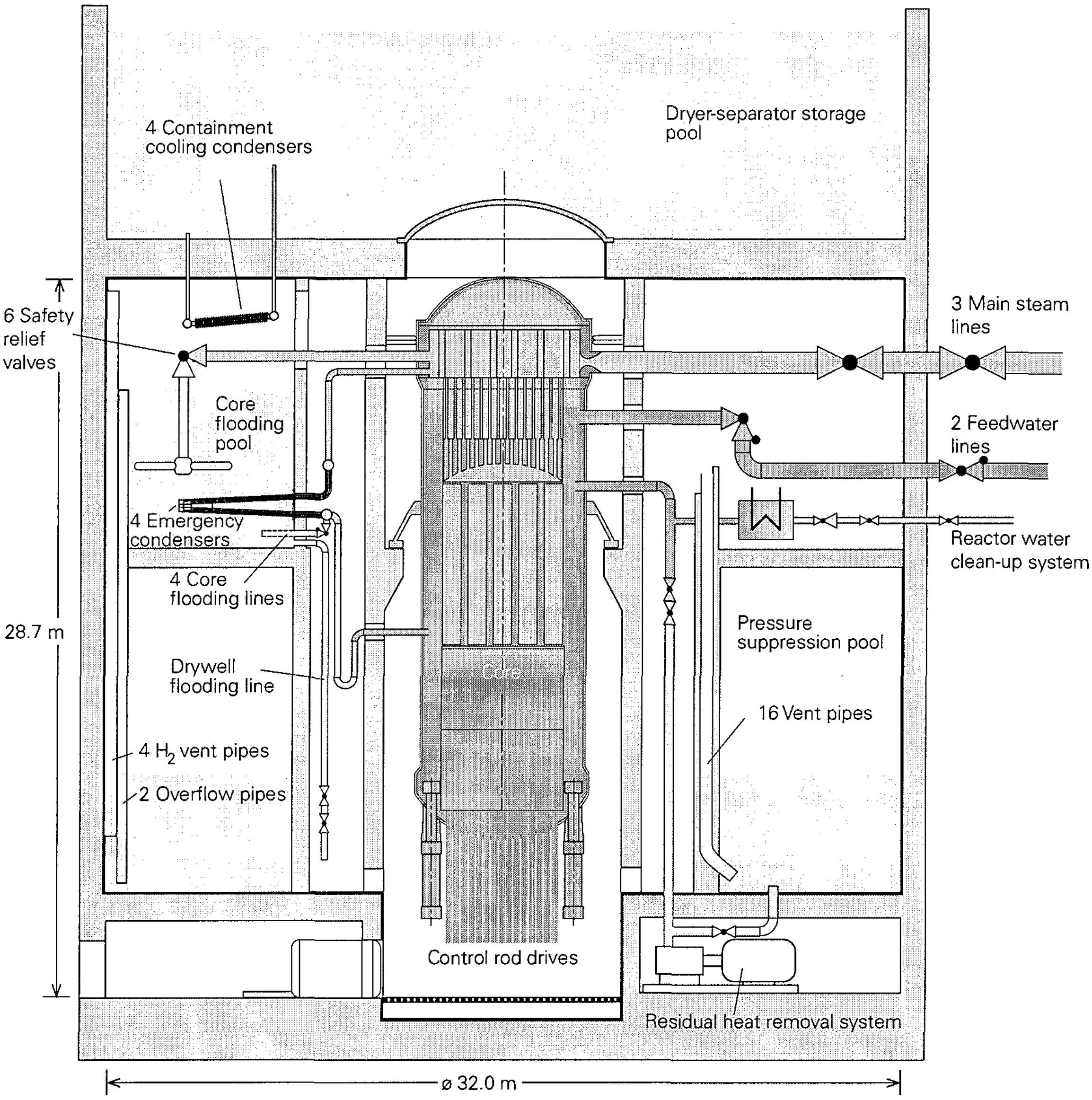

Fig. 2: Containment with active and passive safety systems

- Main Steam and Feedwater Cycle/Turbine Generator Set
  The plant has three main steam lines and two feedwater lines and is designed for once-though cooling. To keep down capital cost, a 3000-rpm turbine generator set has been selected which also makes the turbine building smaller than at existing BWR plants. The feedwater tank has been replaced by a surface-type feedwater heater.

