Advanced light-water reactor development in the United States

A number of design concepts are being pursued

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In 1983 the Electric Power Research Institute (EPRI) launched an aggressive programme to develop the next generation light-water reactor (LWR) for deployment on US utility grids.* The programme was undertaken at the behest of the utility advisory structure of EPRI which had become concerned that if a development programme were not undertaken the utility industry might not have an improved and viable advanced LWR design for deployment in the late 1990s to meet anticipated utility load growth. The foundation of this programme was based on two major factors:

- The development of a strong utility steering committee to guide the efforts of the programme and ensure that the utility experience gained from operating the country's 110 commercial nuclear power plants was effectively fed back into the next generation design.
- An early and close working relationship with the Nuclear Regulatory Commission (NRC) to ensure that the designs developed from the advanced light-water reactor (ALWR) programme not only met the utilities' operational needs but also met the regulatory mandates of the NRC, thus helping assure a smooth and quick licensing process for the final product.

Since the ALWR utility founders' initial act of faith, the ALWR programme has taken root and grown to the point that it is now a major factor in the emerging new direction of LWR technology. Their early vision of the next LWR has crystallized as a plant design concept which is:

- substantially simplified compared to current nuclear units;
- rugged and forgiving, with substantial design margin;
- based solidly on proven technology; it is "advanced" in the sense of applying the best experience of existing plants.
- Sharply focused on the man-machine interface, and on the needs of the operators who must assure its safe, efficient performance.

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* "Next Generation Light Water Reactor" by Stahlkopf, K.E., Noble, D.M., and Taylor, J.J., *Proceedings of the American Power Conference*, Volume 48, Illinois Institute of Technology (1986).

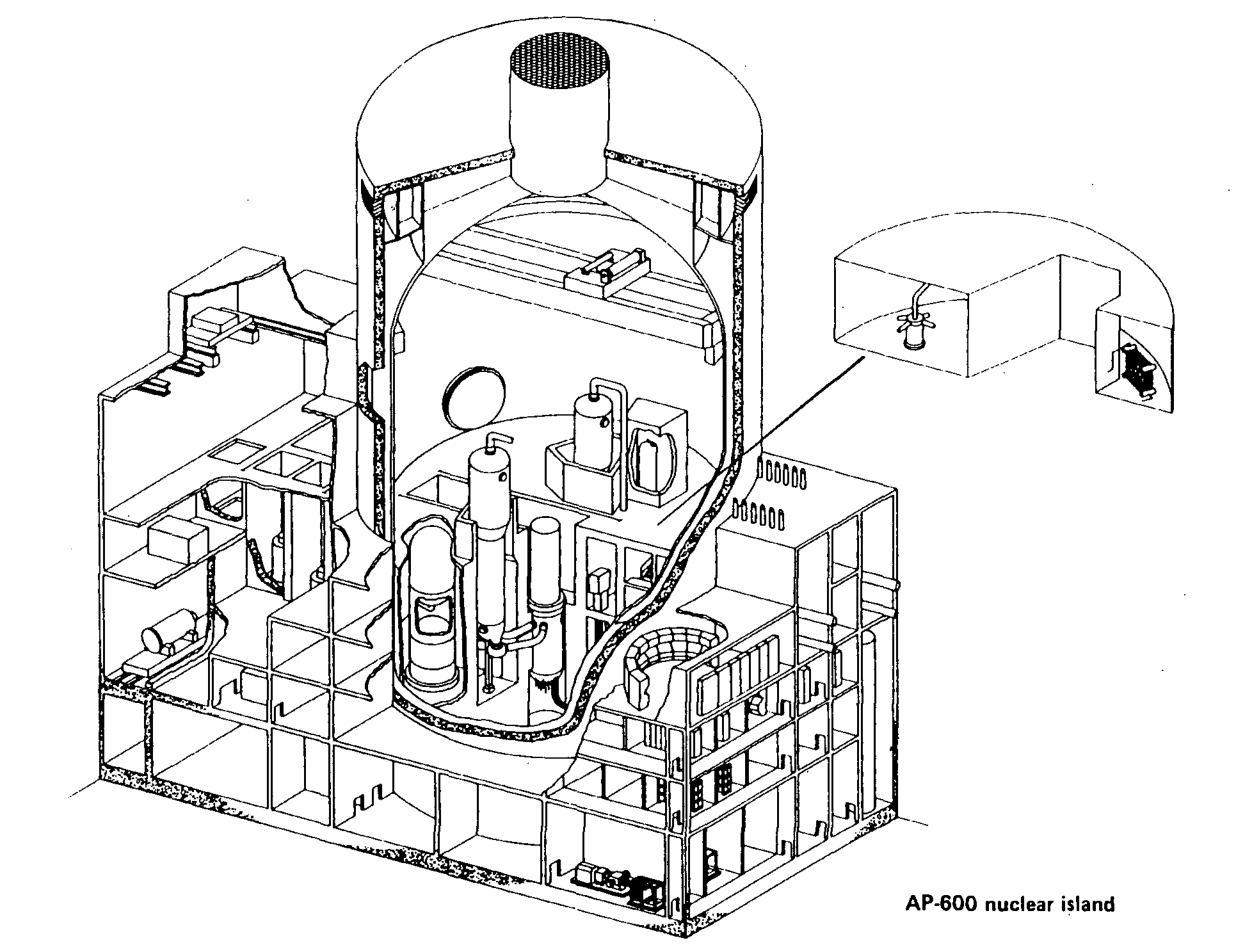
An "evolutionary plant"

