HR0000051

CANDU 6 -- THE HIGHLY SUCCESSFUL MEDIUM SIZED REACTOR

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ABSTRACT

The CANDU 6 Pressurized Heavy Water Reactor system, featuring horizontal fuel channels and heavy water moderator continues to evolve, supported by AECL's strong commitment to comprehensive R&D programs.

The initial CANDU 6 design started in the 1970's. The first plants went into service in 1983, and the latest version of the plant is under construction in China. With each plant the technology has evolved giving the dual advantages of proveness and modern technology. CANDU 6 delivers important advantages of the CANDU® system with benefit to small and medium-sized grids.

This technology has been successfully adopted by, and localized to varying extents in, each of the CANDU 6 markets. For example, all CANDU owners obtain their fuel from domestic suppliers.

Progressive CANDU development continues at AECL to enhance this medium size product - CANDU 6. There are three key CANDU development strategic thrusts: improved economics, fuel cycle flexibility, and enhanced safety. The CANDU 6 product is also enhanced by incorporating improvements and advanced features that will be arising from our CANDU Technology R&D programs in areas such as heavy water and tritium, control and instrumentation, fuel and fuel cycles, systems and equipment and safety and constructability.

1) INTRODUCTION

The 700 MW class CANDU 6 Nuclear Power Plant design is a successful mid-sized application of the CANDU® reactor system, which has been deployed both in Canada and in a range of export projects. The CANDU 6 is a sister product to the recently-designed 925 MW class CANDU 9 product. This paper describes the background to the development and further evolution of the CANDU 6.

The evolution of the CANDU family of Pressurized Heavy Water Reactors (PHWR) featuring horizontal fuel channels and heavy water moderator is based on a continuous product improvement approach. Proven equipment and system concepts from operating stations are standardized and used in new products. The product evolution is supported by AECL's strong commitment to comprehensive R&D programs. Therefore, CANDU reactor products will incorporate further improvements and advanced features that will utilize results from our CANDU Technology R&D programs in areas such as fuel channels, heavy water and tritium, control and instrumentation, fuel and fuel cycles, systems and equipment, safety technology and constructability.

The CANDU 6 design has evolved successfully since its initial development in the 1970's, with incremental improvements adopted for successive build projects. In the future, the CANDU 6 will continue to evolve, with a series of enhancements ready for the next project, and with further improvements currently in development. Looking farther ahead, the CANDU 6 will be the springboard for the next generation of mid-sized CANDU designs, which will be developed ready for the emerging electricity markets of the coming decades.

2) CANDU 6 DESIGN BACKGROUND

CANDU 6 continues to be the mainstay of AECL's product line. The 700 MWe class CANDU 6 nuclear power plant has an outstanding operating performance record since the startup of the first four CANDU 6 units in 1983. Cernavoda-1, the most recent European nuclear plant, started operation in 1996. The latest project to achieve startup is Wolsong-4, which achieved full power in 1999. Most recent of all is the Qinshan project, near Shanghai in China, which started construction in 1998.

The CANDU system, as deployed in the CANDU6 design, has some distinct benefits for application in small and medium-sized grids. For example, the excellent reactor control characteristics of CANDU allow for efficient, reliable operation in reactor-following-turbine mode, where the reactor thermal output responds directly to the grid demand. Another important advantage stems from CANDU's use of on-power refuelling. This means that planned plant outages, e.g. for routine maintenance, can be timed at the plant operator or grid operator choice, unlike the case for LWR's, where outages for refuelling must occur at imposed intervals. Other CANDU attributes which are attractive to operators in small- and medium-sized grids, include a very reliable response to upsets such as grid disturbances or loss of line. Finally, of importance in power supply planning, CANDU 6 units can be delivered via manufacturing/construction/commissioning in a very short time. For example the recent Wolsong-3 project was placed into commercial operation on schedule in 1997, only 69 months after the project contract-effective date.

These CANDU attributes have been demonstrated in successful applications with smaller grids. In the province of New Brunswick, Canada, the Point Lepreau CANDU 6 unit represented 1/3 of the provincial grid supply capacity when it came on-line in 1983. Since then, reliable operation of Point Lepreau has been an important contributor to the effective performance of the New Brunswick grid. Similarly the recent startup and successful operation of the Cernavoda-1 CANDU 6 unit has been an important component in energy supply in Romania.

