THE AECL REACTOR DEVELOPMENT PROGRAMME

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Abstract

The modern CANDU-PHWR power reactor is the result of more than 50 years of evolutionary design development in Canada. It is one of only three commercially successful designs in the world to this date. The basis for future development is the CANDU 6 and CANDU 9 models. Four of the first type are operating and four more will go on line before the end of this decade. The CANDU 9 is a modernized single-unit version of the twelve large multi-unit plants operated by Ontario Hydro. All of these plants use proven technology which resulted from research, development, design, construction, and operating experience over the past 25 years. Looking forward another 25 years, AECL plans to retain all of the essential features that distinguish today's CANDU reactors (heavy water moderation, on-power fueling, simple bundle design, horizontal fuel channels, etc.). The end product of the planned 25-year development program is more than a specific design - it is a concept which embodies advanced features expected from ongoing R&D programs. To carry out this evolutionary work we have selected seven main areas for development: Safety Technology, Fuel & Fuel Cycles, Fuel Channels, Systems & Components, Heavy Water & Tritium, Information Technology, and Construction. There are three strategic measures of success for each of these work areas: improved economics, advanced fuel cycle utilization, and enhanced safety/plant robustness. The paper describes these work programs and the overall goals of each of them.

1. INTRODUCTION

The Canadian-originated CANDU® reactor system is now a mature and substantial contributor to the world's nuclear-electric energy system. It is fully competitive with other available reactor types with regard to economics, safety, and fuel utilization. The world, however, is constantly changing in its expectations of electricity generating systems. New competitors have eroded the small-reactor end of the market. The public is wary of any nuclear power system regardless of its technical merits. AECL is deeply involved in meeting these new challenges posed by changing economic, social, and regulatory conditions. Fortunately, the CANDU system offers a high degree of flexibility which allows the required design adaptations.

A competitive market in which the individual dollar commitment by a power utility is very large leads to a conservative buying policy. The owners are understandably reluctant to commit large-scale funds on unproved products. As a result the nuclear plant market is dominated by designs which are somewhat obsolescent; little opportunity is offered for technology advancement as the reactor vendors move from one project to the next.

It is obvious that AECL must evolve the CANDU plant design in full accordance with the customers' needs; this is a simple business criterion. Additional design flexibility sometimes will be accepted by a customer, especially if that customer and the local industry of the nation can take an active part in some aspect of the project. Thus, development opportunities, economics and social policy become entwined with the technological factors in successful major projects such as these. CANDU plants are competitive with others' nuclear plant offerings from all these points of view.

Recently, the rapidly-evolving technology of natural-gas turbines arrived on the scene and upset the carefully-crafted competitive schemes of nuclear vendors. At the present time it appears imperative to achieve a major reduction in nuclear plant costs. AECL is looking at this issue in an evolutionary manner in both the short and medium term. The result in the long term likely will seem revolutionary in the light of today's knowledge; nonetheless it will be achieved.

2. EVOLUTIONARY DEVELOPMENT

First, we can fix the starting and end points for the 25 year development program illustrated in Figure 1.