To implement these principles, the ALWR programme team took on the task of creating a utility requirements document, a comprehensive statement of performance and design requirements for an "evolutionary plant" version of the ALWR.* This evolutionary plant is envisioned as a large, approximately 1200-megawatt-electric (MWe) unit, employing substantial simplifications and improvements in plant safety systems and instrumentation and control systems. It is a direct descendent of today's ALWRs and its safety systems and regulatory base largely follow conventional approaches. As part of the creation of this requirements document, the ALWR team worked closely with the NRC to identify and resolve significant, outstanding issues of reactor safety and to incorporate these resolutions into the ALWR requirements document.

This requirements document effort is still working toward its final objective of a completed and comprehensive document reflecting a consensus of prospective utility users and approved by an NRC Safety Evaluation Report. Twelve of its 13 chapters have been prepared, and already the document is serving as a reference for US and worldwide users, and influencing the design of reactors which could be in place by the end of this century.

The ALWR requirements document is filled with design improvements for safety and reliability. These include: (1) increased thermal margins; (2) strengthened reactivity requirements, i.e., negative temperature coefficient through the entire fuel cycle; (3) lower maximum reactor coolant temperatures; (4) improved resistance to embrittlement in reactor vessels; (5) reactor vessels made of ring forgings so that vertical welds are not necessary;

* "US ALWR Program Set Out Utility Requirements for the Future", by Stahlkopf, K.E., DeVine, J.C., and Sugnet, W.R., *Nuclear Engineering International* (November 1988), and "Light Water Cooled Reactors — Expected Developments", by Culler, F.L., Stahlkopf, K.E., and Braun, C., *Revue Roumaine de Physique* (April 1988).



AP-600 nuclear island

(6) alternate on-site AC power source; (7) natural circulation decay heat removal; (8) higher pressure decay heat removal systems; (9) increased coolant inventories; (10) larger, more robust containments; (11) separation of safety system functions from normal operating system functions; (12) greatly improved man-machine interfaces; that is, control rooms which are much easier to operate safely.

Along with the technical progress achieved by the ALWR programme to date, it has emerged as the focal point and catalyst for the co-operation of US and international utilities in directing the course of their future nuclear reactor designs. From its early days as an embryonic EPRI/US utility programme, the ALWR work has gained visibility and respect among US participants, and it has attracted the financial and technical support of a number of Asian and European utility participants. Presently Kansai Electric, Japan; Taipower, Taiwan, China; KEPCO, Republic of Korea; EdF, France; ENEL, Italy; and KEMA, Netherlands, are active partners and participants in the ALWR programme. The synergistic effect of this growing US and international collaboration has been very significant. As international partners have joined the programme, its technical strength and credibility has increased directly; as that has happened, the influence that the programme's technical output has been able to exert on US and international vendors of nuclear steam supply systems has increased as well, encouraging in turn even more US and international support.

