The 1250 MWe Boiling Water Reactor
Gundremmingen B+C, operating since 1984 and 1985
THE NEED TO SECURE LONG-TERM ENERGY SUPPLIES, STABILIZE ENERGY COSTS AND COMBAT GLOBAL WARMING, ARGUES IN FAVOR OF A WIDE AND DIVERSE ENERGY MIX. IN THIS CONTEXT, NUCLEAR POWER, WHICH IS PROVING INCREASINGLY COMPETITIVE, SAFE, RELIABLE AND ENVIRONMENTALLY FRIENDLY ELECTRICITY, HAS A VITAL ROLE TO PLAY.

All over the world, AREVA supplies its customers with solutions for carbon-free power generation. With its knowledge and expertise in these fields, the group has a leading role in meeting the world’s energy needs.

Ranked first in the global nuclear power industry, AREVA’s unique integrated offering covers every stage of the fuel cycle, reactor design and construction as well as related services. In addition, the group is expanding its operations in renewable energies, notably offshore wind, biomass and concentrated solar power.

The KERENATM reactor is AREVA’s Generation III+BWR (Boiling Water Reactor). It is designed to meet the needs of electrical utilities with a preference for boiling water reactor technology and for customers interested in the 1250 MWe power output range. It is based on the evolution of BWR technology in Germany, especially the Gundremmingen plants, and developed in close cooperation with reference utilities including E.ON, RWE, EnBW, Vattenfall (Germany), EdF (France), TVO (Finland), along with technical institutes – Technical Research Centre of Finland, Paul Scherrer Institute (Switzerland), Forschungszentrum Jülich (Germany) and Nuclear Research & Consultancy Group (Netherlands). The KERENATM reactor benefits from E.ON’s support for the completion of the basic design. E.ON holds shares in twelve BWRs across Europe and brings comprehensive, long-standing operating experience and technical expertise to the undertaking.

The KERENATM reactor offers competitiveness and flexibility in operation, together with an optimal redundant and diverse mix of BWR active and passive safety systems, while leveraging AREVA’s design, construction and licensing experience.
KERENA™: THE BOILING WATER REACTOR BY AREVA

THE KERENA™ REACTOR BLENDS YEARS OF EXPERIENCE IN DESIGN, CONSTRUCTION AND OPERATION OF BWRs WITH CAREFULLY CONSIDERED NEW CONCEPTS, TO ACHIEVE AN OPTIMUM BLEND OF INCREASED SAFETY AND REDUCED COSTS. IT HAS BEEN DEVELOPED WITH THE INPUT OF REFERENCE NUCLEAR OPERATORS TO PROVIDE A SAFE AND RELIABLE SOURCE OF ECONOMICALLY COMPETITIVE ELECTRICITY.

PROVEN DESIGN CONCEPT
The basic design concept of the KERENA™ reactor as well as the systems and components provided for plant operation are based on the extensive and comprehensive experience gained from AREVA’s operating boiling water reactors. Operating experience from existing BWR plants has been applied to simplify systems engineering for the KERENA™ reactor allowing to streamline the design:
- Simple passive safety systems
- Three main steam lines
- Two feedwater lines

BALANCED ACTIVE AND PASSIVE GEN III+ SAFETY
In addition to optimizing systems already present in current BWRs, the KERENA™ design is characterized by an innovative approach that entails active safety features combined with redundant and diverse passive safety. These utilize basic laws of nature, such as gravity and heat transfer, enabling passive systems to function without electrical power supply or actuation by instrumentation and control (I&C) or manually. The new concepts, for example, provide passive protection of the core without external intervention for up to three days after the onset of an event, while minimizing costs and system complexity.

COMPETITIVE POWER GENERATION COSTS
Total capital investment is reduced through simpler design compared to operating BWRs.
Operation and maintenance are optimized through:
- Maximized power output: 92% availability design target
- Excellent load follow capabilities
- Less maintenance due to fewer components, systems and structures
- Fewer operating personnel necessary on site

The Fuel Cycle costs are decreased through 37% efficiency design target, discharge burnups of up to 65 MWd/kgU, MOX ability of up to 50%, and the use of flow variation to improve fuel utilization (spectral shift).

INNOVATIVE FEATURES DEMONSTRATED BY FULL-SCALE TESTS
In parallel with the basic design phase, the function and effectiveness of KERENA™’s passive safety systems are experimentally verified. A comprehensive testing program, today already in a mature stage, is conducted at AREVA’s testing facilities and at partner research centers in Switzerland and Germany.
Isar 1, operating since 1979

KERENA™ full-scale test facility in Karlstein
PART OF A VALUE ADDED REACTOR PORTFOLIO

THE KERENA™ REACTOR COMBINES A UNIQUE SET OF BWR SPECIFIC CHARACTERISTICS WITH THE COMMON BENEFITS OF THE FULL AREVA REACTOR PORTFOLIO. AREVA’S RANGE IS DESIGNED TO MEET THE FULL BREADTH OF ITS CLIENTS’ NEEDS, FROM THE INTRODUCTION TO NUCLEAR POWER TO THE INDUSTRIAL PRODUCTION OF COMPETITIVE AND CLEAN ELECTRICITY.

AREVA offers a portfolio of three nuclear reactor models: EPR™, ATMEA1™ and KERENA™. These are latest generation (III+) pressurized and boiling water reactors, designed to enable electricity providers to achieve their competitiveness, safety and power generation capacity objectives.

PERFORMANCE & PROFITABILITY
- Maximized plant availability: design target above 92%
- High plant efficiency: design target 37%
- Low O&M costs
- Load follow mode & frequency control

CERTAINTY & PREDICTABILITY
- Maximized standardization for reliable project implementation
- Continuous engineering and manufacturing experience
- Extensive in-house manufacturing capabilities
- An expanding international supply chain
- Unique worldwide licensing experience, from Europe and the US to China

OUTSTANDING SAFETY
- Designed against the most stringent licensing requirements (Germany, France, Finland …)
- Large commercial airplane crash resistance
- Advanced severe accident management
- Safety systems with multiple redundancy and diversity to prevent any adverse impact to the environment

ENVIRONMENTAL PROTECTION
- CO₂-free power generation
- Reduced natural resources consumption
- Reduced collective dose
- Less final waste through high efficiency and recycling
### AREVA PRODUCT RANGE

<table>
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<th></th>
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<th>1100 MWe PWR</th>
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<td>Developed by</td>
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**Boiling Water Reactor (BWR)**: A type of nuclear reactor in which water is boiled to produce steam for a turbine.