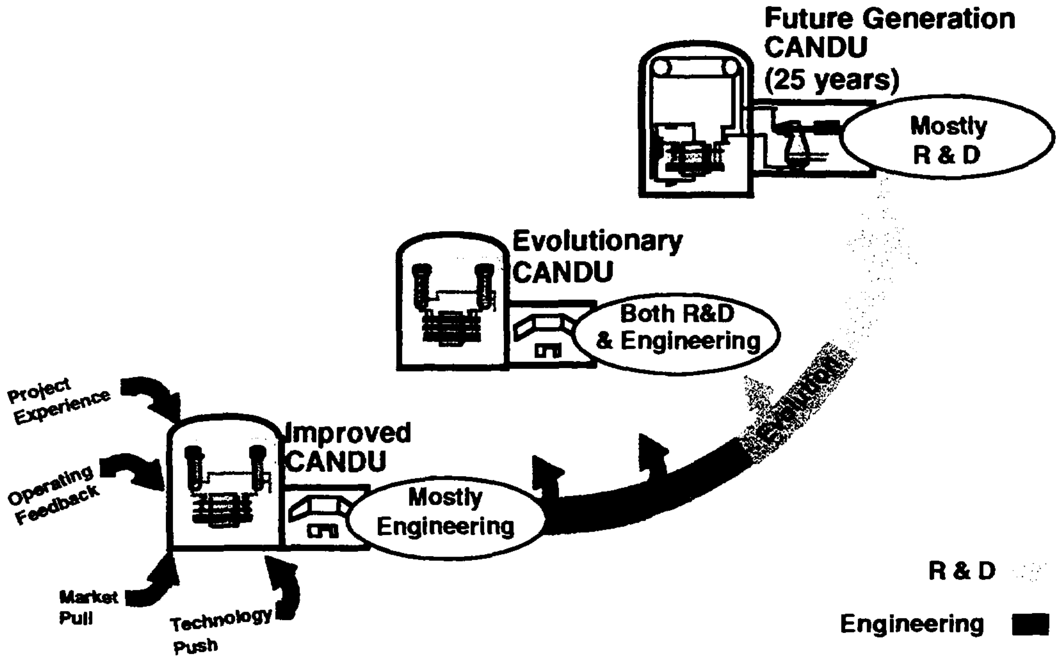

Figure 1: The Evolution of CANDU Reactors

Currently, AECL offers two products: the CANDU 6, of which there are four operating plants and four additional plants that will go critical before the end of the decade, and the CANDU 9, which is based on the twelve large multi-unit plants being operated by Ontario Hydro. These plants all use proven technology that was developed from R&D programs carried out in the past, mainly in Canada.

The 25 year development program retains all the essential features of CANDU reactors (heavy water moderation, on-power fueling, simple fuel bundle design, horizontal fuel channels, etc.). These are the features that make CANDU unique and enhance flexibility with respect to fuel cycles, safety, and cost. Within this framework, there are several opportunities for advancing the technology.

The end product of the 25 year program is not a specific design - it is a concept that includes the advanced features arising from our R&D programs. Moreover, since the approach to CANDU development is evolutionary, the final product will not suddenly just appear; rather, new features will be incorporated into our designs as the knowledge base is advanced. Also, as a result of the modular nature of the CANDU design, it will be possible to backfit many of these advances into existing reactors if there are sound economic or strategic reasons for doing so.

To carry out this evolutionary work, we have divided CANDU technology into 7 main areas: Safety Technology, Fuel & Fuel Cycles, Fuel Channels, Systems &

Components, Heavy Water & Tritium, Control & Instrumentation, and Constructability. There are three key strategic thrusts for these areas over the next 25 years: improved economics, fuel cycle flexibility, and enhanced safety/plant protection. Each of the 7 technology areas has specific goals associated with the three key strategic thrusts. In what follows, some aspects of these initiatives will be described.

3. ECONOMICS

Nuclear power plant economics depend on several factors, including initial capital cost, capacity factors, operating and maintenance costs, and output power.

While the overall unit energy costs averaged over the life of a nuclear plant are very competitive (owing to inexpensive fuel), nuclear plants have relatively higher initial capital costs when compared to, for example, natural gas plants. However, capital costs can be reduced significantly by improving components and by assembling the components faster. This, in fact, occurs for all high-technology products - at least, for those that are successful. For example, the first electronic devices used vacuum tubes, which required relatively large amounts of material to manufacture and high energy to operate. Vacuum tubes were replaced by discrete transistors that used much less material and energy. Discrete transistors were then replaced by integrated circuits that used even less material and energy. This was accomplished by constantly adding knowledge to the product - that is, knowledge replaced material and cost. The same process can be applied to nuclear plants, and every system and component in CANDU reactors is being assessed to do everything "faster, better, cheaper" using advanced knowledge.

Capacity factors, and operating and maintenance costs are affected by such determinants as operability of the plant, component lifetimes, and ease of maintenance. CANDU reactors already enjoy relatively high capacity factors, and occupy 7 of the top 25 lifetime capacity factor positions for operating plants above 300 MWe. Nevertheless, improvements are possible using more advanced information technology systems, reducing the complexity of systems, and incorporating long life components. CANDU fuel channels are a good example of how knowledge evolution has led to improvements. By understanding in some detail the various mechanisms affecting such phenomena as fracture toughness, creep and growth, and corrosion we have been able to make substantial improvements to fuel channels over the past decade. Current fuel channels will last much longer than those used in the earliest CANDU plants. They are defect free, are less affected by radiation, and contain smaller amounts of initial hydrogen that could adversely affect performance. By continuing to understand the basic phenomena affecting component lifetime and operability, and by developing advanced materials, we are confident that even greater gains can be made for most CANDU components.