"Passive plant"

As the work proceeded in developing the evolutionary plant requirements, the ALWR programme team also began to explore a new LWR concept, which they called the "passive plant".* This passive plant was envisioned as a smaller reactor which would employ primarily passive means — gravity, natural circulation, and stored energy — for its essential safety functions.

The passive ALWR design concept was considered to be potentially attractive to utility investors, for several reasons:

- Due to the fundamental simplicity of the passive safety concept, it could offer an opportunity to effect a large simplification (in the form of reduction of many valves, pumps, tanks, instruments, etc.,) with attendant improvement in construction cost and schedule, plant operability, and maintainability.

*"The US Advanced Light Water Reactor Program — A Case for Simple Passive Safety Systems", by Taylor, J.J., and Stahlkopf, K.E., *Proceedings, International Topical Meeting on Safety of Next Generation Power Reactors*, Seattle, Washington (May 1988).

● By eliminating reliance on active components and human intervention, the passive plant could accommodate a wide range of upset conditions and internal and external plant threats, such as loss of all electrical power.

A reference size of 600 MWe was selected by the passive plant studies. In theory, the passive plant could be of any size, but it is likely that ratings significantly higher than 600 MWe will prove impractical or not cost effective, because of the relatively large component sizes (such as reactor vessel, cooling water tanks) involved. Furthermore, a smaller plant size may prove to be an advantage in its own right in that plants of 500 to 600 MWe may fit more easily into the capacity planning schemes of most US utilities. Also, smaller plant sizes offer a potential for shorter construction time, more extensive modularization of plant equipment, replication learning curve, and other factors that can improve overall plant economics.

Phase-1 of ALWR passive plant work was a design competition from which two promising conceptual 600-MWe passive designs — a pressurized-water reactor (PWR) and a boiling-water reactor (BWR) — were selected for further development. Both concepts employ passive safety systems and offer fundamental advances compared to existing plants. The most important of these is the design criterion that no operator action shall be required for a period of three days following a design basis event to protect the plant or public.

Phase-2 of the ALWR passive plant development, conducted in collaboration with the US Department of Energy (DOE) involved expanding the details of these concepts through extensive technical studies and equipment and system development activities.

These passive plant designs, while still at a preliminary engineering stage, are already bright prospects for successful development. Brief descriptions of the PWR and BWR design concepts follow:

PWR design concept. The passive PWR concept, referred to as AP-600, is being developed by a design team led by Westinghouse with assistance of Avondale Industries, Burns & Roe, and others.* This 600-MWe PWR features an improved reactor coolant system configuration utilizing canned motor reactor coolant pumps directly coupled to the steam generator outlet. *(See accompanying figure.)* This configuration removes the "cross-over leg" from the reactor coolant system (RCS), lowering the overall system flow resistance, and improving the performance with respect to a small break loss-of-coolant accident (LOCA). This simplified arrangement also allows a single support for the combined steam generator and pump assembly, greatly simplifying the RCS loop support configuration.

* "AP-600 Development", by Vijuk, R. and Bruschi, H., *Nuclear Engineering International, 33,* p.23 (November 1988).

Bulk quantity comparison of AP-600 and standard two-loop pressurized-water reactor

Bulk commodity	Reduction
Valves	60%
Large pumps	50%
Piping	60%
Heat exchangers	50%
Heating, ventilation and cooling ducting	35%
Seismic building volume	60%
Control cable	80%

The AP-600 also features a natural circulation heat exchanger that removes decay heat from the RCS at full temperature and pressure, eliminating the need for a pumped emergency feedwater safety system. A gravity-driven emergency core cooling system (ECCS) with full pressure core makeup tanks, in-containment refuelling water storage tank, and depressurization capability eliminate the need for a pumped ECCS.

The containment cooling function is also accomplished passively in the AP-600 concept. The cylindrical steel containment building is surrounded by a vented concrete shield building; airflow between the two structures removes heat from the containment shell. Water is allowed to gravity drain to the outside of the steel shell to increase the heat transfer coefficient by evaporation for about the first day after an accident.