**Pressurized Water Reactor (PWR)**: A type of nuclear reactor where water is under pressure to prevent it from boiling, thus increasing the energy output of the reactor.

**EPR (European Pressurized Reactor)**: A design of reactor developed by AREVA and other European partners, intended for the generation of electric power.
BOILING WATER REACTOR
TECHNICAL OVERVIEW

Feedwater steam cycle
1 Reactor pressure vessel with reactor core
2 Reactor water recirculation pumps
3 Turbine
4 Moisture separator/reheater

Cooling water circulation
5 Condenser
6 Main condensate pump
7 Feedwater preheater
8 Feedwater storage tank (optional)
9 Feedwater pump
10 Cooling tower (optional)
11 Circulation water pumps

Power generation
12 Generator
13 Generator transformer

Saturated steam

Main feed water
The plant is equipped with a boiling water reactor to generate steam at a thermal output of 3370 MWth. Saturated steam, at 7.5 MPa, is routed through the HP turbine and the moisture separator/reheater to the LP turbine. The net electrical output is approximately 1250 MWe. The steam leaving the low-pressure turbine sections is condensed in the main condensers. The condensate is returned to the reactor by condensate and feedwater pumps via the feedwater heating train.
# MAIN PLANT DATA

## OVERALL PLANT

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## SYSTEMS FOR...

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<td>Reactor shutdown</td>
<td>Hydraulic scram system, fine-motion control rod drives, fast-acting boron injection system</td>
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<tr>
<td>RPV pressure relief and depressurization</td>
<td>8 safety-relief valves, each with spring-loaded, diaphragm and solenoid pilot valves</td>
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<td>Core flooding</td>
<td>Active: 2 low-pressure RHR/coolant injection systems Passive: 4 flooding lines</td>
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<tr>
<td>Residual heat removal</td>
<td>Active: 2 low-pressure RHR/coolant injection systems Passive: 4 emergency condensers 4 containment cooling condensers</td>
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<td>Initiation of reactor scram, containment isolation and RPV depressurization</td>
<td>Active: reactor protection system Passive: passive pressure pulse transmitters</td>
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17 REACTOR AUXILIARY BUILDING
17 REACTOR SUPPORTING SYSTEMS BUILDING
17 TURBINE BUILDING

KERENA™ Containment Close-up
KERENA™
REACTOR LAYOUT

1 REACTOR BUILDING
The reactor building houses the containment, the safety-related mechanical components and the required support and protection systems. It provides protection against natural and man-made external hazards and ensures activity retention in the event of accidents.

The structural concept is divided into three parts, as follows
- Outer shell with penetration protection
- Inner structure, which is largely decoupled from the outer shell
- Containment, whose structures are decoupled from the outer shell except via the base plate.
The reactor supporting systems building contains the hot workshops and parts of the waste processing and storage system, as well as the central access point to the controlled area. This building houses components of the following systems:

- Intake and exhaust air system
- Sanitary facilities, changing rooms
- Laboratory
- Hot workshop and decontamination facilities
- Reserved space for mobile concentrate treatment with a drum store for low-active waste

The reactor auxiliary building contains systems and components for the treatment and storage of radioactive wastewater, including the evaporator system.

The selected arrangement of the liquid waste storage and processing system ensures short piping connections with the system and equipment areas in the turbine building and the reactor building.

The turbine building contains mainly the systems and components of the steam, condensate and feedwater cycle, with condensate and feedwater pumps and feedwater preheaters as well as the turbine and generator. The turbine building is part of the controlled area of the plant.
20 Reactor Pressure Vessel and Internals
22 Reactor Core and Fuel Assemblies
22 Reactor Water Recirculation Pumps
22 Control Rod Drives
23 Steam, Condensate and Feedwater Cycle
NUCLEAR STEAM SUPPLY SYSTEM

THE NUCLEAR STEAM SUPPLY SYSTEM IS LOCATED IN THE REACTOR BUILDING AND IS SURROUNDED BY A STEEL-REINFORCED CONCRETE CONTAINMENT EQUIPPED WITH A STEEL LINER.

REACTOR PRESSURE VESSEL AND INTERNALS

The reactor pressure vessel (RPV) encloses the reactor core and the RPV internals. The main dimensions of the RPV are comparable to those of a 1300 MWe BWR. As a result of this large volume, and due to the low positioning of the core inside the RPV, core uncovery does not occur in the event of automatic depressurization, even without coolant makeup. The core shroud as well as the upper and lower core grids mainly serve to align the core, the control rods, the in-core instrumentation and to guide core flow. Steam separators and steam dryers are installed in the RPV to separate the steam-water mixture leaving the core. A chimney is located between the core and the steam separators. All RPV internals are designed to allow removal and replacement as needed. The RPV is supported by a support skirt mounted around the top half of the RPV. The RPV internals, such as the core shroud, upper and lower core grid, steam separators and steam dryers, for example, are essentially based on the proven technology used in AREVA's 1300 MWe BWR design.
**REACTOR CORE AND FUEL ASSEMBLIES**

The KERENA™ core represents an evolutionary development of previous standard BWR core designs. While no fundamental changes have been made to the basic structure of the BWR core design, certain modifications have been introduced. These modifications include reducing the active height of the core and increasing the size of the fuel assemblies.

By reducing the active core height, the core can be positioned lower inside the RPV. As a result, there is a greater water inventory available inside the RPV above the core, which facilitates transient control.

