CANDU®: Setting the Standard for Proliferation Resistance of Generation III and III+ Reactors

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Abstract. Factors contributing to the proliferation resistance of CANDU reactors are examined, from the point of view of both intrinsic design features (related primarily to fuel cycle details and operational requirements), and extrinsic measures (primarily IAEA safeguards). It is shown how the technical features of CANDU reactors and fuel cycle, in most cases derived from the fundamental physics of heavy-water power reactors, together with effective IAEA safeguards, demonstrate a degree of proliferation resistance that sets the standard for Generation III and III+ reactors.

1. Introduction

One of the most important challenges facing today's global nuclear power industry is the assurance that nuclear power plants and their fuel cycles achieve the highest degree of proliferation resistance. This is not a new issue: the goal of ensuring that civilian nuclear technology does not contribute to the spread of nuclear weapons has existed since the dawn of the nuclear power age. What is new is the priority being assigned to this, and the visibility it has on the international agenda. In this respect Canada has taken a leading role in establishing an international consensus on methodologies for assuring enhanced proliferation resistance in existing and new nuclear energy systems. Canada's involvement in the development and support of international safeguards dates, in fact, to the founding of the IAEA.

The complexity of today's geo-political environment, coupled with the serious consideration being given to nuclear power in many countries as a way of satisfying growing demands for safe, secure and non-polluting energy supply, is strongly coupling the technical and political dimensions. The common objective of both technology suppliers and political leaders is to ensure, with transparency and confidence, that nuclear power continues to support the non-proliferation of nuclear weapons.

The nuclear renaissance will bring new safeguards challenges before the IAEA in the form of non-traditional fuel cycles and system designs, in states that may or may not have an existing nuclear program. The considerable near-term build campaign of Generation III and III+ reactors will necessitate a reliance on proven technologies and processes wherever possible. It is imperative that these technologies incorporate the highest degree of proliferation resistance.

In this paper, the proliferation resistant features of the CANDU reactor and its fuel cycle are described, along with IAEA safeguards that are typically applied at each facility. CANDU technology is unique among commercial nuclear energy systems for its use of on-load refuelling and heavy water moderator. While these design considerations give CANDU reactors unmatched fuel cycle efficiency and flexibility that can contribute to global fuel cycle sustainability [1][2], these same design features, viewed superficially, can lead to misperceptions about CANDU proliferation resistance. It will be shown how the technical features of CANDU reactors and fuel cycle, in most cases derived from the fundamental physics of heavy-water power reactors, together with effective IAEA safeguards, demonstrate a degree of proliferation resistance that sets the standard for Generation III and III+ reactors.

2. Proliferation Resistance

Proliferation resistance is defined by the IAEA as “that characteristic of a nuclear energy system that impedes the diversion or undeclared production of nuclear material, or misuse of technology, by States intent on acquiring nuclear weapons or other nuclear explosive devices” [3]. In general, proliferation resistance results from a combination of, *inter alia*, technical design features, operational modalities, institutional arrangements and safeguards measures. In CANDU technology, these features are strongly linked and self-enforcing, with the result that their combination is greater than the sum of the parts.

A number of expert bodies have examined the issue of how to assess Proliferation Resistance of new nuclear energy systems, including two notable recent contributions by the INPRO project of the IAEA [4] and the Proliferation Resistance and Physical Protection (PRPP) methodology of the Generation IV International Forum (GIF) [5]. Both the INPRO and GIF approach recognize the distinction between “intrinsic” or “inherent” design features of a system, and “extrinsic” or “institutional” measures.

Intrinsic proliferation resistance features are those that result from the technical design of nuclear energy systems, including those that facilitate the implementation of extrinsic measures. Examples of intrinsic features are:

- the nuclear material's chemical form, radiation field, heat generation, and spontaneous neutron generation rate;
- the complexity and time required for modifications necessary to misuse a civilian facility for weapons production purposes;
- the mass and item quantity of nuclear material relevant to weapon production (e.g. one Significant Quantity as defined by the IAEA);
- the expertise and time required to divert or produce nuclear material and convert it to weapons useable form; and
- design features that limit access to nuclear material.

The GIF PRPP methodology describes four measures that one may use in assessing intrinsic proliferations resistance of specific diversion strategies involving specific nuclear energy systems: technical difficulty of the strategy, proliferation time, proliferation cost, and fissile material quality.