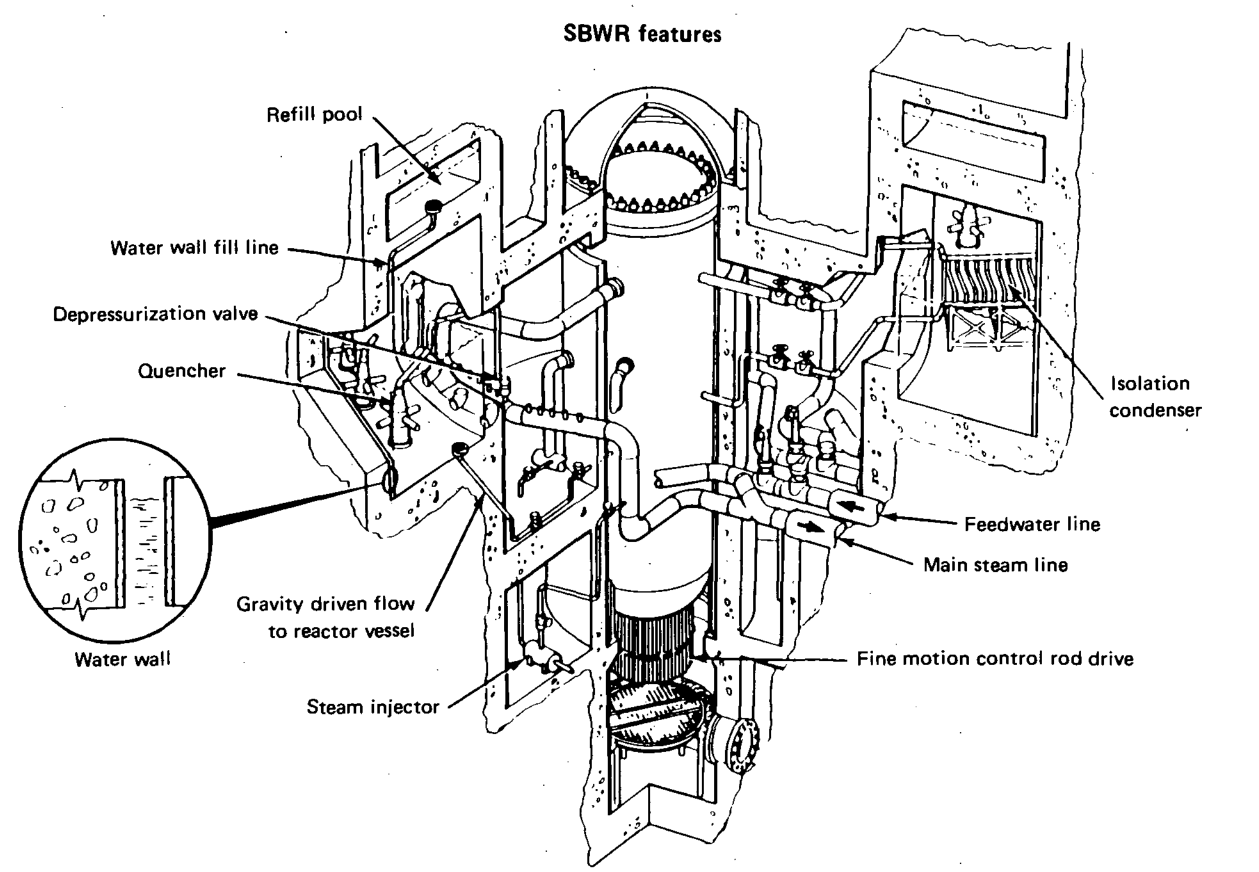
Together these features accomplish all the plant's necessary safety functions by passive means, and with substantial reduction in the necessary pumps, valves, and supporting electrical and cooling systems.