The aforementioned modification of the fuel assemblies consists of enlarging the existing ATRIUM™10 fuel assembly design (10x10-9Q) to a ATRIUM™12 fuel assembly (12x12-16Q). Fuel rod diameter and pitch, on the other hand, remain unchanged from the ATRIUM™10 fuel assembly. As a result of this new design, there are fewer core fuel assemblies. This reduces handling times during refueling and also reduces the number of control rods and control rod drives.

Flexible operating cycles are planned for the KERENA™ plant. For example, the core can be operated in cycles lasting from 12 to 24 months. All of these core design attributes contribute to the economic efficiency of KERENA™ operation.

**REACTOR WATER RECIRCULATION PUMPS**

The reactor water recirculation pumps (RRP) provide flow of coolant through the core. Comparative studies of natural and forced coolant circulation in the RPV have shown that it is advantageous to retain the forced circulation flow. The forced circulation provides better fuel utilization and load cycling capability when compared to natural circulation designs. The KERENA™ design utilizes eight internal RRPs. The KERENA™ reactor water recirculation pumps are driven by wet rotor motors, thereby eliminating the need for mechanical seals. This design offers certain operational advantages, and has been proven in Swedish and Finnish BWR plants.

**CONTROL ROD DRIVES**

The KERENA™ retains the fine motion control rod drive design proven by operating experience at all existing AREVA BWR plants. The length of the control rod drives is adjusted to the reduced core height. The electric motor drive unit and the hydraulic drive unit are installed and removed from the control rod drive compartment below the RPV.
STEAM, CONDENSATE AND FEEDWATER CYCLE

Similar to the boiling water reactors in operation today, the KERENA™ operates according to the direct-cycle principle. The live steam generated in the RPV passes directly to the high-pressure (HP) section of the steam turbine via main steam lines fitted with combined stop and control valves. After undergoing partial expansion in the HP turbine section, the steam passes through a moisture separator/reheater to the low-pressure sections of the turbine. The condensate is removed from the condensers of the LP turbine sections and returned to the RPV via the feedwater heating system. This system consists of condensate pump, condensate cleanup system, LP feedwater heaters, feedwater pumps and HP feedwater heaters.

Steam, Condensate and Feedwater Cycle

1 Reactor
2 HP turbine section (2-flow)
3 Moisture separator
4 LP turbine section
5 Generator (1500 rpm)
6 Condenser
7 Main condensate pump
8 Condensate demineralizing system
9–12 LP feedwater preheaters
13–14 Auxiliary condensate pumps
15 Feedwater pump
16–17 HP feedwater heaters
18–19 Reheaters
20 LP condensate cooler
21 Reheater condensate cooler
CONTAINMENT AND INTERNALS
Boiling Water Reactor Opening of the Reactor Head
A cylindrical containment made from steel-reinforced concrete equipped with an inner steel liner and pressure suppression system was selected for the KERENATM reactor design. The containment is divided into a drywell and a pressure suppression chamber, as required by the pressure suppression system.

The containment design also takes into account the hydrogen release from a postulated 100% oxidation of the zirconium present in the RPV in the event of a core melt accident.

**DRYWELL**
In addition to the RPV, the three main steam lines and two feedwater lines, the drywell contains:
- four large hydraulically-linked core flooding pools
- the emergency condensers and containment cooling condensers for passive heat removal
- the flooding lines for passive flooding of the core inside the RPV
- the passive pressure pulse transmitters for initiation of safety functions
- the drywell flooding line for flooding of the RPV exterior in case of a core damage

Moreover, the drywell is equipped with two 100%-capacity recirculation air cooling systems. The high-pressure part of the reactor water cleanup system (HP cooler and pressure-reducing station) and the lines of the residual heat removal system are also located inside the drywell.

**CORE FLOODING POOLS**
The four core flooding pools act as a heat sink for the emergency condensers and the safety relief valve system. The water in the core flooding pools is used for passive flooding of the reactor core following RPV depressurization in the event of a LOCA. In this function, spring check valves automatically open the flooding lines. In the unlikely event of a serious core melt accident, the water inventory in the core flooding pools is used for cooling the RPV from the outside.

The core flooding pools are located above the pressure suppression chamber, and are approximately two-thirds filled with water. The physical separation of the core flooding pools is achieved via four containment compartments in which components, piping and ventilation units are located. Each core flooding pool houses an emergency condenser, a containment cooling condenser (above the water level), a RPV flooding line connection, and the relief lines of the safety relief valves with steam quenchers. In addition, a flooding line for external RPV cooling leads from one of the core flooding pools into the bottom part of the drywell.

**PRESSURE SUPPRESSION CHAMBER**
The pressure suppression chamber acts as a heat sink in the event of accident conditions and provides a water inventory for RPV makeup via the residual heat removal system.

As part of the pressure suppression system, the pressure suppression chamber is located between the outer and inner cylinder below the core flooding pools and is one-third filled with water. The pressure suppression chamber is connected to the drywell via vent pipes embedded into the concrete of the inner cylinder. In addition, the pressure suppression chamber and core flooding pools are connected to each other via submerged water overflow and hydrogen overflow pipes. The pressure-equalizing dampers (check valves) in existing BWR plants between the drywell and the air space of the pressure suppression chamber are eliminated.

**CONTAINMENT AND INTERNALS**

The primary function of the containment is to protect against release of radioactive materials under all accident conditions.
The main steam lines and feedwater lines connected to the RPV are each equipped with two containment isolation valves, one located inside and one outside of containment penetrations. Apart from the main steam and feedwater lines, there is no high-energy piping conveying reactor medium (with the exception of instrumentation lines) exiting the containment, the isolation valves of which remain open during operation.

