# PRESSURE TUBE REACTORS AND A SUSTAINABLE ENERGY FUTURE: THE ULTRA DEVELOPMENT PATH

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## Abstract

Nuclear energy must be made available, freely and readily, to help meet world energy needs, concerns over energy price and security of supply, and alleviating the uncertainties over potential climate change. The perspective offered here is a model for others to consider, adopting and adapting using whatever elements fit their own strategies and needs. The underlying philosophy is to retain flexibility in the reactor development, deployment and fuel cycle, while ensuring the principle that customer, energy market, safety, non-proliferation and sustainability needs are all addressed. Canada is the world's largest exporter of uranium, providing about one-third of the world supply for nuclear power reactors. Pressure tube reactors (PTRs), of which CANDU® is a prime example, have a major role to play in a sustainable energy future. The inherent fuel cycle flexibility of the PTR offers many technical, resource and sustainability, and economic advantages over other reactor technologies and is the subject of this paper. The design evolution and development intent is to be consistent with improved or enhanced safety, licensing and operating limits, global proliferation concerns, and waste stream reduction, thus enabling sustainable energy futures. The limits are simply those placed by safety, economics and resource availability.

## 1. Introduction: Classic, Lite and Ultra

With expectations of significant expansion in nuclear power programs worldwide and the resultant concerns about uranium availability and price, and the prior emphasis on simplistic fuel cycles, there is a growing desire to improve resource utilization by extracting more energy from each tonne of mined fissionable material. Attention is therefore being increasingly focused on fuel cycles that are more energy efficient, reduce waste streams and ensure sustainable energy futures. The developments usually focus on fast spectrum reactors for the distant future. There are also many compelling reasons to continue to utilize and optimize advanced fuel cycles in PTR (CANDU-type) thermal spectrum reactors, including "closable" and sustainable cycles. Hence the PTR development path utilizes complementary designs that are directed at specific customers and markets, both now for meeting present energy needs and for addressing future environmental and sustainability requirements. These are the PTRs that address the multiple requirements of energy security, competitive cost, sustainable fuel cycles, reduced waste storage and streams, and assured licensability, and I use CANDU as an example:

a) The CANDU "Classic", being presently the D2O/D2O (C-6) system, optimized for natural and slightly enriched uranium use to provide independence from uranium enrichment sources and hence supply surety, as a reliable and proven introductory unit, and which as a result has a slightly positive CVR and an extremely simple fuel design.

b) The CANDU "Lite", being presently the D2O/H2O Advanced CANDU Reactor (ACR) system, optimized for competitive power markets with lower capital cost and LUEC, using

LEU to provide a slightly negative CVR and higher efficiency, and hence has a slightly more complex fuel with a burnable poison as in current LWRs but also able to use alternate fuel cycles as resources shift in supply and cost.

c) The CANDU "Ultra", being a D2O/H2O variant (SCWR), optimizing the development pathway for mass global deployment, requiring higher efficiency (50%), no core melt, size flexibility, cogeneration options and includes an alternate new fuel cycle (thorium), reduced licensing uncertainty, and implementing in a smooth development pathway that avoids switching the nuclear technology but capitalizes on the advances made in the thermal power industry.

Experience of building each builds towards building the next. The lessons learned, are the keys to success: effective project management, an assured and proven "buildability", and a defined and fixed cost with firm schedule adherence. This is *not* standardization of design as pronounced by some to reduce costs and uncertainty: it is learning from experience as an essential element of the "learning curve". After all, as a simple example, no one now buys an auto that is a sixty year old design, that has the same motor, efficiency, safety systems and features as that originally as was sold and developed all those years ago. The Super Critical Water Reactor (SCWR) is the true "concept car' of the future.

Assuring these elements of flexibility and continuity not only minimizes risk and maximizes returns; it also provides the owner/operator with an assured product for the full lifetime, and for whatever extension and flexibility that is possible in the foreseeable and unforeseeable future.

## 2. DC to AC: Waste to Energy

The learning concept is firmly embedded in this CANDU development pathway, as so-called Generations of reactors continuously evolve towards more efficient, safer, cheaper and simpler advanced reactors (Generation II to Generation V).

But there is another constraint to examine: that of fuel resources. A simple calculation [1] shows that although there is no shortage, there is a finite lifetime, because the present demonstrated fuel cycle (DC) without recycling is both wasteful and has too much unused energy in the spent fuel, which is often regarded as waste.

Many present thermal reactors (LWRs) use uranium as the main fuel supply, with some recycling of Pu mixed-oxide fuel (MOX). The cycle is essentially a once-through system, with fuel irradiated to about 40,000 MWd/t or so, and then stored until cooled and ready for Pu separation, or kept in interim storage buildings (e.g., Zwilag in Switzerland), until ready for sending to the underground repositories planned in many countries (Finland, France, Canada, etc.). As an order of magnitude, an operating once-through cycle 1 GW (e) LWR today uses about 180t/a of U for fuel [2].

With over 400 reactors operating today, present world demand is ~70,000 t/a. Today's estimates of identified reserves are about 5 MtU at a cost of <$130/kg, [3, 4]. Even allowing a doubling or tripling of this estimate to, say, 10 MtU, just 1000 reactors operating for 60 years will use all the world's cheapest uranium (or by about 60,000 reactor operating-years) with present fuel cycles technology.

Only the present 400 reactors could be kept going for another 150 years, leaving a shortfall is about 3000 reactors (or some ¾ of the need) in the anticipated energy future before 2050 or so. This is not a cause for alarm - there is plenty of uranium, and more uranium reserves will be found but at higher prices (cf. oil, gas and other commodity markets). Aggressively adopting recycling and increased fuel utilization might even allow up to 1500 reactors.