The elimination of the active emergency core cooling systems with associated pumps, valves, and piping along with other passive design features, allows a significant simplification in design when compared to conventional units. The results of this simplification show the reduction in bulk commodities and components of an AP-600 as compared to a conventional 600-MWe Westinghouse-designed nuclear power plant. *(See accompanying table.)*

BWR design concept. A design team led by the General Electric Co., and including Bechtel and MIT, is well along in developing a BWR version of the passive ALWR, called SBWR.* *(See figure on page 16.)*

The SBWR is a 600-MWe unit designed to meet similar ambitious targets, including no dependence on operator action for three days after a core-damaging event, and a 3-year construction duration.

* "ASBWR, An Advanced Simplified Boiling Water Reactor", by Duncan, J.D. and McCandless, R.J., and "Improvements in Boiling Water Reactor Designs and Safety", by Wolfe, B.R. and Wilkins, D.R., *Proceedings, International Topical Meeting on Safety of Next Generation Power Reactors,* Seattle, Washington (May 1988).



The SBWR reactor is designed for operation at full power without recirculation pumps. Elimination of recirculation pumps and piping permits a simpler reactor vessel design, reduces vulnerability to LOCA events, and reduces maintenance requirements. The larger reactor vessel needed for natural circulation provides the additional benefit of greater inventory of water over the core at the initiation of any upset conditions.

Safety features of SBWRs are imaginative and, at the same time, very simple. They include: a gravity drain cooling system that will keep the core covered and cooled in the event of a loss-of-coolant accident; a steam injector system which uses residual steam as a driving force for injecting water into the reactor to make up for leakage when no AC power is available; an isolation condenser located in an elevated water tank, providing capability for residual heat removal by natural circulation, and a containment of the pressure suppression type, which is passively cooled under accident conditions.

The capability provided by the passive safety features in the AP-600 and SBWR plants can accommodate all design basis events, and there is no need for a safety-grade emergency diesel generator or a class 1E AC distribution system.