The containment inertization during power operation ensures fire prevention and prevents hydrogen-oxygen reactions in case of a severe core damage accident.
KERENA™
SAFETY
CONCEPT
30 PASSIVE SYSTEMS FEATURES
32 REACTOR SHUTDOWN SYSTEMS
32 CONTAINMENT ISOLATION OF MAIN STEAM LINES
33 RESIDUAL HEAT REMOVAL (RHR) AND LOW PRESSURE COOLANT INJECTION (LPCI) SYSTEM
34 EMERGENCY CONDENSERS
35 PASSIVE CORE FLOODING SYSTEM
36 PASSIVE PRESSURE PULSE TRANSMITTER (PPPT)
37 PASSIVE OUTFLOW REDUCER
39 CONTAINMENT COOLING CONDENSERS (CCC)
39 SAFETY RELIEF VALVE SYSTEM
40 SEVERE ACCIDENT MITIGATION
Redundancy and diversity of the KERENA™ reactor is ensured by two active and four passive qualified safety systems. The reactor is designed such that, with preponderance, the active safety systems are used for reactor protection before the passive systems commence operation. Furthermore, the design allows for active and passive transient control to be achieved without any unallowable interactions between the two systems, thus not requiring any direct prioritization or reciprocal activation and deactivation of the active and passive systems. The active and passive safety features complement and reinforce each other, resulting in a simplified system design with excellent reliability.

The following safety functions must be assured for most transients as well as in the event of accidents:
- Reactor scram
- Containment isolation
- RPV pressure relief and depressurization
- Heat removal from the RPV
- Control of reactor coolant inventory (RPV water level)
- Heat removal from the containment

Furthermore, increasing the reliability of the plant, the passive safety equipment is capable of controlling any postulated transient conditions arising during power operation assuming all active control fails.

PASSIVE SYSTEMS FEATURES

Passive systems are characterized by the fact that they utilize the laws of nature (e.g., gravity, pressure differentials, temperature differentials) to perform their designated safety functions with no need for active components (e.g., motor-driven valves and pumps).

Events requiring system function (reactor shutdown, maintaining reactor coolant inventory in the RPV and residual heat removal) are anomalies in plant operation, so-called transients. In the event of a loss-of-coolant accident (LOCA), actions to inject water into the RPV are necessary to prevent core uncovering. In both types of events, the residual heat is removed from the containment to the shielding/storage pool located outside the containment via the containment cooling condensers.

One of the newly developed key features of the KERENA™ reactor lies in its ability to store residual heat inside the containment over a longer period.

**AS A RESULT, IN CASE OF FAILURE OF ACTIVE SYSTEMS, IT WOULD NOT BE NECESSARY FOR OPERATORS TO INITIATE ANY ACTIONS UNTIL SEVERAL DAYS AFTER THE ONSET OF ACCIDENT CONDITIONS.**
KERENATM Passive Safety Features

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REACTOR SHUTDOWN SYSTEMS

Diverse systems are available for shutdown of the reactor:

- the control rods, with their diverse drive systems
  (electric motor drive for operational shutdown processes, and hydraulic drive for reactor scram)
- fast acting boron injection system, which causes reactor shutdown independently of the control rods and is completely independent of control rod operations

The scram system is based largely on the multiple accumulator tank concept implemented in German BWR plants, whereby the energy required for fast control rod insertion by hydraulic means is stored in tanks under nitrogen pressure. Instead of nitrogen, KERENA™ uses steam, much like a PWR pressurizer, to provide the required driving head and to eliminate the use of nitrogen for pressurization. With this modification any risk of nitrogen entering the RPV in case of a malfunction of a tank closure valve is eliminated. The water-filled tanks’ steam pressure blanket is generated by electric heaters in the upper area of each tank. This modification enables the reduction of the tank size.

The boron injection system is also based on the pressure tank concept: The quantity of natrium-pentaborat solution required for subcriticality is stored in a nitrogen pressurized tank and injected into the RPV via 6 injection lines which are connected to a manifold.

CONTAINMENT ISOLATION OF MAIN STEAM LINES

The main steam lines are equipped with isolation valves positioned inside and outside the containment at the containment penetrations. The system-fluid-actuated valves are of diverse design; both valves are quick-closing gate-valves, one operating according to the pressurization principle and the other operating according to the pressure relief principle. Containment isolation is initiated, as in existing BWR plants, via safety I&C systems. In addition to the normal active isolation initiation, passive initiation is provided for the KERENA™ via parallel diaphragm pilot valves that are actuated by Passive Pressure Pulse Transmitters (PPPTs).
Residual Heat Removal (RHR) and Low Pressure Coolant Injection (LPCI) System

The KERENA™ concept includes an active low-pressure coolant injection and residual heat removal system with two redundant trains, which are comparable to the systems in existing BWR plants in terms of their range of tasks.

The system performs the following tasks:

- Reactor cooling during shutdown conditions
- Water transfer operations prior and subsequent to refueling
- Operational heat removal from the core flooding pool and pressure suppression pool water
- Heat removal from the containment in the event of loss of the main heat sink by cooling the pressure suppression pool and core flooding pool water
- Low-pressure feed of coolant to the RPV and simultaneous heat removal in the event of a loss-of-coolant accident

The systems are actuated via safety I&C and system-associated electrical loads and connected to the emergency power supply system.

High-pressure injection systems for the RPV are no longer required in the KERENA™ design due to introduction of the emergency condensers.

As in existing BWR plants, the RHR system is cooled by a closed cooling water system, which is cooled in turn by a secured service water system. The difference with respect to existing BWR plants lies in the fact that each closed cooling water system is divided into two system areas, which are cooled by a common closed cooling water heat exchanger.
EMERGENCY CONDENSERS

The emergency condensers serve to remove heat from the reactor upon a drop in RPV water level. The tubes of the emergency condensers are submerged in the core flooding pools and are filled with water when the water level in the RPV is normal. If reactor water level should drop, the water drains from the tubes. Steam from the reactor then enters the tubes and condenses, the resulting condensate flowing by gravity down back into the RPV. The emergency condensers come into action automatically without any need for electric power or switching operations.