Extrinsic proliferation resistance measures are those that result from States' decisions and undertakings related to nuclear energy systems. Examples of extrinsic measures include:

- IAEA comprehensive safeguards and additional protocol;
- commitments to effect international nuclear non-proliferation norms and guidelines such as the Nuclear Suppliers’ Group Supply Guidelines;
- bilateral treaties concerning nuclear co-operation for peaceful purposes; and
- national policies and laws regarding exports.

The GIF PRPP methodology describes two measures that one may use in assessing extrinsic proliferations resistance of specific diversion strategies involving specific nuclear energy systems: detection probability and detection resource efficiency (or cost-benefit of safeguards). For example, these two measures taken together would assess effectiveness and efficiency of IAEA safeguards.

It is recognized that both intrinsic and extrinsic aspects are necessary and complementary components of effective proliferation resistance; i.e. that intrinsic features, by themselves, are insufficient for providing an acceptable barrier to proliferation. Of particular importance are the intrinsic features that enable an efficient and effective safeguards approach, a characteristic referred to as “safeguardability”. The safeguardability of the CANDU reactor (represented in the Gen III and Gen III+ classification as Enhanced CANDU 6 and ACR-1000, respectively) can be traced to a number of inherent proliferation barriers and safeguards-enabling features that derive from the fundamental physics of heavy-water power reactors.

In the following sections the major contributors to intrinsic and extrinsic proliferation resistance of CANDU reactors will be discussed in more detail.

3. Description of the CANDU Reactor

Two commercial variants of the CANDU design will be discussed in this paper. Both designs utilize heavy-water (D_2O) in a low-pressure moderator, which surrounds hundreds of pressurized fuel channels containing fuel and pressurized coolant. The fuel is in the form of 50-cm long bundles, each weighing roughly 20 kg, which are refuelled continuously while the reactor operates. This on-load refuelling is necessary to keep the core within its prescribed reactivity envelope.

The CANDU 6 reactor is the design currently operating in five countries (Argentina, Canada, China, South Korea, and Romania). It uses natural UO_2 fuel bundles located in 380 fuel channels, and operates with an electrical power output of about 700 MWe, and an average design burnup of 7500 MWd/Te.

The ACR-1000 reactor is a new design with an output in the 1100 MWe range. The ACR-1000 is also heavy-water moderated and on-load refuelled, but utilizes LEU UO_2 fuel bundles (2 wt% enrichment) located in 520 fuel channels. The ACR-1000 is designed for higher power output but similar core size to the CANDU 6, as the fuel channels are closer together. The average design fuel burnup in ACR-1000 is 20,000 MWe/Te.

A schematic diagram of the ACR-1000 is given in Figure 1. This diagram also serves as a schematic for CANDU 6, with the exception of the labelling of light-water coolant in the legend.

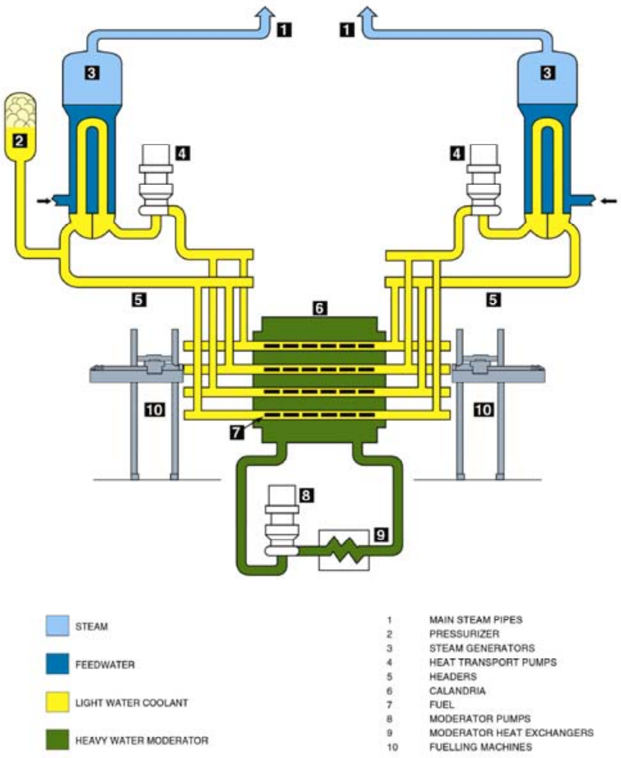

FIG. 1 Schematic of ACR-1000 Design

4. Intrinsic Features Contributing to CANDU Proliferation Resistance

The intrinsic proliferation resistance features of CANDU technology can be separated into those related directly to the fuel cycle, and those related to specific operational characteristics.