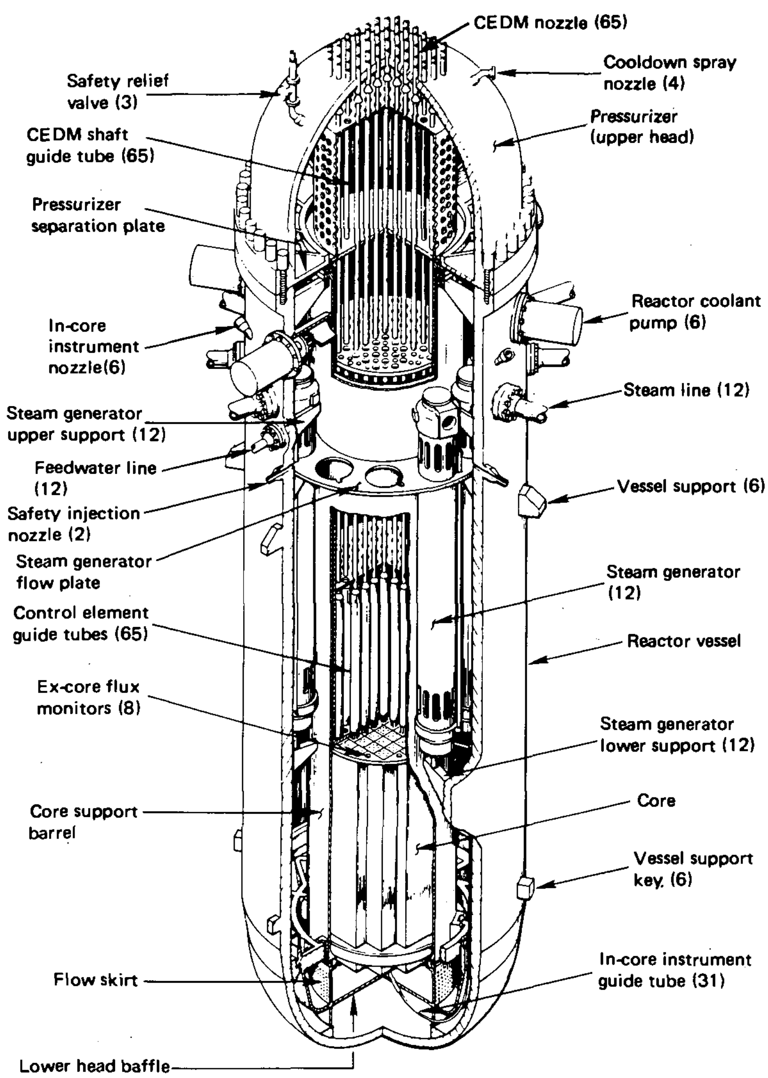
Safe integral reactor

In addition to the SBWR and the AP-600 being developed in the EPRI/DOE programme, there is a later entrant in the advanced passive light-water reactor design race with the introduction of the Safe Integral Reactor (SIR). It is being jointly developed by Combustion Engineering, Rolls Royce and Associates, Ltd., Stone & Webster Engineering Corporation, and the United Kingdom Atomic Energy Authority.* This is a concept which utilizes a primary coolant system in which the reactor core, the pressurizer, and the steam generators are contained in a single reactor pressure vessel with the reactor coolant pumps being mounted on the side of the reactor vessel; thus, it eliminates the traditional reactor coolant loop primary system piping associated with more conventional pressurized-water reactors. *(See accompanying figure for a simplified system design.)*

The safety systems of SIR are primarily passive relying on natural circulation and a large heat capacity rather than active AC power and equipment. The SIR reactor is 325 MWe; its size is limited by the practical construction and transportation requirements of the reactor vessel which contains not only the core but all primary loop systems. There are several unique features of the SIR in that it contains a pressure suppression containment and 12 cylindrical once-through steam generators, only 11 of which are needed to reach full power.

Reactor control of the SIR is maintained by the utilization of control rods and burnable poisons with the traditional PWR boron shim being eliminated for the sake of system simplicity and corrosion protection.

* "The SIR Project", by Hayns, M., *Atom* (June 1989).



Safe integral reactor

Although not currently a part of the EPRI/DOE ALWR programme, the SIR designers have stated their intention to meet the requirements for the passive LWR being developed in the ALWR Program.

Initially this passive plant development was an intriguing but low priority part of the ALWR Program. It seemed to be a promising concept, but one which required much development, and more importantly, a fundamental shift in technical philosophy and direction in reactor design. However, as the work has proceeded, there has been a clear shift in the interest of the utilities in the USA and around the world. The first two phases of work have been technically very successful and have shown promise of better things to come. The designs which have emerged clearly meet the vision and technical principles established by the ALWR Utility Steering Committee at the programme's outset. The passive plants can be dramatically simplified compared to today's plants, with rugged design and conservative design margins. They provide outstanding "operator friendliness", particularly in terms of providing long grace periods before operator action is required in the event of upset or emergency conditions. At the same time they are rooted in fundamentals and proven technology — the passive reactor is a "back to basic design" incorporating the key lessons learned (some perhaps temporarily forgotten) since the beginnings of LWR technology.

At the completion of the current phase of work (passive plant Phase-2), scheduled for the first half of 1990, the passive plant concept will have been thoroughly investigated. A passive plant ALWR requirements document will have been produced and approved by the ALWR Utility Steering Committee, and the passive safety regulatory foundation will have been developed.

Conceptual designs for the passive plant concepts outlined above will be complete. Together these will constitute an excellent foundation for further passive plant development. However, more work will be needed before this passive plant can be considered attractive to investors, either from a technical or licensing standpoint.

A follow-on programme — passive plant Phase-3 — is needed to take the passive plant to the point that it truly is a viable ALWR candidate, one demonstrated to meet the needs of utilities, regulators, and the public, and a sound basis for utility investment.

Future directions

EPRI and DOE are working together to create such a follow-on ALWR passive plant programme. DOE is proceeding with a major passive plant design certification effort, contingent upon industry cost sharing. EPRI and the ALWR Utility Steering Committee are structuring an international partnership of utilities working together to support the design and development of passively stable ALWRs. The objective of this co-ordinated programme will be to carry existing passive plant design concepts to the point that they are considered "investment ready". More specifically, Phase-3 will achieve:

- a well-understood and stable set of regulatory requirements, confirmed via NRC certification of one or more passive plant designs;