The emergency condenser system consists of four separate subsystems. Each emergency condenser subsystem consists of a steam line leading from a nozzle in the steam space of the RPV (top connection) to the emergency condenser, the condenser itself and a condensate return line back to the RPV (lower connection). Each return line is equipped with an anti-circulation loop. The emergency condensers are connected to the RPV without any isolating elements and are actuated according to the natural law of communicating tubes.
PASSIVE CORE FLOODING SYSTEM

When reactor pressure has been sufficiently reduced by depressurization, water from the core flooding pools flows by gravity down into the RPV through flooding lines. The system consists of four flooding lines each equipped with a self-actuating check valve. The flooding lines are connected to the RPV via the return lines of the emergency condensers.
As a new device, the functional capability of the PPPT was tested in the emergency condenser test facility at Germany's Jülich Research Center. The actuation pressure of 6 bar (gauge) was reached in < 10 seconds.

Passive Pressure Pulse Transmitter

Passive pressure pulse transmitters are small heat exchangers that operate according to the same principle as the emergency condensers. Upon a drop in reactor water level, steam enters the top connective line and when it reaches the PPPT, pressure builds up on its secondary side. This pressure is then used to initiate safety-related switching operations, depending on the water level in the RPV (for reactor scram, automatic depressurization and containment isolation at the main steam lines), without any need for electric power or manual or I&C signals. Passive pressure pulse transmitters (PPPTs) are installed in the KERENA™ for safety-classified initiation operations. These devices function entirely independently, and are therefore a diverse basis to the I&C equipment. Their integration into the plant's systems engineering is (configuration: two 2-out-of-2) such that spurious actuation of a single PPPT does not lead to initiation of actions, but also such that loss of one PPPT cannot prevent initiation.
PASSIVE OUTFLOW REDUCER

The task of the passive outflow reducer is to significantly reduce the discharge mass flow from the RPV in the event of a break in the emergency condenser return line. The passive outflow reducer is a component with no moving parts, which has a low flow resistance in the normal direction of operational flow. However, flow resistance increases by approximately two orders of magnitude when the direction of flow is reversed. This increase of resistance is achieved by the reduction of the inflow cross section causing flashing of the fluid and by the swirling effect resulting in a velocity component in circumferential direction.

With the KERENA™ passive outflow reducer the discharged outflow is low enough to ensure that the emergency core cooling (ECC) avoids fuel heat up.

THIS NEW DEVICE HAS BEEN TESTED AT AREVA’S LARGE VALVE TEST FACILITY IN KARLSTEIN, GERMANY.
CONTAINMENT COOLING CONDENSERS (CCC)

If the containment temperature should rise due to a release of steam into the drywell atmosphere, the containment cooling condensers remove heat from the containment to the water of the shielding/storage pool located above it. These components require neither electric power nor switching operations to begin functioning. The system consists of four heat exchangers. Each heat exchanger consists of tubes at a slight angle to horizontal. The condensers are connected to the shielding/storage pool via an inlet to the lower end and a discharge line at the higher end. The feed line and discharge line as well as the condenser tubes are filled with water from the shielding/storage pool. All connecting lines to the shielding/storage pool are open during plant operation. Since the system functions entirely passively as a function of the thermal gradients, no actuation is necessary for startup.

SAFETY RELIEF VALVE SYSTEM

The safety relief valve system serves the following purposes:

- Protection of the reactor coolant pressure boundary against pressure in excess of allowable limits (pressure relief)
- Automatic depressurization of the RPV in the event that the RPV level falls below specified values or in the event of a pressure rise in the containment (LOCA in the containment)
- Depressurization for severe accident mitigation to prevent high pressure melt ejection

The safety relief valves are of a diverse design: Four operate according to the pressurization principle, four according to the pressure relief principle, thus excluding a loss of all safety relief valves due to a common mode failure. The safety relief valve system is located inside the containment and consists of the safety relief valves and relief lines with steam quenchers, which are installed in the core flooding pools. This system follows proven system concepts used in the existing AREVA BWR plants.
SEVERE ACCIDENT MITIGATION

With a $8.0 \times 10^{-8}$ core damage frequency, KERENATM design provides an extremely low likelihood of a severe accident with core melt, two orders of magnitude lower than today’s IAEA requirements. Despite the very improbable nature of this event, design features of KERENATM are, however, provided for controlling such an event and reducing its consequences to the plant itself.

DESIGN CHOICES FOR LIMITING THE CONSEQUENCES OF A SEVERE ACCIDENT

Loss of all active and passive injection functions is assumed for the postulated severe core melt accident. To control this severe accident scenario, the following additional mitigation systems are planned for the KERENATM design:

Core melt at high pressure is ruled out by the design of the depressurization system. The core melt is retained in the RPV at low pressure by cooling the RPV exterior. A flooding system is installed for this purpose, it feeds water into the lower area of the drywell from the core flooding pools. The flooding system is permanently isolated and activated upon challenge.

The steam arising from cooling of the RPV from the outside is condensed at the CCCs that transfer the heat from the containment to the water of the shielding/storage pool. Refilling of the shielding/storage pool, which only becomes necessary several days after the onset of accident conditions, enables long term heat removal. The containment design considers the pressure buildup due to the hydrogen arising from a zirconium-water reaction of 100% of the zirconium inventory present in the core. Hydrogen release always occurs via the drywell, and hydrogen is also partly flushed into the pressure suppression chamber depending on the given pressure conditions. Any further pressure buildup due to detonation or deflagration of the hydrogen is not possible.

Long-term pressure relief in the containment after the onset of accident conditions is effected via the gaseous waste processing system already installed in all current BWR plants, with catalytic hydrogen recombination. All containment gases as well as the liquids formed during hydrogen recombination are returned to the containment.
ELECTRICAL SYSTEMS

Diverse and Redundant Power Supply

Normal power supply

Emergency diesel generator

Emergency power supply

I&C power supply
The generator feeds into the public grid via a generator circuit breaker, the generator transformer and the main grid connection. The power required for the auxiliary power system is tapped off between the generator breaker and the grid breaker and fed to the auxiliary power supply system via two three-winding auxiliary normal transformers with on-load tap changers.

In case of simultaneous loss of main offsite power system connection and main generator availability, an independent standby grid connection, consisting of an auxiliary standby power transformer and a standby offsite power system connection, can be used to supply the auxiliary power for plant shutdown and heat removal.