4.1. Fuel Cycle Features

It is important to note that proliferation resistance is a characteristic of the entire fuel cycle, and not just the reactor technology. In this respect a significant feature of the CANDU-6 natural uranium fuel cycle is the lack of enrichment, and the consequent simplification of fuel cycle safeguards.

With regard to the normal operating envelope, the fissile plutonium assay of used CANDU natural uranium fuel is comparable to that of PWR spent fuel (roughly 70% fissile weight fraction), as shown in Table I. This result, which may appear counter-intuitive since the average burnup of CANDU fuel is significantly less than that of PWR fuel (by a factor of at least five), is due to the uniquely well-thermalized neutron spectrum in the CANDU. The CANDU plutonium isotopic ratio in Table I was calculated using the lattice code WIMS-AECL for the CANDU 6 design, but the numbers are indicative of the ratio in ACR-1000 spent fuel as well.

A CANDU reactor is a relatively sparse generator of plutonium as a weight percentage of its used fuel. In order to obtain enough plutonium for a nuclear explosive device (a "significant quantity" or SQ, by IAEA standards, equivalent to 8 kg Pu), over 100 irradiated CANDU fuel bundles with a total mass of over 2 tonnes would be required. The comparable number for a commercial PWR is about two spent fuel assemblies. The relatively high mass and item count necessary for successful diversion of an SQ of CANDU fuel demonstrate an inherent proliferation resistant benefit.

Table I. Plutonium Isotopic Content in Spent CANDU and PWR fuel

	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu	% Fissile
CANDU	0.1%	66%	27%	5%	1%	**71%**
PWR [6]	1.3%	63%	25%	6%	5%	**69%**

CANDU spent fuel has a high degree of uniformity in burnup from bundle to bundle, which means that the fissile plutonium isotopic ratio does not vary appreciably among spent fuel bundles – a marked contrast to batch-fuelled cores that see significant variation in spent fuel content between the centre of fuel elements and their lesser-irradiated end regions, where fissile plutonium isotopic ratio would be higher. In general the relative uniformity of burnup in CANDU fuel leads to simple characterization of the fissile content of the spent fuel, which is a positive feature from a proliferation resistance standpoint.

This relative uniformity of burnup is achieved through both axial shuffling of CANDU fuel during residence in the core, and a high degree of axial and radial flux flattening in the core achieved through on-line refuelling. Since CANDU fuel channels are only partially refuelled during a single refuelling operation, each fuel bundle is moved along its respective fuel channel during its residence in the core, seeing changing levels of neutron flux. Axial flux flattening is achieved through bi-directional refuelling patterns, whereby neighbouring channels are refuelled from opposite directions. Radial flux flattening is achieved through differential refuelling rates between radial zones of the core.

4.2. Operational Features

Whether considering the CANDU 6 or the ACR-1000 design, on-load refuelling is a continuous operation, necessary in order to maintain criticality and regional safety margins in a reactor core that has little excess reactivity. Remotely controlled and fully automated fuelling machines perform all refuelling operations; the reactor cannot be refuelled manually. The fuelling machines represent one of the most complex and critical components of CANDU technology, drawing upon decades of evolutionary engineering for reliable performance at the required duty cycle only; they cannot, with any reliability, be pushed significantly further.

Because of these features (low excess reactivity and constraints of fuelling machine operation), it is not credible that a CANDU reactor core could be operated for significant durations at low core burnup for the purpose of high-purity fissile plutonium production. The fuelling machines are not capable of the sustained duty cycle this would require and hence the reactor would not be able to maintain safety margins, nor remain critical.

The CANDU core as a whole is sensitive to fuel management decisions, and regional reactivity must be monitored and balanced as an integral part of steady-state operation. The flux throughout the core is measured with an array of in-core flux detectors, and this information would clearly indicate any deviations in fuel management from nominal operation. As this information is available to the IAEA for verification of declared operation parameters, this provides an additional level of oversight of the operation of CANDU, and confidence that it is being operated within its design envelope.