- Buildings and Structures
  The smaller scope of systems and components enables the plant buildings and structures to be considerably reduced in size. Fig. 4 shows the interior volumes of major buildings at an existing BWR plant compared to those of the SWR 1000.

Safety Concept

The safety concept for accident control is based on interaction between active systems and passive safety equipment. Also after plant shutdown, use can be made of heatup and evaporation processes combined with simple makeup actions initiated after several days in order to provide for passive accident control (and prevention of core degradation). Prior to initiation of the passive safety functions, all accidents can be controlled by the active systems, activated by the reactor protection system.

The passive safety systems include the following:

- Hydraulic scram system for rapid control rod insertion
- Fast-acting boron injection system for reactor scram
- Emergency condensers for heat removal from the RPV
- Containment cooling condensers for containment heat removal
- Flooding lines for passive core flooding in the event of a LOCA
- Safety-relief valves for reactor pressure relief and reactor depressurization
- Main steam and feedwater containment isolation valves
- Passive pressure pulse transmitters for actuation of reactor scram, reactor depressurization and closure of the main steam containment isolation valves
- Passive drywell flooding system for cooling of the RPV exterior and in-vessel melt retention in the event of a core melt accident.

The active safety systems comprise:

- Reactor protection system
- Emergency power supply system
- Two low-pressure RHR and coolant injection systems.

The probabilistic safety analyses conducted to date for this safety concept with safety systems featuring a high degree of redundancy and diversity of design have revealed that, in the case of the SWR 1000, the integral frequency of core hazard states re-sulting from plant-internal events occurring during power operation is approximately 5×10^{-8}/a and the frequency of core damage states arising after plant shutdown is around 6×10^{-8}/a. These figures are well below the targets specified for the safety-related development goal.

Control of Core Melt Accidents

Despite the extremely low probability of occurrence of a core melt accident, this hypothetical event is nevertheless postulated and the following design features are provided for controlling an accident of this kind:

- Drywell flooding for cooling of the RPV exterior and retention of the molten core inside the reactor vessel
- Nitrogen inerting of the containment to prevent hydrogen deflagration or detonation
- Design of the containment with sufficient capacity to accommodate the hydrogen released by 100% zirconium oxidation
- Passive heat removal from the containment by containment cooling condensers.

Analyses of the impact of a core melt accident on the environment have shown that, even in the conservatively postulated case of an unfiltered release of radioactive materials from the containment atmosphere via the plant vent stack, the lower dose level of ICRP Publication No. 63 for evacuation of the population will not be reached. This verifies that the consequences of a core melt accident will remain restricted to the plant and that there would be no need for emergency response actions such as evacuation or relocation in the plant vicinity.

Protection of Buildings Against Natural and External Man-Made Hazards

The plant is designed in accordance with the European Utility Requirements to withstand the effects of natural and external man-made hazards such as seismic events, aircraft crash and explosion pressure waves. One of the goals in designing the plant was to accommodate the systems and components that require protection against these hazards in such a way inside the plant buildings that as few buildings as possible would have to be designed to withstand the loads from such events. Since all safety-related systems and components as well as those containing a high activity inventory are housed in the reactor building – except for the redundant emergency diesels along with their 690-V switchgear and the two safety-related closed cooling water and service water systems – the concept implemented for building protection is as follows.

The reactor building is the only building protected against all three major postulated hazards (seismic events, aircraft crash and explosion pressure waves). The buildings containing the emergency diesels and safety-related cooling water systems are protected against the effects of aircraft crash through physical separation (by a distance of more than 40 m) and are designed to safely accommodate the loads imposed by a seismic event or an explosion pressure wave. Since none of the other buildings contains safety-related equipment or components with a high activity inventory, they are only designed to withstand seismic loading according to standard industrial practices.