For Qinshan, further improvements from the reference plants at Wolsong have been incorporated, both in plant design and in product delivery. The Qinshan design is tailored to meet stringent local requirements including tornado protection and tight requirements on emissions to allow the Qinshan site to be used for up to 5 projects. The Qinshan plant design incorporates further improvements to such auxiliary systems as fire protection (additional redundancy of water supply system). In addition, the continuing development of fuel channel design has led to the use of improved surface finish of calandria tubes. This has the added advantage of increasing heat transfer margins if the moderator were to be required as an emergency heat sink. Consistent with the 40-year design life target, improvements in feeder material selection, using trace additions of chromium, will enhance resistance to long-term corrosion effects. Similarly, careful attention has been paid to specifications of key components such as the steam generators to allow in-service inspection and cleaning to ensure their capability for a 40-year design life. Specifications are optimized to ensure the design fully meets requirements, without placing unnecessary restrictions on manufacturers.

A further important step in CANDU 6 evolution is the adoption of advanced control room features for Qinshan (see figure 1). Based on the successful original CANDU 6 control room design, the Qinshan Advanced Control Centre incorporates a sophisticated computer-driven Plant Display System, which provides readily accessed plant status information to the operator. This includes an advanced alarm message listing and prioritization system which improves operator response to upset conditions. In addition, the Qinshan control room also includes two large mural overview displays which allow convenient representation of the status of the whole plant in one view, as a plant management aid.

Building on the successful application of CADDS models for Wolsong 2, 3 and 4 construction support, Qinshan project engineering and construction will be based on a comprehensive set of 3-D CADDS models. These will be linked to electronic databases covering wiring (INTEC) equipment specifications (TeddyBase) and materials management (CMMS). This will improve the effectiveness of engineering and procurement processes, and in particular will minimize plant design inconsistencies such as physical interference's, material or performance interface errors etc. For example, the occurrence of physical equipment interferences at Qinshan has been reduced to a small fraction of the already-reduced value at the recent Wolsong project.

As a result, the construction and installation stages of the project will be subject to much less schedule or cost risk. Constructability has been further improved by the adoption of open-top techniques for work both within the reactor building and in the balance of plant. This is based on the use of a very-heavy-lift crane to install major equipment before completing the reactor-building dome. Specific equipment items were installed this way for Darlington NGS. Full scale application of this technique has allowed an ambitious project schedule of 72 months from contract effective to first unit in-service to be committed; this despite an extremely restricted site, and the natural additional challenges inherent in the first project in a new environment.

Future CANDU 6 projects will build upon the latest version of the product under construction in Qinshan, China. Design enhancements being considered are in the areas of capital cost reduction, improved licensability, elimination of obsolescence and improved operability. Such design enhancements will continue to be introduced in an evolutionary manner, ensuring that each new feature is fully proven and that its plant-wide impact is fully accounted for in design.

3) CANDU 6 DESIGN ENHANCEMENTS

Development work continues at AECL, to identify, design and prove out enhancements to the CANDU 6, based on the following drivers:

- Response to Customer and Other Feedback
- Enhanced Safety

- Improved Product Delivery
- Improvements to Operating Performance
- Reduced Capital Costs

Examples in each area have been and are being incorporated ready for future CANDU 6 projects.

Operational Feedback

AECL has recognized the importance of operational feedback in improving the CANDU product. AECL has been active in the CANDU Owners' Group on Information Exchange program where good operating practices are exchanged, events are reported, and data relevant to safe plant operation is collected screened, and distributed to COG members. In recent years, there have been a total of four COG/IAEA Technical Committee on Exchange of Operational Safety Experience of PHWRs where all PHWR utilities world wide can share and exchange their operational experience and solutions to safety issues.

To complement these activities, AECL has initiated a systematic feedback process which incorporates regular, formal review of lessons learned from not only operations, but also from construction, commissioning, regulatory activities as well as incorporating R&D results (Reference 1). Recent examples of operational input to designs are:

- ECC performance improvements including strainer design for long term circulation of emergency coolant;
- Improvements to liquid relief valve component and system design for heat transport pressure and inventory control
- Improved safety system signal monitoring with updated digital displays, increased computerized testing for reduced operation burden and increased system reliability
- Steam generator operational improvements such as provision of additional access ports for chemical cleaning and improved divider plates for long term performance

Safety Enhancements

AECL has been enhancing the performance of CANDU reactors under postulated severe accident conditions that go well beyond the normal design basis for nuclear power plants. The presence of the heavy water moderator surrounding the fuel channels effectively mitigates the impact of postulated severe accidents. To enhance this capability, make up water supply to the moderator to account for any loss of inventory is included in the current CANDU 6 . A number of additional features have also been included in the latest CANDU 6 design.

