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SYNERGISTIC NUCLEAR FUEL CYCLES OF THE FUTURE

by

D.A. Meneley, Chief Engineer, and A.R. Dastur, Engineer Emeritus
ATOMIC ENERGY OF CANADA LIMITED
2251 Speakman Drive, Mississauga, Ontario L5K 1B2 - CANADA

P.J. Fehrenbach, General Manager CANDU Technology Development
ATOMIC ENERGY OF CANADA LIMITED
Chalk River Laboratories, Chalk River, Ontario K0J 1J0 - CANADA

K. H. Talbot, Director, Bruce A
Ontario Hydro
Bruce Energy Centre, Tiverton, Ontario N0G 2T0 - CANADA

ABSTRACT

The long-term future of nuclear fuel cycles is discussed. The strategies which can provide guidance to short-term development programs are examined. This includes the role of the CANDU reactor in resource conservation and reduction in waste. A survey of synergistic fuel cycles that will achieve these such goals is given. The implementation of such fuel cycles in currently operating CANDU plants is described.

INTRODUCTION

The objective of this paper is to look at the long-term future of nuclear fuel cycles. Its purpose is to examine some of the strategies which can provide guidance to short-term development programs. The cumulative effect of such programs will, of course, determine our long-term future; for this reason it is important to define short term plans to permit realization of a beneficial nuclear energy system in the long term. While our present technology continues to benefit mankind we need to be sure that this benefit will continue, and that the direction in which we are moving is the correct one.

In the early days of nuclear energy, a major concern was fuel supply; this led to a period of intensive work on breeder reactors whose "raison d'etre" is extension of the limited known reserves of uranium. Subsequent discovery of large deposits of uranium, primarily in Canada, Australia, and Russia has led to a relaxation of the thrust toward breeder reactors and a concentration on thermal power reactors *(5)*. The "winners" of the thermal-reactor race so far are the PWR, BWR, and PHWR systems. Fast breeder reactors can be considered as being in a pre-commercial stage of development, with no fully commercial application as yet.

The current status of nuclear fuel supply is characterized by a plentiful supply of natural uranium and thorium. The natural uranium is available at low prices. In addition there is a large inventory of depleted uranium, a moderate inventory of reprocessed uranium and plutonium, and a large inventory of highly enriched uranium and plutonium extracted from weapons as a result of the ongoing disarmament programs of major nuclear weapon states.

The issues addressed in this paper are related to finding the best use of these resources to maximize the long-term utility of what will be a very large nuclear-electric generating system within the next fifty years. Specifically, we will examine the role which the CANDU-PHWR power system can play in this enterprise. The paper is intended to establish a framework on which CANDU development programs can be based.

WORLD NUCLEAR FUEL INVENTORY

The central question underlying this paper is whether or not we need to worry about the supply of nuclear fuel in the world during the next fifty years. An answer can be obtained by comparing the economical uranium reserves with cumulative uranium usage based on world projections.

According to a paper presented at a recent KAIF/KNS meeting *(1)*, usable world uranium reserves would not be depleted for thousands of years even if the total capacity of nuclear plants were very high and if only today's reactor types were used. The more relevant figure for planning purposes is the amount of uranium available at a given price. Using latest estimates, uranium supplies under $30 per kg can meet the world demand for only a few decades. Clearly, some improvement is needed. In this type of market uranium price will respond immediately to increased demand. When fuel shortages develop the price of uranium will rise to the break-even level corresponding to the cost of recycled fuel, at which time fuel reprocessing will become a competitive alternative. Reprocessing is, even now, commercially available in Britain and France but the cost of reprocessing services is high. The resulting inferred cost of recycled fuel is too high for practical consideration. Under these conditions used fuel will be stored rather than being reprocessed.

Recycling, and the consequent expansion of fuel reserves, will not be viable if the break-even level is high. Therefore, a major factor in the continuing use of nuclear energy will be the cost of reprocessing. This cost effectively will fix the price of fuel for all nuclear energy systems. Unless this cost can be well defined and controlled, fuel supply concerns on the part of potential buyers of nuclear plants will constrain the installation of new plants early in the 21st century. Therefore, it is prudent to consider ways in which we can "stretch" the existing fuel supply.