The passive safety systems are capable of controlling all postulated accidents during power operation. This enables active backup power systems to be sufficient as two 100%-capacity trains. As a result, electric power supply to the plant itself (both the auxiliary and emergency power supply grids) are designed on a two-train basis.

The emergency power supply grid supplies all electrical loads that have to remain in operation or come on-line in the event of loss of the auxiliary power supply grid. In the event of loss of the auxiliary power supply grid, an emergency diesel generator takes over independent power supply of all connected electrical loads. Electrical loads for which a period without power is allowable during run-up of the emergency diesel generator are connected to the distributors of the emergency power supply grid.

Electrical loads which must remain in operation on an uninterruptible basis or have to be connected immediately in the event of loss of the auxiliary power supply grid are connected to the uninterruptible power supply. These loads are supplied with power either directly by the DC system or via the downstream inverter and the distributor connected to it, or supplied directly via local uninterruptible power supply systems. The uninterrupted DC/AC power supply system is divided into four functional independent trains, the I&C power supply being ensured through the four trains of the DC system. This four train concept is in accordance with the design of the I&C safety systems.
**INSTRUMENTATION AND CONTROL**

The KERENA™ boiling water reactor is based on an optimal combination of passive and active safety systems. Its Instrumentation and Control (I&C) System, in addition to facilitating the operation of the plant, provides safety-qualified full redundancy to the passive safety system.

**SIMPLIFIED I&C CONCEPT**

Due to safety improvements in the KERENA™ design, achieved by the introduction of passive systems to perform safety functions in the event of transients and accidents, the I&C concept has been considerably simplified in comparison with current BWR plants, as the passive safety systems operate independently of electrical power supply and without actuation by I&C systems.

The digital I&C concept for KERENA™ is made up of three basic subsystems – operational, safety and screen based Man-Machine Interface.

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**OPERATIONAL I&C**

The operational I&C encompasses all systems and components required for plant process control in normal operating conditions (power operation, shutdown, refueling, etc.), such as:

- The Process Automation System including sensors, automatic controls and component protection functions in Function Units (FU)
- The Process Information and Control System including the man-machine interface in the Main Control Room (MCR) and the Emergency Control Room (ECR) with help of Communication Processor Units (CPUs)
- Plant Bus and Terminal Bus systems
- Diagnostic and Engineering System
SAFETY I&C: REDUNDANCY AND DIVERSITY

The safety I&C system is subdivided into a number of redundantly configured subsystems, the most important being the Reactor Protection System (RPS). Its task is to process and monitor key process variables important to reactor safety and environmental protection. This system detects transient and accident conditions and automatically initiates countermeasures in addition to the passive features, maintaining reactor condition within safe limits. The safety I&C does not actuate during normal operation, but takes priority over all operational I&C system actions when required.

The monitored process variables are acquired in a multiply redundant manner. Further processing of measuring signals, limit value formation and logic gating, generation of actuation signals and majority voting of trip signals are all performed within the digital system, which provides excellent accuracy and performance. The trip signals actuate the process components via electrical systems switch-gear.

The RPS is designed to withstand the postulated failure situation of “single failure plus maintenance”. However, even if in accident situations it should fail completely, the passive safety equipment is able to bring the reactor to a safe condition as an independent and diverse back-up control system.

MAN-MACHINE INTERFACE

The screen-based Process Information and Control System is the overall information source with a plant overview panel on large screens and multiple screen-based workplaces. Intelligent information processing and compression enables this system to display all process conditions and process sequences with high information content for safety and operational tasks. Comprehensive archiving functions for offline analysis of plant events and interface capability for intelligent diagnostic and maintenance systems is also provided.

The Process Information and Control System is complemented by an independent Safety Information and Control System ("Safety Panel" and “Post Accident Monitoring System”) that provides manual control capability and screen based accident monitoring. This system is driven by the safety I&C system and is diverse to the operational man-machine interface.

LEVERAGING THE BENEFITS OF DIGITAL I&C

Both the operational and the safety I&C system provide all benefits of digital I&C:

- High reliability and failure detection capability due to online self-monitoring and self-test features
- Reduced number of hardware module types and thus reduced spare parts scope
- Easy maintenance with implemented diagnostic systems providing detailed failure indication and comprehensive diagnostic functions
- Implemented engineering systems enabling the plant staff to perform application software modifications, if necessary.
- Low maintenance effort due to immediate failure detection, low failure rates and short repair time, which is proven by operation experience in many applications

Low maintenance effort for periodic surveillance testing is achieved, especially for the safety I&C. Since comprehensive and immediate failure detection is provided, the periodic test intervals can be extended to plant refueling intervals without reducing the system reliability from the safety viewpoint.
PLANT OPERATION, MAINTENANCE AND SERVICES
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PLANT OPERATION, MAINTENANCE AND SERVICES

STREAMLINED DESIGN SOLUTIONS WILL ENABLE THE KERENATM REACTOR TO OFFER A HIGHER OPERATIONAL PERFORMANCE THAN THE EXISTING BWR FLEET WHILE ACHIEVING A SAFETY LEVEL THAT MEETS AND EXCEEDS THE MOST STRINGENT REQUIREMENTS.

DESIGNED WITH AND FOR THE OPERATOR

Operational performance highlights
- Maximized power output: 92% availability design target
- Excellent load follow capabilities
- Less maintenance due to fewer components, systems and structures
- Fewer operating personnel necessary on site
- Decreased Fuel Cycle costs through 37% efficiency design target, discharge burn-ups of up to 65 GWh/tU, MOX ability of up to 50%, and the use of flow variation to improve fuel utilization (spectral shift).

EXCELLENT AVAILABILITY DESIGN TARGET

The KERENATM reactor is designed for an availability exceeding 92%. This is enabled by component and system design based on AREVA’s extensive engineering experience and on significant operational feedback from the current BWR fleet. The reactor pressure vessel is designed with the aim of reducing outages, and maintenance and repair time. Features with a positive impact on availability include a permanently installed RPV-drywell seal, in-service inspection of RPV from outside so that no extended in-service inspection outage is necessary. Moreover, the introduction of larger fuel assemblies results in fewer fuel assemblies, control rods and control rod drives, reducing handling time, while replacement of incore detectors is carried out from below and hence does not affect the critical outage path. Outage durations can therefore be significantly reduced, making it possible for the operator to achieve typical refueling-only outage times of as low as 11 days.