Additional safety features under development which will form the basis of forthcoming CANDU 6 design enhancements include:

- Improved fuel thermal margin through the use of CANFLEX fuel and improved core flow and temperature monitoring.
- Reactor shielding vault and system design optimized to enhance inherent emergency heat sink capability for severe core damage accidents.

- Simplified, high-pressure design containment, eliminating requirement for fast-acting dousing pressure suppression.
- Emergency core cooling system gas / H_20 / D_20 isolation using simplified, passive components.
- Increased redundancy and operating flexibility of both auxiliary and emergency feedwater systems.

Enhancements in Product Delivery

As noted above, recent CANDU 6 build projects have incorporated successive advances in the use of advanced engineering tools, continuing to the Qinshan project where a full 3-D CADDS model is used as the basis for CANDU 6 design. Electronic data transfer to engineering tools for such activities as support design, and stress analysis, has streamlined project execution.

For future CANDU 6 projects, AECL's suite of software tools will be fully linked, with the inclusion of key functions of equipment specification (through TeddyBase the Tagged Equipment Database, and CMMS project (CANDU Material Management System), along with intelligent databases for document and other deliverable control.

At this point, AECL has developed, and gained real-world project experience with, a comprehensive suite of engineering tools, which enable efficient, timely generation and communication of engineering information throughout the project team, and throughout the duration of project execution.

Future CANDU 6 projects will also build on the experience on the Qinshan project, to enhance the application of open top construction techniques. For example the CANDU 6 improvements program has identified and designed 8 selected system modules which can be pre-fabricated and lifted into position "over-the-top", in addition to structural modules and rebar prefabrication. These delivery improvements will lead to further project schedule reductions.

Performance Enhancement

1) Operability

The next CANDU 6 projects will include the full implementation of the Advanced CANDU Control Centre (Reference 2). In addition to the enhancements noted above for Qinshan, this will feature:

- Real time plant information, and historical data, communicated throughout the plant via a Local Area Network.
- Extended automation of safety system on-line testing and calibration.
- Touch-screen context-sensitive CRT's as the first-line operator interface.

The comprehensive, linked use of engineering tools, as described in section 6 above, allows a much more accurate, organized, and easily retrievable body of operating support information. The inclusion of plant operational history storage, available on the station LAN to both operations, maintenance and technical support staff to make maintenance planning decisions.

AECL is carrying out studies in partnership with CANDU utilities to identify how this improved information availability can be used to generate and implement Condition-Based Maintenance (CBM) procedures for key systems. Condition Based Maintenance optimizes preventive maintenance and inspection plans, to reduce maintenance staff burden while at the same time improving equipment reliability. In support of this, additional Equipment Status Monitoring instrumentation is being included in the CANDU 6E design for key plant equipment. In addition, AECL's development programs have established and tested equipment improvements in instrumentation self testing and signal noise analysis, which improve equipment status knowledge.

2) Emissions reduction

Recent work has led to emissions-reduction improvements, via design or via operations optimization, in areas which comprise significant contributors to offsite emissions from CANDU. In each case, improvements are driven by careful analysis of operating experience, together with comprehensive design attention to every significant source of emissions.

Operational experience (PLGS and Gentilly-2), supported by resin breakdown assessments and laboratory test results, indicates that an appropriate service time (on line as opposed to time from resin change-over) for the ion exchange column is no more than 2 to 3 months. If CANDU operators adopt this exchange frequency, moderator Carbon-14 releases will be dramatically reduced, typically by factors of 5 or more, in comparison to operation with longer residence times.

For the next CANDU 6 project, an assessment of operating experience in CANDU 6 units, and a design assessment of reactor building atmosphere control has been undertaken. Based on this, the design of the reactor building ventilation system and vapour recovery systems has been adapted to ensure that all reactor building air is completely dried before exit to the plant stack.

Further improvement in tritium control is achieved by moving moderator purification system equipment from the service building into the controlled atmosphere of the reactor building. In addition, improved orientation of dryer equipment to cover areas such as D_2O drumming stations, controls remaining source points for airborne tritium.

Based on measured emissions sources for existing plants it is estimated that, for comparable operating conditions, the Wolsong 2-4/Qinshan design will reduce plant airborne tritium emissions to less than 50% of those from the original CANDU 6 design. Further, the improved ventilation system routing for future CANDU 6 is estimated to reduce airborne emissions to less than 25% of those from the original design.