Power increases can have a large beneficial effect on the unit cost of electricity, especially if they can be accomplished with relatively small changes in plant costs. One approach to increasing the power of CANDU reactors is to introduce Slightly Enriched Uranium (SEU) fuel containing 0.9 to 1.2% U-235. The SEU can be used to flatten the radial power distribution to produce about 15% more power, without changing the core design. Alternatively, owing to the modular nature of the core, it is possible to add more fuel channels. For example, the CANDU 9, a 925 MWe plant based on the large multi-unit stations used by Ontario Hydro, contains 480 fuel channels. The number of channels could be increased to 640 in a calandria vessel of essentially the same size, with an increase in power to 1275 MWe. In the longer term, it may be possible to operate the primary heat transport system at much higher temperatures (perhaps as high as 400-500° C, compared with the current 312° C) using organic coolants or molten salts, thereby substantially increasing the thermodynamic efficiency. Such a change would require considerable advances in our understanding of materials at these elevated temperatures under reactor conditions, but the efficiency gains could have a significant impact on unit energy costs.

4. ALTERNATE COOLANTS

Many designers have attempted to increase the primary coolant temperature in order to improve the overall system economics. With the possible exception of the LMR these attempts have been unsuccessful for one reason or the other. In the light of modern materials and chemistry knowledge, AECL intends to search over this field due to its very high potential payoff in plant capital cost. Using water as a coolant becomes less and less attractive as temperature increases due to the high pressures involved as well as the corrosive properties of high-temperature water.

The objective is to increase temperature and decrease pressure. At the same time the essential features of the CANDU concept will be retained. It is very likely that the fuel will be enriched slightly to compensate for additional absorption introduced by in-core materials required to tolerate high temperatures.

This is a research project and, as such, is not easy to quantify in hard schedules or plant data. It is uncertain in another sense – it will, almost certainly, require some form of prototype prior to commercial introduction.

5. SUSTAINABILITY - LONG-TERM FUTURES

The high neutron efficiency, simple fuel bundle design, and on-line fueling, make these reactors particularly well suited to burning a variety of fuels, as illustrated in Figure 2. The use of natural uranium (0.7% U-235) fuel is a major attribute of CANDU reactors and has allowed countries adopting CANDU technology to manufacture fuel without dependence on a source of enriched uranium.

However, the use of slightly enriched uranium (SEU) has the potential to increase uranium utilization and to reduce fueling costs by about 30%, if 1.2% enriched SEU is used. Indeed, power increases and/or cost savings could also be effected by using a waste product from LWR fuel reprocessing - reprocessed or recovered uranium (RU), which contains 0.9% U-235. Currently, most RU is stored at the reprocessing plants awaiting final disposition by utilities that recycle the Pu from spent LWR fuel. While in principle the RU can be re-enriched and recycled in LWRs, almost twice the energy can be extracted by recycling RU in CANDU reactors.

All nuclear fuel ultimately comes from U-235. As uranium resources become more expensive (perhaps some time in the latter part of the next century), it will be necessary to ensure that we make optimal use of existing fuel resources. One way of doing this is to extract the maximum possible energy from spent LWR fuel. Spent LWR fuel contains about 1.5% fissile material (0.6% Pu-239 and 0.9% U-235), compared with 0.7% fissile content in natural uranium fuel. Reprocessing plants can extract the Pu from the spent fuel, and the Pu is recycled back into LWRs. As discussed above, the RU with 0.9% U-235 is suitable for use in CANDU plants. However, both the Pu and U could be used as CANDU fuel by simply recycling LWR fuel without separating the Pu and U. Such processes are considered to be more proliferation resistant, since Pu is never produced in a pure state.