This also affects the capability for rapid refuelling of selected channels, but also the capability to maintain regional overpower margins, and ultimately core reactivity. Thus the inherently low excess reactivity of the CANDU core, the highly complex and mission-oriented nature of the fuelling machines designed to maintain steady core power under these restrictive conditions, and the requirement to fully characterize the core flux distribution on a continuous basis, combine to discourage misuse of the core for the purposes of weapons-grade material production.

Moreover, the automated nature of the entire refuelling process means that a continuous digital record is created that could be potentially tracked in an automated process by the IAEA to verify declared operation, using software to track trends and flag discrepancies with minimal human intervention until required. If desired, this concept could afford a level operational transparency (including fuelling machine location and activity, regional flux levels, etc.) that would be unmatched and unavailable in any other commercial power reactor technology.

Finally, CANDU fuel has historically achieved an exceptionally low defect rate (<0.1%) due primarily to its relatively low burnup, combined with a number of fuel engineering improvements implemented since the first CANDU started operation in 1962. This presents an inherent barrier to the attempted diversion of fuel by disguising it as defective fuel.

5. Extrinsic Measures Contributing to CANDU Proliferation Resistance

The extrinsic proliferation resistance measures applicable to CANDU technology include the supply requirement for having a bilateral treaty with Canada that specifies the necessity for nuclear material used by and produced by CANDU technology to be subject to IAEA comprehensive (or facility-specific) safeguards, as a measure to verify peaceful uses only. These treaties all call for a full suite of consent rights on reprocessing, high enrichment (of Canadian supplied uranium), and equipment, material and technology re-transfers.

IAEA safeguards provide independent international verification that nuclear material is not diverted from its intended civilian use, and that there is no unreported production of nuclear material in civilian fuel cycle facilities. All CANDU reactors are subject to IAEA safeguards, and there has never been a known diversion of CANDU spent fuel. Moreover, with the high reliability of IAEA safeguards applied to CANDU reactors, the probability of CANDU spent fuel being successfully diverted is low, as is the probability of undeclared material being irradiated without detection.

Methods and equipment for IAEA safeguards for CANDU reactors were established in the 1970s and 1980s. The CANDU safeguards system consists of installed IAEA technology for surveillance and item accountancy verification, reviewed either through IAEA inspections or through remote monitoring supplemented by unannounced inspections. The remotely operated and highly automated fuel handling process in CANDU reactors makes automated monitoring of individual fuel bundle movement a highly reliable and straightforward exercise. It is possible to track every CANDU fuel bundle throughout its life cycle, as well as detecting with high probability any undeclared irradiation and movement of fuel bundles. This level of comprehensiveness in CANDU safeguards, enabled in part by the automated and transparent nature of the fuelling process, in unmatched in any other commercial power reactor technology.

CANDU safeguards equipment is constantly upgraded as new and improved technologies are introduced. For example, see Table II for a list of current CANDU 6 safeguards equipment, and Figure 2 for further description.

Table II. Common IAEA Safeguards Equipment for CANDU (implemented as required)

Safeguards Device	Location	Description
Core Discharge Monitor (CDM)	Reactor vault	A combination of neutron and gamma radiation detectors in the reactor vault is used to count irradiated fuel discharges from both reactor faces.
Spent Fuel Bundle Counter (SFBC)	Irradiated fuel discharge path from vault to bay	A set of radiation detectors is used to count irradiated fuel bundles as they are transferred through the irradiated fuel discharge port in the vault to the spent fuel bay.
Closed Circuit Television (CCTV) Surveillance System	Spent Fuel Bay and some vault penetrations	Video cameras monitor for undeclared fuel movements. All CANDU facilities have cameras in the spent fuel bays. Cameras may also be located in other locations to monitor for undeclared removal of irradiated fuel.
AECL Random Coil (ARC) Sealing System	Spent Fuel Bays	Irradiated fuel is stored in tamper-indicating enclosures with a lid fastened using IAEA-approved ARC seals to ensure that bundles are not removed.
Yes/No Radiation Monitors	Fresh Fuel Port, Auxiliary Port, two pipes in spent fuel bay.	Radiation detectors are used to detect discharge of irradiated fuel through vault penetrations other than the irradiated fuel discharge port; specifically, the fresh fuel port and the auxiliary port.
Spent Fuel Verifier	Spent Fuel Bays (only where ARC Sealing is not used)	A collimated gamma spectrometer is lowered into the spent fuel bay to verify the authenticity of spent fuel during IAEA inspections. This instrument is used at some stations that do not use the ARC Sealing System.
Cerenkov Viewing Device	Spent Fuel Bays (only where ARC Sealing is not used)	The CVD is used to verify the authenticity of spent fuel stored under water by amplifying the faint Cerenkov glow and making it visible to the inspector.