Reductions in Capital Costs

Design enhancements such as those discussed above have value in enabling cost reduction for the as-delivered plant, as well as in performance and safety improvement. In particular, the use of electronic engineering tools and advanced construction techniques both improves the quality of product delivery and allows major reduction in the as-delivered cost.

The CANDU 6 product optimization program has established a series of design improvements to reduce capital costs while also enhancing performance, operating life, and safety margin. Recent examples include:

- Heat transport system purification optimized for precise control of pH and related chemistry parameters.
- Moderator system design with optimized core D_2O flow distribution, to allow higher temperature operation and save on heat sink equipment cost.

In addition, studies are preparing the way for incorporation of further incremental improvements:

- Moderator waste heat recycle via low-pressure feedwater heating, allowing over 1% improvement in output while achieving equipment cost reductions.
- AECL-developed CECE catalytic exchange process to improve cost- effectiveness of heavy water in-plant upgrading.

4) FUTURE DEVELOPMENT THRUSTS

Looking ahead, AECL foresees continued scope for development, continuing the themes of safety enhancement, performance improvement and cost reduction, and also developing CANDU's natural advantages in fuel-cycle flexibility.

Fuel Cycles

The inherent excellent neutron economy from the use of heavy water technology gives the PHWR the ability to use different low fissile materials, and provides opportunities in continuing improvements in uranium (or other fissile materials) utilization and reactor/fuel optimization, to decrease in plant capital cost (Reference 3). CANDU fuel cycle flexibility arises naturally from the neutron economy associated with the use of heavy water, and the use of on-power fuelling and simple fuel design. The exploitation of this flexibility results in fuel cycles that optimize the use of uranium resources.

The CANDU 6 core design is readily adapted to optimization for variations in fuel cycle (in fact, existing CANDU 6 plants can be fuelled with slightly enriched fuel (SEU) with no backfit requirements except flux detector recalibration). The use of slightly enriched fuel at 0.9-1.2% enrichment levels allows CANDU 6 fuel burnups to be extended to three times current values, with corresponding benefits in fuelling cost. Other fuel cycle applications to the CANDU 6 can provide future opportunities to reduce fuelling cost, improve uranium utilization, or make maximum use of alternate fuel sources such as Recovered Uranium (RU), MOX, or thorium.

Light Water Reactors (LWR) are designed to burn enriched uranium (about 3.5% U-235) fuel down to a fissile content of 1.5% (0.9% U-235, 0.6% Pu) at the end-of-life of the fuel. CANDU NU fuel starts with 0.7% U-235, which is burned down to concentrations of enrichment plant tailings (about 0.2%). Therefore, CANDU reactors are in a unique position to take advantage of the relatively high fissile content of spent LWR fuel, and the LWR can be viewed as an efficient source of fissile material for future advanced CANDU designs via a number of potential once-through combined fuel cycles. This exploitation of the natural LWR/PHWR synergism will assure long-term fuel supply even if uranium resources become scarce. Also the use of recovered uranium fuel, and the use of mixed oxide fuel with plutonium and depleted uranium, including the recycling of transuranic mix from spent fuel reprocessing, can help to reduce long lived waste. All these fuel cycles are part of the overall strategy for sustainable development of the next generation CANDU products.

Safety Enhancements – Passive Safety Features

Passive emergency heat sink concepts have been under development for CANDU over the last several years, and application to the CANDU 6 can be readily achieved. A general purpose passive emergency water system (PEWS), would be introduced into containment for containment cooling, decay heat removal and/or emergency depressurization of the steam generators, and for the moderator in its role as a backup to the emergency core cooling system. The PEWS heat sink consists of a vented water pool in the containment dome. Its 2000m^3 volume can accept decay heat for three days via boiloff to atmosphere (see Figure 2).

Steam generator depressurization (for a LOCA or steam line break) can be effected via blowdown to heat exchangers in the PEWS water tank.

Containment heat rejection is through air cooler tube banks high in the reactor building. They are cooled by natural circulation to the PEWS tank, and are inclined to give a preferential flow direction for the water or steam. The same flow patterns give good hydrogen mixing in severe accidents and allow placement of passive autocatalytic hydrogen recombiners in the stream of mixed air, steam and hydrogen.