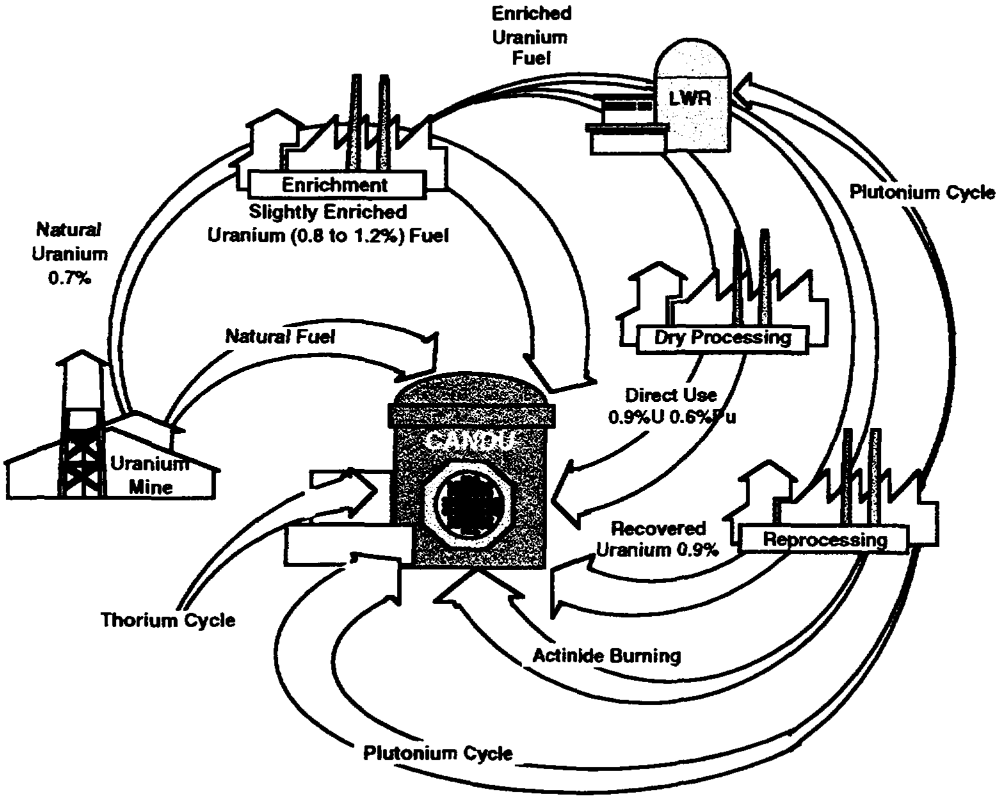

Figure 2 -- CANDU Fuel Cycles

AECL and the Korean Atomic Energy Research Institute are currently working together to develop a viable process for achieving this, called DUPIC - Direct Use of Pressurized water reactor fuel In CANDU (note that there are two types of LWR: pressurized water reactors, PWR, and boiling water reactors, BWR; DUPIC contains the name "PWR" since these are the types of LWR operated by Korea). The process refabricates spent LWR fuel elements into CANDU fuel bundles without going through a wet chemistry separation process.

Even the actinide wastes with long half lives from reprocessing plants can be used as fuel in CANDU reactors. For example, if the actinides wastes were placed in an inert fuel matrix (i.e., a matrix without fertile or fissile materials), then the actinide waste would only need to provide about 5% of the fissile content of natural uranium fuel to produce energy. Therefore, some of the wastes from spent fuel are actually resources when LWR/CANDU synergism is considered.

In summary, CANDU reactors can be used to extend current supplies of fuel by adopting one or more of the above options. Figure 3 shows the improvement in uranium utilization using some of these options, relative to a reference pressurized water reactor.