The simplest way to stretch the fuel supply is to use reactors with high energy production per megagram of uranium or thorium mined. The next step is to make used of tandem cycles from reactors which require high enrichment to those which can use the lower fissile inventory in used fuel. This will minimize the cost of reprocessing per unit of energy production. Third, additional fissile atoms can be produced by accelerator breeders or fast and thermal breeder reactors to provide appropriate fuel for thermal reactors. In this case it is important to choose thermal reactors with high conversion ratio, so as to maximize the energy production from the bred fuel and thereby reduce the fast reactor component, which is the expensive component, of the system.

The world's inventory of thorium represents an additional large energy source. The CANDU reactor is capable of burning thorium, given an initial fissile material inventory.

SYNERGISTIC FUEL CYCLES WITH CANDU

Beginning with the world power station "fleet" as it exists today (today is taken to be the year 2000, in round figures) there are 239 PWR reactors, 91 BWR reactors, and 34 PHWR reactors operating. The two LWR types use 3-4% enriched uranium, and the PHWR uses natural uranium. The PHWR has, necessarily, low parasitic neutron absorption and wellthermalized neutron energy spectrum. These characteristics result in a high uranium to plutonium conversion ratio (and an even higher thorium to uranium conversion ratio) relative to the LWR; the unit energy cost of the PHWR is competitive with that of the PWR. The metal-fuelled fast breeder reactor can be designed with a breeding ratio up to about 1.40. However, the FBR will have a higher specific capital cost than today's thermal reactors. Other reactor types exist at various stages of development; however, the main principles of tandem fuel cycles can be described using only the above four types.

Opportunities exist for coupling the fuel cycles of some of these reactors *(1,2,4,6,7)*. The result can be called a "synergistic" fuel cycle because benefits accrue to both reactor types involved in the cycle. Several of the synergistic fuel cycles provide CANDU with fuel of low fissile content.

CANDU fuel cycles with low initial fissile content operate with relatively high conversion ratio. The natural uranium cycle produces over 55 % of its energy from the plutonium that is created during fuel life. Resource utilization is over 7 MWd/kg NU. This can be improved by slight enrichment (between 0.9 and 1.2 wt % U235) of the fuel. Resource utilization increases to 11 MWd/kg NU. The LWR/CANDU Tandem cycle leads to an additional 77 % of energy. Dry reprocessing of LWR fuel with the OREOX process (a more safeguardable alternative to the PUREX process) provides an additional 50 % energy. Uranium recovered (RU) from separation of plutonium contained in spent LWR fuel provides an additional 15 MWd/kg RU.

In addition to the recycle of plutonium, the reprocessed uranium (REU) from LWR used fuel can be fabricated directly for use as fresh fuel in a CANDU, thereby increasing the energy output from each unit of mined uranium by 50 % with a corresponding decrease in the final volume of used fuel from the combined cycle. Some other feasible combinations are shown in Table I for once-through cycles in each reactor type. Recycling is, of course, an open option. The low concentration of fissile atoms required in CANDU fuel suggest that it will be the last step of any synergistic chain.

Thorium based cycles in CANDU operate at near-breeder efficiency. They provide attractive options when used with natural uranium or separated (reactor grade and weapons grade) plutonium as driver fuels. In the latter case, the energy from the U233 plus the initial plutonium content amounts to 4 GWd/kg Pu-fissile. This provides a plutonium utilization of 20 te/GW(e).y. Waste arisings are correspondingly lower. The same performance is expected from the use of FBR bred plutonium in the CANDU thorium cycle. With lower grade plutonium, such as from LWR spent fuel, as the driver, the utilization is 114 te/GW(e).y and the waste arisings 26 te/GW(e).y. With dry-reprocessed LWR spent fuel (a more safeguardable alternative to the PUREX process) as the driver the utilization is 90 te/GW(e).y and the waste arisings 22 te/GW(e).y. Recycling the U233 in spent CANDU thorium leads to a self-sufficient cycle (SSTC) that is independent of external fissile material. The exit burnup provided by such a cycle depends on specific CANDU design features such as operating flexibility. For current CANDU designs the exit burnup of the SSTC is between 10 and 15 MWd/kg.

