Advanced technology and design for heavy-water reactors

Several countries are investing in the continuing development of HWRs

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There are presently 44 commercial heavy-water reactors (HWRs) operating or under construction in six countries. For a number of years these HWRs have been world leaders in the achievement of high annual and lifetime capacity factors and have proven to be a viable alternative to light-water reactors.

In addition to achieving high capacity factors on base load plants, HWRs have also, when required, given very good load-following service. Operating performance on critical items such as fuel and steam generators has been excellent and HWRs have experienced very low fuelling costs due to the use of natural uranium fuel.

HWRs represent a relatively new technology and the development potential is being actively pursued by the investigations of advanced HWR designs in Argentina, Canada, India, and Japan.

Basic features of heavy-water reactors

Two basic types of commercial HWRs have been developed. One type, developed by Siemens/KWU in the Federal Republic of Germany, employs a pressure vessel containing the complete reactor core. The other type, the Candu reactor, was developed in Canada by Atomic Energy of Canada Limited (AECL) in collaboration with Ontario Hydro and Canadian manufacturing industries.* It employs several hundred pressure tubes rather than a single pressure vessel. Both types of commercial HWRs use heavy water as the moderator and share several key basic features:

- An excellent neutron economy permits the practical use of the once-through natural uranium fuel cycle. A wide variety of other fuel cycle options is also possible.
- On-power refuelling which offers several fundamental benefits: higher capacity factors by eliminating periodic refuelling shutdowns, reduced need for in-core reactivity and flux distribution control mechanisms, on-power replacement of defective fuel, and easy access for in-service inspection.

Commercial heavy-water reactors currently in operation or under construction

	No. of units	Gross output (MWe)
Pressure vessel type		
Argentina	2	367–750
Pressure tube type		
Argentina	1	648
Canada	22	540–935
India	12	220–250
Pakistan	1	137
Republic of Korea	1	679
Romania	5	705
Total	44	25 013

- Reactivity changes over the full range of operating conditions from cold shutdown to full power are small. This reduces the required reactivity worth of control devices and minimizes local flux distribution perturbations, minimizing potential problems due to transient local overheating of fuel. This also facilitates closed-loop automatic reactivity control, which improves flexibility in load-following.

The relatively large geometric separation of the lattice cells of HWRs permits the coolant to be physically separated from the moderator. Pressurized heavy water is used as the coolant in all currently operating commercial HWRs; however, experimental and prototype pressure-tube HWRs have been built in several countries to evaluate the use of carbon dioxide, light water, and organic fluids as coolant options. Japan has recently announced its intention of constructing a commercial-sized (600 MWe) demonstration reactor employing boiling light water as the coolant.

Most HWRs currently use natural uranium fuel, often with the objective of being independent of uranium enrichment facilities. The use of slightly enriched uranium fuel results in a significant improvement in fuel cycle costs and uranium utilization. Plutonium and/or uranium from

* Candu is a registered trademark.

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spent light-water reactor (LWR) fuel can also be efficiently burned in existing HWR designs, offering a synergism between HWRs and LWRs. In the long term, dependency on uranium can be significantly reduced through the use of thorium.

Design and development objectives

The challenge of the continuing design and development programmes is to reduce generating costs while maintaining high nuclear safety and good performance. It will also be important to achieve enhanced confidence in the safety of advanced HWR designs since this is a world trend for all reactor types. This will be done by demonstrating that the improved safety is based on operating experience, proven technologies, and conclusive research and development.

Safety enhancement. HWRs have already proven to be safe in operation, and the safety of operating plants has been continuously improved by incorporating the results of experience and technological development. For future plants, a number of objectives have been identified by various countries to maintain or improve plant, worker, and public safety and to enhance confidence in that safety.

A target which is being pursued in several national programmes is to reduce the radiological burden on operating and maintenance staff. This is being achieved through such means as careful optimization of tritium management, early detection of leaks, rapid location and on-power removal of failed fuel, improved shielding and coolant purification, and better control of sealing materials. A related target in some countries is to maintain or reduce the normal station release which is already typically less than 1% of the regulatory release limit.

Advanced Candu control centres are being developed to improve the effectiveness of the operator and to reduce the potential for operational errors. These advanced control centres build upon the many years of experience in commercial Candu reactors with digital computer controls. The improvements will include the utilization of expert systems and other computer-assisted techniques to reduce the workload on the operator and to enhance the quality of the information presented.

Many of the basic features of HWRs provide inherent safety characteristics. The large water-to-fuel ratio is of particular interest since the moderator provides a heat sink with a separate cooling circuit. The cool moderator of pressure-tube type HWRs also offers a benign environment for reactivity control devices and permits the use of fully independent drop rods and liquid poison injection shut-down systems. This is of assistance in achieving low core-melt frequencies.

The addition of passive cooling methods to the moderator cooling system is seen as the next logical step in improving this feature. Provision of passive decay heat rejection to the environment via containment cooling or moderator cooling would substantially reduce the probability of severe accidents and increase the grace period for the reactor.

Cost reduction. The capital cost of the plant is the most significant aspect of the generating costs. In order to effectively reduce the capital cost, it is necessary to both reduce the cost of equipment and labour as well as minimize the interest during construction. These objectives are being met in a number of different ways: (1) basic changes in plant layout to facilitate a significant reduction in the construction schedule; (2) the development of large piping or building modules that can be factory-built and transported by sea or land to the final site. This not only reduces cost, but also improves schedule and quality control; (3) use of standardized plant designs that are suitable for a wide range of sites and contractual arrangements to reduce cost and schedule; (4) computer-aided design, drafting, documentation, and management systems are being enhanced and integrated to reduce the direct cost of labour and improve the quality of the work.