TYPICAL OUTAGE DURATIONS: THE KERENATM REACTOR IS DESIGNED TO HELP OPERATORS TO ACHIEVE OPTIMAL OUTAGE DURATIONS. A TYPICAL OUTAGE FOR PREVENTIVE MAINTENANCE AND REFUELING MAY BE REDUCED TO AS LITTLE AS 16 DAYS, WHILE A REFUELING-ONLY OUTAGE IS ESTIMATED AT 11 DAYS. FURTHERMORE, DECEN-NIAL OUTAGES WILL BE IN LINE WITH CURRENT INDUSTRY STANDARDS.
ATRIUM™ 12 FUEL

By enlarging the existing ATRIUM™ 10 fuel assembly to an ATRIUM™ 12 design, while still maintaining the fuel rod diameter and pitch, fewer core fuel assemblies are required, reducing handling times during refueling and the number of control rods and control rod drives.

Furthermore, by having more water inventory inside the RPV above the core, transient control is improved and as such, reactor trips are rarer, helping to achieve both better safety and availability. To this end, the active core height is reduced by design, allowing the core to be positioned lower inside the RPV.

This optimized fuel assembly concept, combined with high operating performance and efficiency rate allows KERENA™ to be more competitive by consuming less uranium than existing BWRs.
LOAD FOLLOW CAPABILITIES: DESIGNED FOR FLEXIBILITY

Designed for high operational flexibility, the KERENA™ reactor will contribute to fleet optimization and grid stability management, especially for the integration of renewable capacity. Its load follow mode performance is enabled due to the following design features:

- Recirculation pumps: variation of the water flow enables rapid power changes
- Control rod movement: further reduction in power outside the usual range for load follow
- In-core detectors: continuous online monitoring of local power density for low response times

The typical range of power variation is between 70% and 100% of rated power. Load changes are accomplished by changing the speed of recirculation pumps, which can be performed within minutes over the full range. As such, the normalized power distribution in the core largely remains nearly constant. For load variations at levels below 70% of rated power, the rod control processor performs control rod movements in predefined groups.

Under normal operation conditions, the power level can vary by 5% per minute. However, when necessary, the KERENA™ reactor can vary power at the much higher rate of 0.5%/s, which provides the operator significantly increased flexibility, particularly useful in the event of sudden variations of power output on the grid, such as large wind farms going offline.

LOAD FOLLOW MODE

<table>
<thead>
<tr>
<th>Under normal operation mode</th>
<th>Exceptionally possible</th>
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<tbody>
<tr>
<td>100%</td>
<td>100 – 70% at 0.5%/sec</td>
</tr>
<tr>
<td>70%</td>
<td>70 – 40% at almost 0.5%/sec but including partly inserted control rods</td>
</tr>
<tr>
<td>40%</td>
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MAINTENANCE AND RADIOLOGICAL PROTECTION

The ease of maintenance and repair of a nuclear power plant has a significant impact on availability and occupational safety, while also influencing the radiation protection of personnel. The KERENA™ reactor is therefore designed in order to minimize the necessity of maintenance and repair, while also reducing the time and personnel involved in maintenance and repair work.

To this end, the number of components inside the plant is reduced, primarily by means of systems engineering simplification due to the introduction of passive safety features.

First Offshore AREVA Multibrid M5000 Installed in the North Sea, 2009
BWR FORUM

The European BWR Forum brings together European BWR Utilities in order to facilitate exchanges on plant operating experience. Pooling the experience of each member with that of AREVA NP is an invaluable asset for improving plant safety, reducing environmental impact, increasing plant reliability, and conducting joint R&D programs.

The Forum is comprised of members from a combined power-generating capacity of around 18,000 MW, produced by 19 BWR units at 13 sites in Finland, Germany, Spain, Sweden and Switzerland. The Forum is unique in bringing together operational experience from three different BWR vendors, AREVA NP being one of them.

AREVA’s role in the Forum is primarily that of a coordinator, organizing meetings and performing engineering work at the request of the Forum or its project groups. In this role, AREVA NP also contributes its vast experience in the field of BWR design and services, as for example by organizing and presenting papers and expert meetings.
ENVIRONMENTAL IMPACT
ENVIRONMENTAL IMPACT

TO FULLY CAPITALIZE ON THE ENVIRONMENTAL AND ECONOMIC BENEFITS OF A NUCLEAR POWER PLANT, ITS IMPACT ON THE ENVIRONMENT MUST BE MINIMIZED. COMPLEMENTARY ACTIONS BY THE REACTOR VENDOR, OPERATOR, SAFETY AUTHORITIES AND VARIOUS OTHER ORGANIZATIONS ARE NECESSARY TO ACHIEVE THIS GOAL. AS VENDOR, AREVA IS COMMITTED TO MINIMIZING THE ENVIRONMENTAL FOOTPRINT OF ANY NUCLEAR PLANT AT EVERY STAGE IT INFLUENCES IN THE PLANT’S LIFE CYCLE.

DESIGN
The KERENA™ reactor, with its optimal balance of Boiling Water Reactor active and passive safety systems, is designed to significantly reduce the probability of incidents and accidents, and to reduce their consequences to the plant itself, without impact on the environment at large.

In addition to its superior safety standard, the plant’s improved thermodynamic efficiency ensures effective use of the plant and minimized use of cooling water. Optimized processes also reduce quantities of radioactive and chemical waste by using the most effective demonstrated methods, at the most competitive costs.

CONSTRUCTION
The KERENA™ reactor is designed to use less raw material and to reduce overall environmental impact by employing fewer components and a smaller building volume compared with current nuclear power plants. This improvement is made possible through streamlined safety and operational systems.