6. Summary

Nuclear weapons proliferation is ultimately a political decision that can be mitigated through technological barriers and institutional controls. Historically, civilian nuclear power reactors under international safeguards have not proven to be attractive targets for nuclear weapons proliferation, but do present a valid proliferation risk that must be managed. Accordingly, achieving the highest degree of proliferation resistance is both a responsibility of technology suppliers and an expectation of the public and political leadership, with transparency and confidence afforded through international oversight, such as that provided by the IAEA.

CANDU technology has incorporated intrinsic proliferation resistance features since its outset, derived mainly from the fundamental physics of heavy-water moderated reactors. While these intrinsic features minimize the attractiveness of CANDU technology as a target for proliferation, extrinsic measures are still required to provide verification and deterrence through timely detection. IAEA safeguards have been successfully incorporated in CANDU reactors for decades, and continue to evolve as newer technologies are introduced.

Through these intrinsic features and extrinsic measures, CANDU technology has a proliferation resistance that is second to none. Combined with its unparalleled safety and fuel-cycle flexibility, CANDU technology provides an attractive platform for meeting the global needs of safe, secure, and non-polluting energy supply.

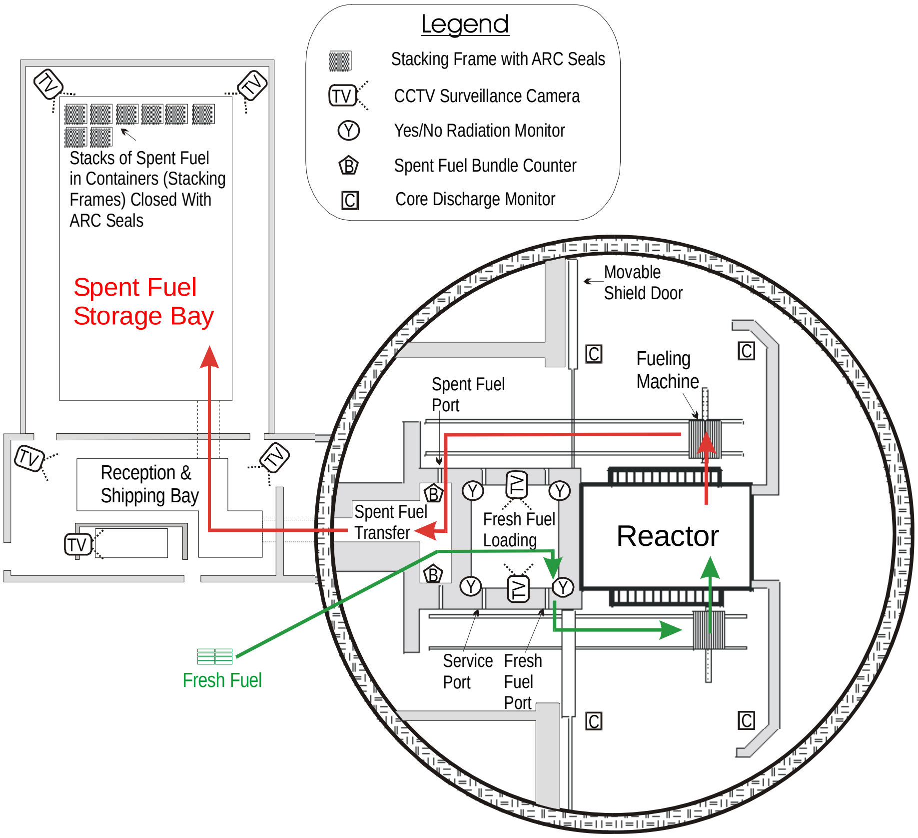

FIG 2. Typical IAEA Safeguards Equipment for CANDU [7]

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