The CANDU thorium cycle that uses natural uranium as the driver fuel provides a non-reprocessing option. However, the thorium inventory of the core is limited in such a cycle. It depends, as in the SSTC on the reactivity load that is built into the system. For current core designs, the inventory is limited to about 20 % of the core. But the energy contribution of the thorium is a high as in the SSTC. CANDU's low fissile requirement provides the possibility, through the use of non-fertile targets, of extracting energy from the minor actinides contained in spent fuel.

In addition to the resource utilization advantage described above, there is a corresponding reduction in waste arisings with such cycles. This is especially significant when separated plutonium is available as a fissile resource.

FUEL ACCUMULATION IN STORAGE

In the short term, stockpiles of ex-weapon fuels may be difficult to control and safeguard. Incorporation of these materials with appropriate other isotopes in a once-through fuel cycle could decrease their potential value for re-use in weapons as well as producing valuable electricity. In addition to partial "denaturing" of ex-weapon materials, these materials might be used to upgrade the quality of other potential fuels. For example, a small amount of highly-enriched uranium or weapons grade plutonium could be combined with thorium and the mixture used to fuel CANDU units.

The reactivity of fresh uranium-thorium fuel could be adjusted to achieve a relatively high burnup; burnable poisons could be added to reduce power peaking. While it is unlikely that used fuel could be recycled economically in the short term, a storage period of about 50 years would greatly reduce the activity level of stored fuel and hence would reduce the cost of eventual reprocessing.

In general terms, we can use today's favourable fuel supply and demand situation to create "accumulated fuel reserves" in used fuel bays and dry storage canisters. These reserves will increase the inventory of usable potential energy from uranium and thorium in the long term when resource prices rise. Criteria for creation of such secondary fuel reserves will help to define the best reactor types for use in the short and long term.

REACTOR TYPES FOR THE FUTURE

The next question which arises is whether or not we have the correct reactor types to meet the needs of the next century. Introduction of a new type will require at least twenty five years of development work. What are the alternatives available to meet this need if, in fact, new reactor types are needed? How should we adapt the present reactor systems so that we can introduce these new reactor types in an orderly way?

A recent paper *(3)* illustrates many opportunities for development of an energy park based on nuclear fission energy. The central element of this proposed system is the Bruce Energy Centre located on Lake Huron in Ontario, Canada. This proposed system is convenient for illustration of future possibilities.

THE BRUCE NUCLEAR POWER DEVELOPMENT TODAY

The generating facilities on this site are eight CANDU units of about 900 MWe capacity each, grouped into two integrated stations. In addition the site contains a heavy water production facility, training centre, a large waste storage facility and a number of other support elements. Adjacent to the Bruce site is a greenhouse farm and alcohol production plant and other agriculture-related industries heated by steam from the Bruce reactors.

The eight nuclear units on this site may be still producing electricity at the end of our 50-year period. They may have undergone major rehabilitations, or may even have been completely replaced. Let us assume that they have been replaced by updated CANDU units with output of 1250 MWe each. New heavy water production methods likely will have been replaced by more efficient and economical units than the Girdler-Sulphide units currently on the site. Otherwise, the Bruce site might look nearly the same at the end of fifty years as it does now. But there are wider possibilities.

A POSSIBLE FUTURE ENERGY CENTRE

The traditional single-purpose electricity production site may well be diversified in the future, as outlined in Reference *(3)*. Close-in facilities near the site could include heavy water production, tritium extraction, electrolytic hydrogen production, synfuel production, and other agriculture-related energy-intensive projects. In general, these facilities would lead to a broad line of products from the Centre rather than only electricity as is the case today from this type of site.

The issues for this site likely will be fuel supply and waste management. Considering the fuel supply, the CANDU units might still be using natural uranium or, if prices have escalated, one of a variety of other fuels. Recycled uranium from reprocessed LWR fuels is an attractive choice, since it should be abundant and have a low market value. Another possible choice is diluted HEU or Pu from ex-weapon inventory - which likely will be still available in fifty years. The essential argument is that the fuel chosen for this site will be the cheapest available; essentially no other limitations exist in this decision.