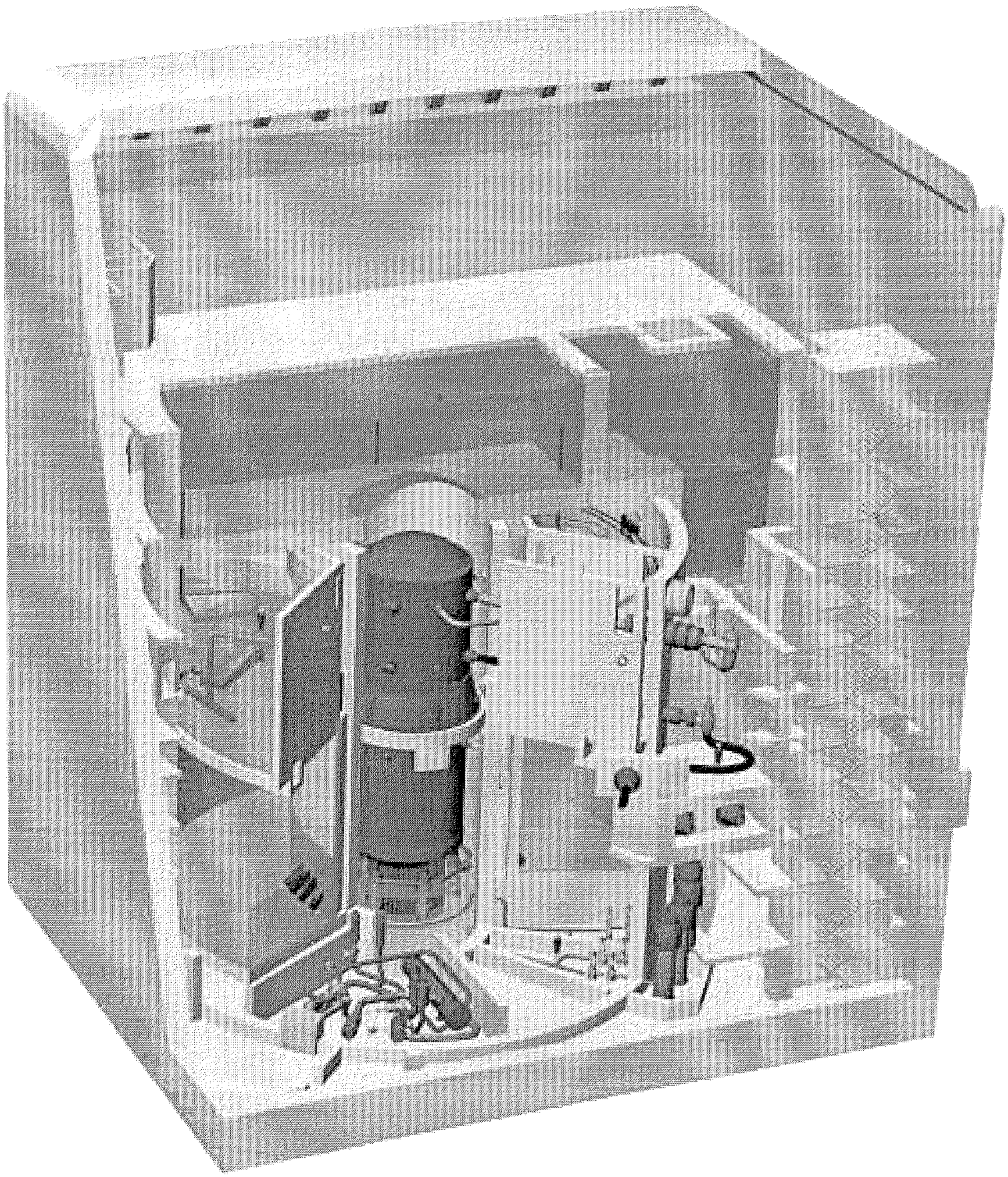

Fig. 3: Reactor building

Economics of the SWR 1000

The power generating costs of a nuclear power plant – like those of a fossil-fired power plant – comprise three basic cost components:

- Capital charges: These are the costs incurred annually for payment of interest and repayment of the capital invested to construct the plant. They only arise during the amortization period of the power plant.