Moderator heat rejection would be through a boiling natural-circulation D_2O loop to a natural circulation H_2O loop connected directly to the PEWS tank. The stability of the natural circulation loop under flashing conditions has been demonstrated in tests at AECL's Chalk River Laboratories.

This application of passive emergency heat sink concepts to CANDU complements the existing inherent safety features of CANDU such as the continuously available moderator emergency heat sink.

Performance and Cost Improvements

AECL's experience in the evolutionary process of continuous improvement to design indicates that further cost reduction can be achieved by incremental improvements. However, there is also scope for significant step improvements to plant economics. One opportunity is to adapt plant design by optimizing for advanced fuel cycles. As noted above, the application of slightly enriched uranium (SEU) fuel allows for reductions in fuelling costs for the current CANDU 6 design. In addition, it is possible to use the benefits of SEU fuelling to optimize the CANDU 6 core for a flatter flux shape and therefore a higher plant power output. Output increases of 5-10% are achievable in this way , for very small costs, which substantially improve specific capital costs in $/MW.

Other opportunities arise in product delivery. One step is to increase the factory assembly of the reactor vessel and internals so that the whole assembly is delivered as a pre-fabricated module on site. This greatly increases labour efficiency, and also reduces construction schedule – a double cost benefit.

5) CANDU DEVELOPMENT POTENTIAL –

Looking farther ahead, their is great potential to extend the CANDU system for mid-sized nuclear power plant units. AECL is studying technologies which will enable a next generation of CANDU designs, building on the success of the CANDU 6 power plant. For example, more compact design of fuel channel components will allow a smaller size core layout, with significant savings in both equipment and civil structure costs. Fuel channel material and configuration improvements under way, combined with plant design optimization for low enriched fuel, allow higher pressure coolant system operation, which will in turn allow higher pressure turbine conditions, with resulting gains in thermal efficiency.

AECL foresees that as these and other parallel enabling technologies are developed, CANDU electricity costs can be radically reduced in future, enabling the CANDU system to be a strong competitor in the deregulated electricity markets of the future.

Figures:

1) Qinshan Advanced Control Centre, artist's impression

2) Passive Heat Sink Options for CANDU

References:

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CANDU 6 Control Room

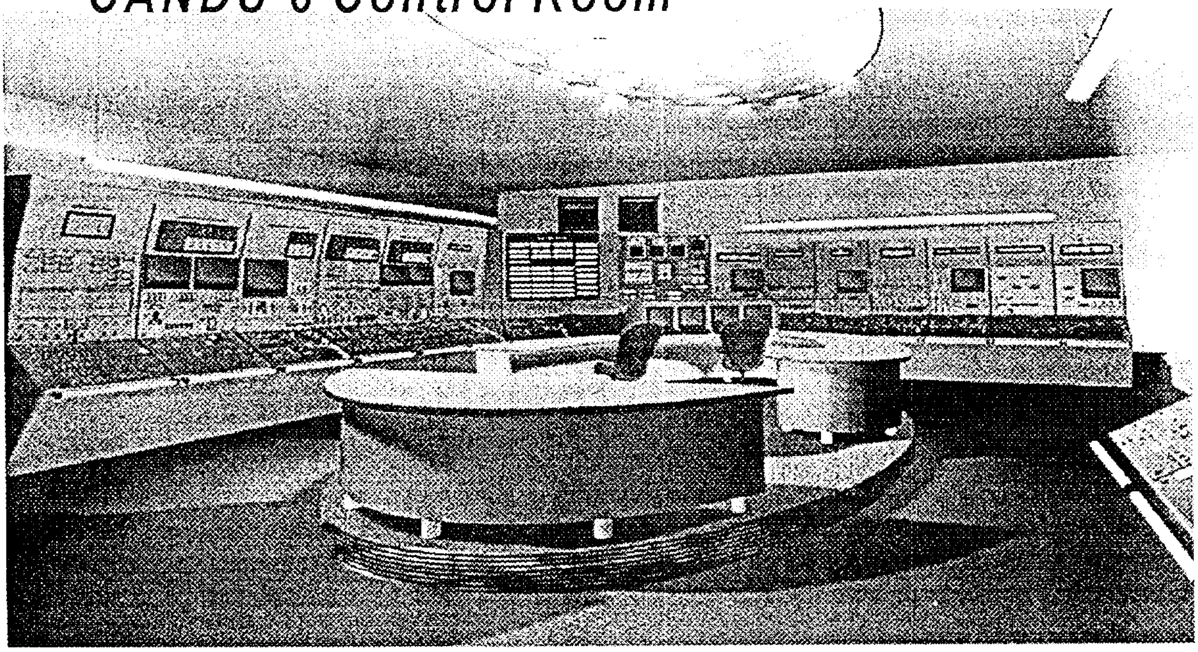

Figure 1: Advanced CANDU Control Room for Qinshan

Figure 3: Passive Heat Sink Options for CANDU

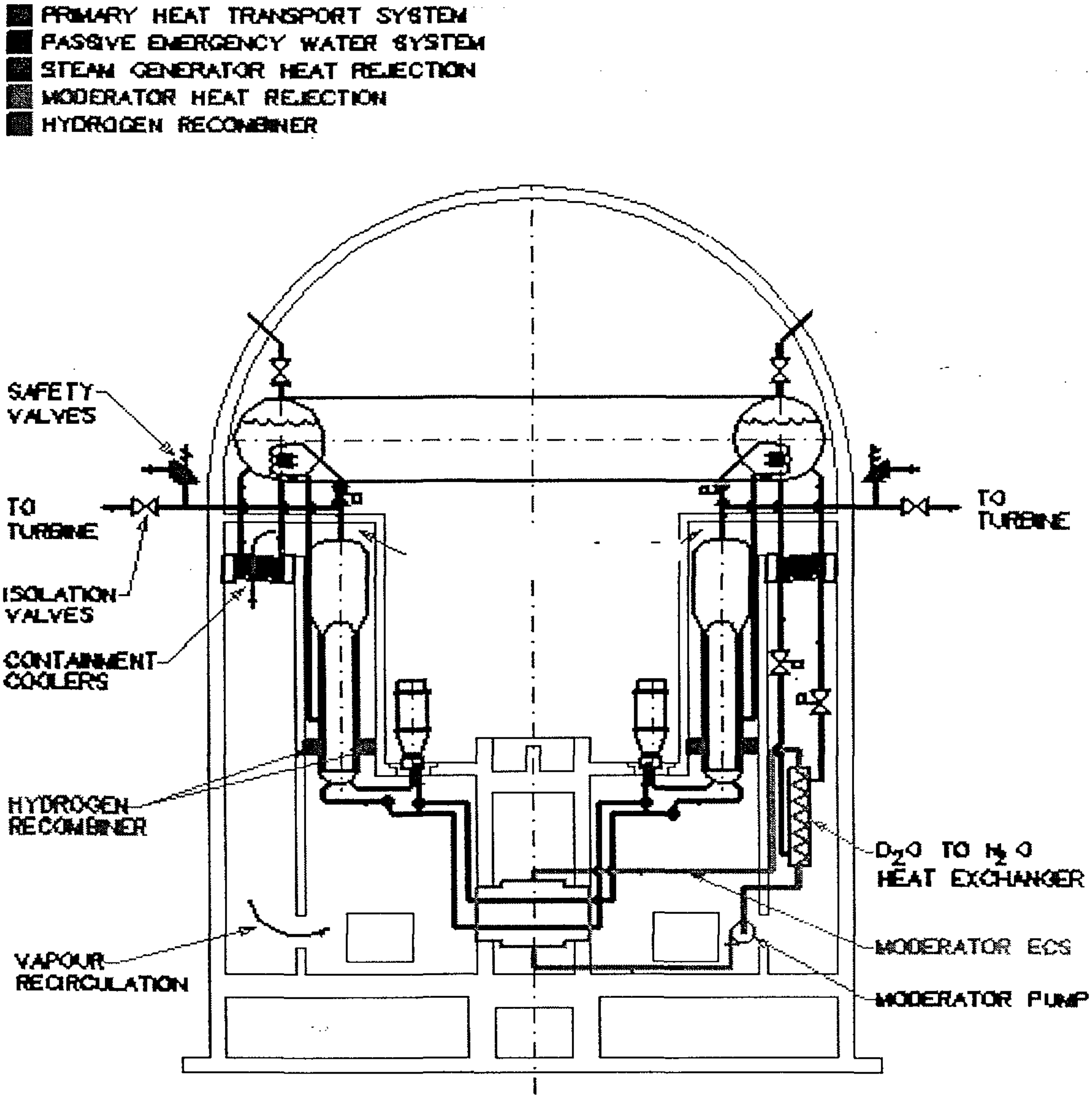

ILLUSTRATION OF PASSIVE CANDU 6 SYSTEM