If we look further into the future (or if we consider a much larger population of CANDU reactors) then fuel prices will inevitably begin to rise at some point in time. The Energy Centre can react to such a change in a number of ways. First, the energy extracted from each unit of natural fuel purchased can be doubled through introduction of thorium as fertile material to increase the internal conversion ratio), so that the increment of unit energy cost coming from fuel price increases is reduced.

A second step for reducing fissile isotope cost might be to introduce a small proportion of LMR (Liquid Metal Reactors) fuelled with uranium or thorium. For example, one IFR (Integral Fast Reactor) on this site could supply enough fissile isotopes to fuel all eight CANDU reactors, if the CANDU's utilized thorium fertile material. Only the IRF would contain an integral reprocessing unit, which would produce both its own fuel and the enriched fuel for the once-through CANDU cycle.

CANDU cycles likely will remain in once-through mode because the fissile concentration of discharged fuel is inherently low due to high neutron economy. An exception may be the charge material for LMR units; CANDU spent fuel is suitable, as is, for blanket fuel in LMR or as makeup to the core fuel stream.

Notice that the type of new thermal reactor to be built on the site, either to increase total capacity or to replace existing units, is an open question. However, the thermal reactors chosen should have a high conversion ratio. The reason is that the IFR is capital cost intensive to build and operate; it is necessary for breeding of fissile material but otherwise represents only an additional capital cost. The site owner naturally would want to install a large number of cheap thermal reactors for each expensive fast reactor. Given that any IFR has a maximum output of excess plutonium for a given size, efficient thermal converter reactors would be preferred to minimize overall electricity cost.

Existing CANDU reactors fully meet this requirement. A short-term strategy of building CANDU reactors will fit with this long-term scenario; the CANDU can burn natural or slightly-enriched uranium until such time as fuel prices rise. Then, an IFR can be installed and the stored used fuel can be "mined". This additional fuel supply can control the fuel cost of the overall system into the long-term future.

WASTE MANAGEMENT

In a system such as the one outlined, the radioactive waste would contain only trace amounts of actinide elements in addition to middle-mass fission products. For this reason the waste will be almost inactive after only 1000 years. Also, a thorium-based fuel cycle produces waste of low radiotoxicity *(8)*, and especially with negligible concentrations of the higher actinides.It may, therefore, be feasible to dispose of these wastes directly under the reactor site, in either a deep mine or in deep drilled holes. On-site disposal is clearly preferred to eliminate the need for off-site waste transportation.

Reprocessing provides several alternatives for waste management. All plutonium and uranium would be burned in one or more of the reactors. The minor actinides could be recycled in the IFR for annihilation or in thermal reactors for transmutation and then annihilation. Heavy water reactors are inherently more useful for burning actinides because of their low fissile requirement and consequently their high operating thermal flux level. The high thermal flux provides a significant rate of a two-stage (transmutation /fission) annihilation process.

Every GW(e) of CANDU installed capacity will annihilate over 4 GW(e) equivalent of actinide production annually. In particular, recycling of the minor actinides in CANDU reactors would maximize the energy yield through transmutation of the non-fissionable to fissionable actinides.

THE WAY AHEAD

If we now consider the energy centre as a long-term goal; that is, a goal to be reached in fifty years, we can look at what needs to be done in the short- and medium-term to reach such a goal. Most of the parts of this program are well known *(9)*. In particular, high-conversion-ratio thermal reactors should immediately become a central feature of utility project planning. One such design (CANDU) exists now, but it needs to be modernized to increase its burnup and decrease used fuel volumes. This project is now underway. Raising the fuel enrichment from 0.71 percent to 1.2 percent greatly reduces the waste volume, especially with the thorium fuel option; it also offers some viable alternatives for reducing the unit capital cost. The burning of fuel discharged from LWR plants appears to be a very attractive alternative because the fissile content of either recycled uranium or uranium plus plutonium matches the fresh-fuel requirement of a CANDU design very well. Use of LWR spent fuel in CANDU increases uranium utilization by 82% and reduces waste volume by the same amount.