During the construction phase, activities such as clearance of the site, excavation, drilling, concrete production and start-up tests have a potential impact on the environment. Therefore, together with stakeholders, AREVA is committed to monitoring the marine and terrestrial environments, freshwater, air, climate, landscape and noise level to minimize possible consequences.

Okiluoto Construction Site
OPERATION

The evolutionary KERENA™ design makes it possible to benefit from experience gained from many years of operation of earlier generation reactors, so that whenever possible, gaseous and liquid releases and waste are reduced and, when this is not possible, the extent and impact of such releases can be accurately predicted and appropriate measures can be planned and implemented.

DECOMMISSIONING

Similar to the construction phase, decommissioning and its respective impact on the environment are reduced by the streamlined nature of the plant, with fewer components and a smaller building volume to be retired and dismantled.

On the basis of experience feedback from dismantling operations performed in various countries on first-generation nuclear power plants, the KERENA™ design includes various features that:

- Minimize the volume of radioactive structures
- Reduce the potential hazard of the waste, for instance with the material choice minimizing hazardous substances
- Lower the irradiation level of components submitted to fuel radiation
- Restrict the spread of contamination and favor systems decontamination, for example with the implementation of radiological zoning
- Facilitate the access of personnel and machines and the evacuation of waste, for instance with the implementation of suitable areas and openings
- Ensure the gathering of building and operating data needed to prepare dismantling correctly

**These features make the dismantling of the reactor the equivalent of IAEA level 3 (return of site to common industrial use), limit the radiation doses of the corresponding operations, and limit the quantity and activity of the nuclear waste produced.**
TREATMENT OF RADIOACTIVE WASTE
An important design objective of the KERENA™ reactor was to ensure reduced volumes of liquid waste and concentrates, achieved, for example, through the choice of materials for piping and components.

SOLID WASTE
Reduction in the volume of solid radioactive waste to lessen the unit's impact on the environment was one of the objectives adopted at the design stage.

For optimal treatment, solid radioactive waste is collected separately in groups according to selected criteria based on further treatment, handling, interim storage and final disposal requirements. Depending on the waste type, different equipment is available for waste treatment to prepare it for interim or final storage, such as the supercompactor, universally applicable equipment for treating combustible and compressible waste.

Used fuel is removed for either reprocessing or storage, and residual waste created is packaged to ensure that radioactive matter is confined for example in glass.

LIQUID WASTE STORAGE AND PROCESSING
Radioactive liquid waste (wastewater) is divided into different categories and collected in separate receiving tanks according to the level of activity, chemical constituents and origin. After separation, it is treated by the most appropriate process: filter systems, evaporator unit or a centrifuge unit.

TREATMENT OF RADIOACTIVE CONCENTRATES
Radioactive concentrates arising are divided into different categories, and are separately collected and held in interim storage tanks according to the level of activity, chemical constituents and origin. The concentrates are treated by the most appropriate processes, such as filters or in-drum drying and may then be stored on site temporarily, before being transferred to long-term storage facilities.

GASEOUS WASTE PROCESSING
The gaseous waste processing system further limits the potential impact of the plant on the environment by reducing the radioactivity in the off-gas significantly below environmental standards.

The gaseous waste processing system consists of the steam jet air ejectors, the recombiner units, and the charcoal delay absorbers including a drying unit. The excellent operating experience of these gas waste treatment system technologies, which have been used in many previous BWR plants, leads to a very high system efficiency and availability.

RECYCLING = 5 TIMES LESS FINAL WASTE WITH NO FISSILE MATERIAL
- No build-up of used fuel
- Recycling of fissile materials: performed mostly in La Hague, an installation under IAEA safeguards with a 50-year operating track record and reprocessing capacity of 1700 metric tons (MT) of used fuel per year, which is equal to all of the used fuel discharged in one year by 90–100 light water reactors
- Final wastes in standard canisters containing no fissile material, free of IAEA safeguards
- Final waste radio-toxicity divided by 10, compared to direct disposal
The impact of liquid and gaseous radioactive waste discharges on public health cannot be measured directly. Radionuclides introduced into the environment by the operation of a nuclear unit cannot be discerned by practical means. Thus, the impact on public health must be assessed theoretically by estimating the effective dose received by a hypothetical group of people, known as the reference group.

This group is considered as the group that would be subject to the maximum effects of the gaseous and liquid waste if members remained permanently in residence and consumed only local produce, and seafood fished at the waste outlets.

For the maximum gaseous and liquid radioactive waste emissions from the entire site, calculating the impact on health, for each inhabitant in the reference group, produces an annual effective dose amounting to a few tens of microsieverts.

In reality, the nuclear units have a lower activity discharge than the maximum activity defined by this theoretical method. Considering the radioactive waste produced by actual units, the impact on public health, for each member (whether adult or infant) of the reference group, produces an annual effective dose which is four to five times lower than the maximum allowed values.
STREAMLINED DESIGN

1. Reactor Building Crane
2. Fuel Pool
3. Reactor Pressure Vessel
4. Main Steam Line
5. Feedwater Line
6. Scram Tanks
7. Shielding/Storage Pool
8. Containment Cooling Condenser
9. Emergency Condenser
10. Flooding Pool
11. Quencher of a Safety Relief Valve
12. Vent Pipes
13. Pressure Suppression Chamber
14. Control Rod Drive Compartment
15. Steam Dryer
16. Steam Separator
17. Mixture Chimney
18. Core
AREVA supplies solutions for carbon-free power generation. Its expertise and know-how in this field are setting the standard, and its responsible development is anchored in a process of continuous improvement.

As the global nuclear industry leader, AREVA’s unique integrated offer to utilities covers every stage of the fuel cycle, nuclear reactor design and construction, and related services. The group is also expanding considerably in renewable energies – wind, solar, bioenergies, hydrogen and storage – to be one of the top three in this sector worldwide in 2012.

Every day, AREVA’s 48,000 employees cultivate the synergies between these two major carbon-free offers, helping to supply safer, cleaner and more economical energy to the greatest number of people.

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