Improved plant performance. In order to maintain high capacity factors a number of design objectives are being addressed. A lifetime capacity factor objective of 94% is the goal for some new designs. Over the next decade, as more reactor units reach the end of their design life, more attention by utilities will be focused on design life and the ability to extend life by component replacement or refurbishing. Since a nuclear power station is characterized by a large capital cost and low operating cost, a plant which is capable of operating for an extended life will be economically attractive.

Prospects for development and deployment

Energy forecasts predict that the world demand for electricity will increase steadily through the next century due to increases in population, increased urbanization, and predictions of greater use of electricity *per capita*, particularly in countries on the threshold of industrialization. Electro-technologies are flexible, clean, safe, and efficient in domestic and industrial applications. Reliable low-cost electricity from nuclear power offers employment opportunities not only in nuclear technology but also in other high technologies seeking locations for lower product production costs.

Large- and medium-sized HWR generating units. Most of the HWRs in commercial service range in output from 540 to 935 MWe gross. It is expected that this size range will continue to be of interest to those countries with large well-established grids and those with a relatively large projected growth rate.

The design of the standardized Candu-6 (previously Candu-600) single unit plant was based on the very successful Pickering A (4 × 540 MWe) station in Ontario, Canada. There are now four Candu-6 single unit HWR stations in service, (two in Canada; one in Argentina, and one in South Korea) and five more are under construction in Romania. These nine units have outputs of 640-680 MWe gross. Over the past 5 years, the Candu-6 design has been improved and it is now called the Candu-6 Mark 2, with an output of about 800 MWe gross. The Candu-6 Mark 2 includes enhancements in safety, availability, and operability. A number of changes have also been made to reduce capital cost and the construction schedule.

The Darlington nuclear generating station (4 × 935 MWe gross) is nearing completion in Ontario, Canada. Darlington represents a continuous improvement in the Candu multi-unit stations evolving from the Bruce-A (4 × 826 MWe gross) and Bruce-B (4 × 845 MWe, gross) stations which have been in service for a number of years. The advances in this design have been focused on improvement of major structures, reduction in the number of major system components, better accessibility to components and systems, and improved use of computers for station control as well as extending their use for safety system operation and monitoring.

In the Federal Republic of Germany, the Siemens pressurized HWR line originated from the multipurpose research reactor MZFR (57 MWe). This line of HWRs, which uses a pressure vessel, was continued in the Atucha-1 reactor and Atucha-2, a 750-MWe HWR currently under construction in Argentina. Improvements have been achieved in terms of reduction of tritium content, hydraulically-driven control rods, fuel storage capacity, and in alternative fuel cycles.

The HWR programme in India has been based upon pressure-tube HWR units rated at 235 MWe. Newer designs of twin 500-MWe units are now being developed and six 500-MWe units have been committed for commercial operation beginning in 1997. The 500-MWe designs will incorporate improvements to plant layout, containment, reactor systems, fuel handling and on-power refuelling, and safety systems. A major underlying theme in the Indian programme continues to be the development of indigenous capability in all aspects of research and development, engineering, manufacturing, construction, and operation. This theme is reflected in the incorporation of evolutionary changes and the standardization of several design features.

In Japan, the advanced thermal reactor (ATR), a heavy-water moderated, boiling light-water cooled reactor, is being designed for plutonium utilization. The design of the ATR is based on Fugen, a 165-MWe prototype reactor that has been in commercial operation since 1979. The expected performance of MOX fuel has been demonstrated successfully by the operation of Fugen. The 606-MWe ATR demonstration plant programme has a target of commercial operation in 1997.

Small-sized HWR generating units. Smaller units promise a better match to a low rate of load growth, to smaller electrical grid systems, and to the pressures of financing. These factors are typical of the situation in many countries.

The Argos, a new 380-MWe HWR being developed by an engineering company in Argentina in co-operation with Siemens in the Federal Republic of Germany, represents an advanced model of the Siemens PHWR series that embodies a number of features to enhance safety and economy of operation and to limit investment costs.

Aerial view of the Darlington nuclear generating station.

In Canada, AECL is developing a new Candu model, the Candu-3, with a gross electrical output of 480-MWe. The Candu-3 design includes enhanced safety, a target of 94% lifetime capacity factor, a 30-month construction schedule, and adaptability to most sites worldwide in either a single unit or a multiple unit configuration. Discussions are ongoing with Canadian utilities and several countries that are expected to result in an early construction commitment for one or more units.

In India the existing base of four 235-MWe pressure-tube type HWRs is being expanded with eight units presently under construction and four more committed for commercial operation after 1996.

Beyond the production of low-cost reliable electricity, HWR technology has potential for use in district heating and for the production of process heat suitable, for example, for the *in-situ* production of oil from tar sands deposits.

Summary

Commercial HWRs have demonstrated many achievements as an electrical power generation system. These achievements include an excellent safety record, high annual and lifetime capacity factors, low fuel cost and a broad range of other performance strengths which together indicate that the technology is fundamentally sound.

HWRs have an excellent potential for continued development. The separation of the coolant and moderator systems provides an opportunity for development of enhanced safety features. The known capabilities not yet fully exploited and future opportunities offered by the flexibility for advanced fuel cycles and diverse applications indicate that the HWR technology will continue to pay strong dividends on research, development, and design investment.