So there emerge at least two views of fuel cycles, which we may summarize as follows.

### 2.1 The traditional Demonstrated Cycle (DC) view

For those with near-term access to uranium, such as the US, France, and Canada, the uranium fuel cycle is already a demonstrated cycle (DC), and is fine while uranium is cheap and assuredly available.

There is always more uranium to find, even though the cycle is known to be unsustainable (as per the above calculations), and most current reactors (LWRs) are not particularly efficient fuel users.

When (or if) uranium becomes too scarce and/or expensive, all one has to do is switch to (breeder) fast reactors, and/or Pu recycle, even if it is more expensive and requires introducing a different reactor technology. Given the large initial Pu load for a fast reactor core, the transition has to occur well before U becomes scarce to maintain any growth in energy production. A number of countries already are planning or talking up this longer-term switch to a plutonium-driven recycle (e.g. Japan, France, Russia, China, Korea,), especially if they do not have long-term uranium supplies.

The U-switch point is far enough away, and it is too costly to use any alternate now in existing thermal reactors. Since spent fuel waste is not an issue and can be stored retrievably anyway and used in fast reactors. Some improved efficiency can even be realized by recycling the uranium in the spent fuel from LWR thermal reactors, such as the re-use of recovered uranium (known as RU) in HWR types that only need low enrichment.

### 2.2 The new Alternate Cycle (AC) view

For those without access to large uranium reserves, or needing energy supply surety, a new alternate cycle (AC) is needed that will ensure sustainable supply and smaller waste streams.

There should be a more intrinsically proliferation-resistant cycle, with no significant Pu generation, thus not requiring all of today's policing and international stress. It also must not require introducing a new reactor technology, and acknowledge the ownership and deployment of U-enrichment technology as a proliferation concern while still allowing vastly expanded reactor builds.

Such a fuel cycle is available now, using Thorium, which is more globally plentiful (perhaps 3 times more than U ?), so meets the future need. With careful fuel design and recycling, a thermal reactor gives a near breeding cycle, so is more sustainable with much lower (up to ten times less) waste amounts and storage needs. This Th-switch would enable more reactor deployment using today's reactor technologies and help stabilize fuel cost and supply, and avoids having to introduce many fast reactors.

Such an AC path is already being explored (e.g., by India, Norway, Canada and others), with the transition to a near self-sustaining predominantly thorium-fuelled cycle being initiated by burning

Pu as the start-up fuel. The cycle thus reduces Pu inventories/stocks during transition to a primarily Thorium near-breeder cycle using separated U233.

This DC-AC schism and/or transition is real and could totally alter the global fuel cycle and the reactor deployment opportunities. In fact, some of India has already chosen to develop this AC route as a national priority. Such AC concepts are in fact not new; what is new is the concept that an alternate sustainable and closable fuel cycle may enable greater benefits from nuclear energy deployment worldwide.

## 3. The CANDU Ultra pathway

Because of inherent technical characteristics, of D2O moderation and distributed channels with flexible fuelling, PTRs have a great deal of fuel cycle flexibility and this has been the subject of significant R&D by AECL, and others. The combination of relatively high neutron efficiency (provided by heavy water moderation and careful selection of core materials), on-line fuelling capability and simple fuel bundle design mean that PTR reactors can use not only natural and enriched uranium, but also a wide variety of other fuels. These include:

a) re-cycled uranium into C6 and ACR;

b) thorium-based fuels with U233 recycle;

c) minor actinides "intermediate burner";

d) MOX fuels in ACR; and

e) re-cycled LWR and ACR fuel into C6/current CANDU fleet.

Synergistically, and to provide highly efficient reactors, advanced reactor concepts include the use of the super-critical/reheat PTR concept (GenIV) "Ultra" reactor[1], which can couple thermal efficiencies of some 50% using a proliferation resistant thorium cycle with a near-breeder cycle. In addition, the advanced PTR lends itself to indirect and direct hydrogen production, which can be coupled with a power grid, which then allows a greater usage of wind power.

## 4. Observations and Conclusions

The optimization and development potential of the PTR design is coupled to the entire global sustainability model for future energy systems, via the fuel cycle and the reactor design, enabling sustainable resource use and the hydrogen age. This view is different from conventional or existing fuel cycle thinking, which envisages a shift in technology, and reliance on existing fuel cycles and raises the consideration and planning for when a DC to AC switch occurs, as it must.

In the meantime, current CANDU technology (C6 and ACR) can and will provide a logical enabling development path towards more efficient designs and fuel cycles.

[1] Ultra-supercritical Thermal Reactor ©

Global nuclear fuel cycle must support and maintain international trade, and address energy and environment needs. While optimizing nuclear power, attention must be given to the associated fuel cycle and waste management technology to ensure economic and environmental sustainability.

Developing alternate "closable" fuel cycles (that require enrichment, reprocessing, separation and advanced cycles) meets all the projected global needs. CANDU technology and its PTR development path (Classic-Lite-Ultra) can help ensure that nuclear power technology remains competitive and contributes to national and international energy supply and security, while addressing proliferation risks.

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## 6. References

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[2] House of Representatives Standing Committee on Industry and Resources, "Australia's uranium – Greenhouse friendly fuel for an energy hungry world", Canberra, Australia, 2006 November.

[3] IAEA, Australia Uranium government report, citing in Table 3.1 on p.150.

[4] OECD-NEA, Uranium 2005: Resources, Production and Demand, pp.15-16, 102-103.