Various such fuel cycle options in CANDU and LWR are compared in Table 1. Note that operation of CANDU and LWR with independent fuel cycles produces significantly higher uranium requirement in the LWR; 217 Mg/GW(e).y compared with 157 Mg/GW(e).y in CANDU. Burning spent LWR fuel in CANDU (Cycle #7) drops the uranium requirements from 217 to 119 Mg/GW(e).y and the fuel disposal volume from 33.2 to 18.8 Mg/GW(e).y. Similarly, recycling LWR-Pu in LWR and LWR-U in CANDU (#6) reduces uranium requirement to 151 Mg/GW(e).y and disposal volume to 23.8 Mg/GW(e).y. Both interdependent fuel cycles show improvements in uranium requirements and disposal volume compared with recycling LWR-Pu and LWR-U in LWR (#3). The latter cycle requires 157 Mg/GW(e).y and produces 24.7 Mg/GW(e).y of waste.

Table 1

FUEL CYCLE OPTIONS FOR CANDU AND LWR

Fuel Cycle Option	Natural Uranium Requirements (Mg/GWy(e))	Fuel Disposal Requirements (Mg/GWy(e))
1. Enriched-U in LWR	217	33.2
2. LWR-Pu recycled in LWR	185	29.2
3. LWR-Pu and re-enriched LWR-U recycled in LWR	157	24.7
4. Natural-U in CANDU	157	157.0
5. Slightly enriched-U in CANDU	114	49.8
6. LWR-Pu recycled in LWR and recovered LWR-U in CANDU	151	23.8
7. LWR-Pu and LWR-U recycled in CANDU	119	18.8
8. Re-clad LWR spent fuel recycled in CANDU	125	19.7

Reprocessing spent fuel has its drawbacks. It adds to fuel disposal volume (This component is not included in Table 1). The use of refabricated CANDU fuel from chemically unreprocessed spent LWR fuel is a viable alternative to conventional reprocessing. Several refabrication options are available but their effect on fuel burnup in the CANDU phase of the fuel cycle are minor. Despite the presence of fission products and the minor actinides this fuel cycle reduces uranium requirements by 42 % over the LWR, (#8).

The thorium-fuelled CANDU reactor has a major role in optimizing the use of fissile material due to its efficiency of conversion of thorium to fissile uranium. Recycling of the fissile uranium results in a self-sustaining thorium-fuelled CANDU system.

An alternative to the use of bred plutonium to drive uranium-plutonium converters, is to use it to drive Thorium-U233 converters. Plutonium-enriched thorium has advantages in thermal reactors. The fuel cycle costs are lower and the newly formed U233 is not contaminated with U235. Furthermore, if the plutonium is concentrated in lumps within the thorium rods the effect on the dynamic behaviour of the reactor is reduced. This is a major advantage for the use of plutonium in thermal reactors. Addition of 1.2 wt % of fissile plutonium to the thorium fuel in CANDU provides an exit burnup of 40 MWd/kg. (The same plutonium content added to uranium gives an exit burnup of 20 MWd/kg.)

Other advanced-fuel reactor projects are being considered, especially in Japan. The Japanese Advanced Thermal Reactor represents another approach to utilization of reprocessed plutonium; ATR is best utilized as a plutonium burner. The technical challenges are very large and should fully engage the engineering research organizations of the world.

The most severe constraint is the last one, the treaty to prevent the spread of nuclear weapons and to eliminate them in states which now have them. In a very real way all of the engineering tasks are and will be held back unless this issue is solved.

COMMENTS

The purpose of this paper is to stimulate discussion about the needs and opportunities of the world's long-term nuclear energy system. It seems feasible to meet the long-term fuel requirements of this system; the future looks possible and achievable. It will not happen without thought and effort. To finish this talk I will give some numbers related to scale, based on OECD and IAEA figures. Nuclear generation now provides 16.5 percent of the world's electricity. Assuming zero increase in electrical demand over time, and assuming a gradual decline in the use of fossil fuels for making electricity and for heating, nuclear generating capacity would be many times larger in 50 years than it is today, or in other words, 2000-3000 units would be operating in the world. This seems a large increase (1500 to 2500 units) but we must remember that it still would satisfy only 25-50 percent of the total world energy demand. A new logic might be called for if we consider very large nuclear energy systems - for example, remote siting with synthetic fuels as the main product of the remote plants.

The nuclear enterprise has only begun. Its beginnings were blessed by people of great wisdom and insight. It is up to this generation to guide development wisely for the next fifty years.

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