- Operating costs: These comprise fixed operating costs such as the payroll for per-sonnel and insurance premiums, as well as variable costs such as costs for main-tenance and repair work and process waste disposal.

- Fuel cycle costs: These costs comprise costs for fuel procurement (uranium, enrichment and fuel assembly fabrication) as well as spent fuel management (storage and disposal). In the latter case a distinction must be made between direct disposal in a final repository and reprocessing accompanied by final storage of the vitrified fission products.

How do these cost components of a nuclear power plant compare to those of a fossil-fired plant?

A nuclear plant's power generating costs are dominated by the capital charges. The generating costs can roughly be broken down as follows, although variations will exist from one country to the next due, for example, to differences in spent fuel management costs as well as amortization conditions:

Capital charges	approx. 60%
Operating costs	approx. 20%
Fuel cycle costs	approx. 20%

The order is the reverse for fossil-fired power plants, especially combined-cycle plants. Here the dominant cost component – at over 60% – is the cost of the fuel whereas operating costs and capital charges are less significant.

The following conclusions can therefore be drawn.

In order to reduce that component of a nuclear plant's power generating costs which makes up the largest portion, namely the capital charges, one must reduce the overall capital cost of the plant – in other words, the amount of capital that initially has to be invested in order to build the plant. The best way to accomplish this is to simplify plant design and shorten the construction period (Fig. 4). Simplifications in system and com-ponent design also result in lower costs for maintenance and repair and conse-quently in fewer personnel being needed for such work.

Since the fuel cost compo-nent is only small, nuclear power generating costs are relatively unaffected by in-creases in fuel prices. For example, an increase of around 10% in the cost of nuclear fuel will only raise total power generating costs by around 1.5%. Although fossil-fired power plants – especially combined-cycle plants – are relatively cheap to build in comparison, their extremely high fuel costs are a considerable disadvantage if, for example, the price of gas should go up, the reason being that increases in gas prices will lead to an almost proportional increase in total power generating costs. A 10% increase in the price of gas, for instance, will result in a considerable increase in power generating costs: namely, around 7.5%.

	SWR 1000	Conventional BWR with 1000 MW
Emergency condenser	4	-
HPCI-system	-	3 x 100%
Spent fuel pool cooling system	Cooler inside fuel pool	3 x 100%
LPCI-system	2 x 100%	3 x 100%
Reactor water cleanup system		2 x 100%
MCP-sealwater system	2 x 100%	3 x 100%
CRD-purging system	combined system	2 x 100%
Turbine	3000 RPM	1500 RPM
Main steam lines	3	4
Feedwater lines	2	4
Feedwater heater train	single train	double train
Reactor building	109,000 m^3	145,000 m^3
Turbine hall	157,000 m^3	238,000 m^3
Auxiliary building	40,000 m^3	70,000 m^3
Switchgear building	20,000 m^3	65,000 m^3
Electrical- / I&C-system	double train (+ passive systems)	3 trains

Fig. 4: Table of system simplifications and interior building volumes

The SWR 1000 with its simplified safety concept combining active and passive systems as well as its simplified systems for normal plant operation excellently fulfills not only the high goals that have been set in terms of nuclear safety but also the economic goal of competitive power generating costs:

- The simplifications in system and component design enable capital cost to be reduced by 30% compared to existing light water reactor plants of the same capacity. This considerably reduces the size of the cost component that dominates the plant's power generating costs.

- Thanks to the simplifications in plant design, maintenance costs are also lower since there are fewer components to be inspected, maintained and repaired and this work can be performed by fewer personnel. The smaller number of fuel assemblies, resulting from use of a larger rod array in the form of the ATRIUM 12 design, together with a reduced maintenance effort enable refueling outages to be shorter, thus resulting in high plant availability. A study conducted by EDF as part of its collaboration on this development project predicted a long-term availability rating of 91.3% for the SWR 1000.