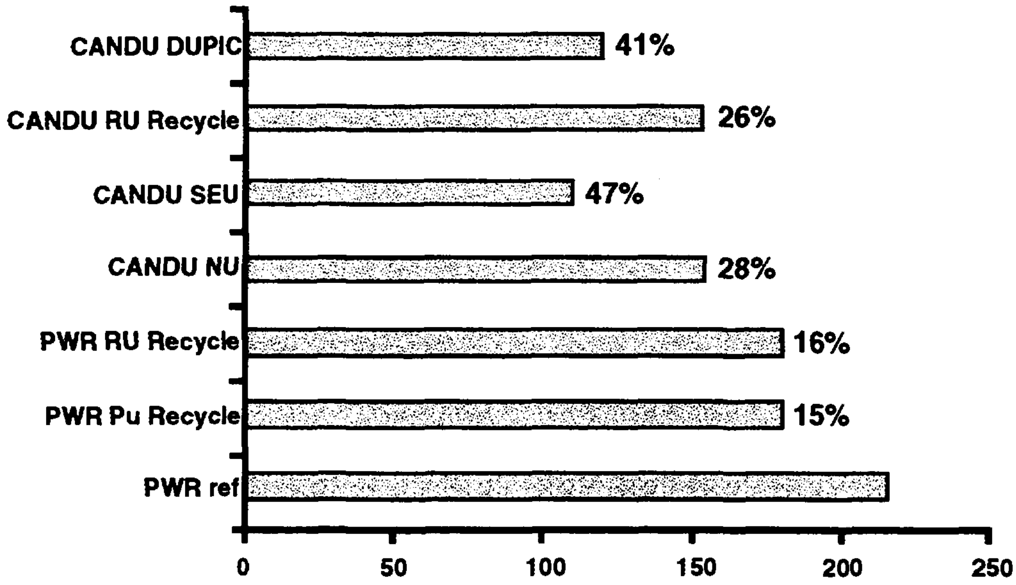

Figure 3: Specific Uranium Use (Mg/GW·a) (% Improvement over PWR ref.)

In the longer term, uranium resources could be extended by adopting thorium fuels for CANDU reactors. The world's resources of thorium are very large - perhaps 3 times those of uranium. India is a country rich in thorium. While thorium does not contain any fissionable material, thorium is a fertile material in which U-233 is produced in a reactor. There are a number of schemes for burning the U-233, including once-through cycles and reprocessing cycles. Using these cycles, CANDU reactors are assured of a fuel supply far into the future.

Another long-term possibility is the synergism between CANDU and Fast Breeder Reactors (FBR). FBRs are being considered by some countries as the long-term solution to dwindling uranium resources. However, FBRs are likely to be very expensive. If FBRs were used to fuel CANDU reactors, and the thorium cycle were adopted to extend fissile resources, then about 8-9 CANDU reactors could be supported for each FBR built. This would be the most economical approach to the introduction of FBR technology.

As the above discussion illustrates, CANDU reactors can not only be used to ensure that the maximum amount of energy is extracted from current fissile resources, but can also ensure security of fuel supply well into the future, even if uranium resources become scarce and/or expensive.

6. SAFETY AND PLANT ENHANCEMENTS

In CANDU reactors, the presence of the heavy water moderator surrounding the fuel channels effectively reduces the consequences of postulated severe accidents.

The reason for this is that if primary coolant is lost from the system, heat is transferred out of the fuel channel and into the moderator water. From the moderator, heat can be transferred to the environment via the normal moderator water cooling system. Even if the moderator were not available, the shield tank surrounding the calandria is capable of containing and maintaining a collapsed core in a cooled state. Therefore, in addition to the usual engineered safety systems in plants that meet international safety standards, CANDU reactors contain a number of passive safety systems that result from the inherent design of the reactor.

In the future, we can make even better use of the moderator system as a passive heat sink, so that in addition to safety considerations, CANDU reactors can be protected against severe damage that would impact on plant economics. New fuel channels are being developed that can transfer even larger amounts of heat to the moderator under loss of coolant conditions. New fuels are being developed that have high thermal conductivity, and that operate at lower temperatures. New moderator cooling systems are being developed for highly efficient heat removal based on natural circulation as opposed to forced convection using pumps. At the same time, such improvements could lead to ease of operation and lower capital costs due to the simplification/elimination of components. All these initiatives will build in an even higher degree of plant protection and safety based on both engineered and natural systems.

7. CONCLUSIONS

CANDU reactors will continue to evolve over the next 25 years, with an emphasis on cost efficiencies, fuel cycle flexibility, and enhanced safety/plant protection features. This will be done by building on the inherent characteristics of existing CANDU technology and by introducing well-proven new design features in a planned and orderly manner.