- Fuel cycle costs are reduced not only by the use of larger fuel assemblies and hence the smaller number of fuel assemblies in the core, but also by the design of the core for operation to high fuel discharge burnups of up to 65 GWd/tU.

Based on present market conditions, a comparison of the power generating costs with those of coal-fired plants and combined-cycle plants already reveals a consider-able cost advantage for the SWR 1000, an advantage that will become even larger as gas prices increase.

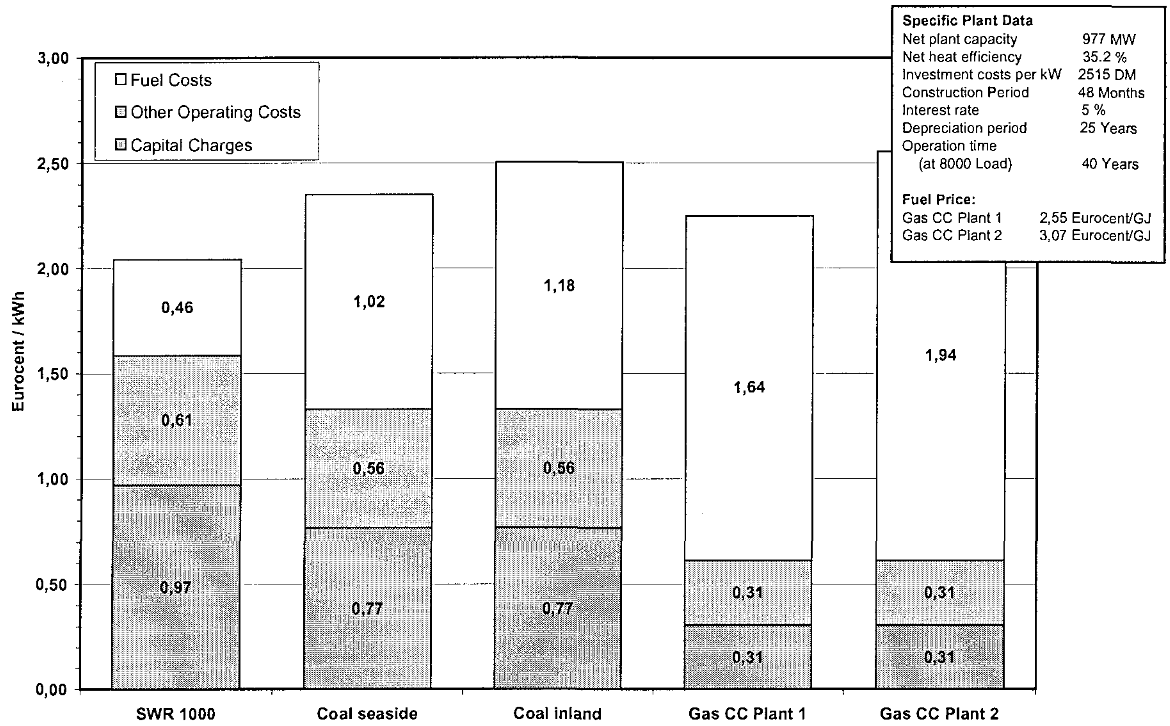

Fig. 5: Comparsion of power generating costs

Conclusion

The SWR 1000 is a design concept for a light water reactor nuclear power plant that meets all requirements regarding plant safety, economic efficiency and environmental friendliness.

- As a result of the plant's safety concept, the occurrence of core damage can, for all practical intents and purposes, be ruled out. If a core melt accident should nevertheless occur, the molten core can be retained inside the RPV, thus ensuring that all consequences of such an accident remain restricted to the plant itself.
- The power generating costs of the SWR 1000 are lower than with those of coal-fired and combined-cycle power plants.
- Power generation using nuclear energy does not release carbon dioxide to the environment, thus meeting the need for sustainable protection of our global climate.

References:

- The BWR 1000 - An Advanced Boiling Water Rector with Medium Power
  Dr. Brosche and J. Mattern
  VGB Power Tech 11/99

- SWR 1000 vor Angebotsreife
  W. Brettschuh und J. Meseth
  atw 45. Jg. (2000) Heft 6 - Juni