OVERVIEW OF THE CANDU® FUEL HANDLING SYSTEM FOR ADVANCED FUEL CYCLES

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ABSTRACT

Because of its neutron economies and on-power re-fuelling capabilities the CANDU system is ideally suited for implementing advanced fuel cycles because it can be adapted to burn these alternative fuels without major changes to the reactor.

The fuel handling system is adaptable to implement advanced fuel cycles with some minor changes. Each individual advanced fuel cycle imposes some new set of special requirements on the fuel handling system that is different from the requirements usually encountered in handling the traditional natural uranium fuel. These changes are minor from an overall plant point of view but will require some interesting design and operating changes to the fuel handling system.

Some preliminary conceptual design has been done on the fuel handling system in support of these fuel cycles. Some fuel handling details were studied in depth for some of the advanced fuel cycles. This paper provides an overview of the concepts and design challenges.

ADVANCED FUEL CYCLES

Various advanced fuel cycles have been developed over the years by researchers in Fuel and Physics. Most fuel cycles are intended to increase the burnup and power of the reactor fuel cycle. There are economic benefits to the utility operator by conserving fuel resources to extract the maximum energy.

Slightly Enriched Uranium (SEU)

Slightly enriched uranium (up to 1.2%); compared to 0.7% in NU[1] fuel.

Mixed Oxide (MOX)

There are two types of MOX fuel.
a)One type would utilize the plutonium from reprocessed LWR[2] fuel, mixed with depleted uranium to form a mixed oxide fuel. Radioactivity would be also greater than for NU.
b)The other type utilizes the plutonium from decommissioned nuclear weapons. It is only slightly more radioactive than NU fuel

Direct Use of PWR[3] Fuel in CANDU (DUPIC)

This is highly radioactive fuel refabricated (not reprocessed) from spent PWR fuel

Recovered Uranium (RU)

This is the uranium left over from reprocessing spent LWR fuel. It is slightly radioactive - perhaps double that of natural uranium. The expectation is that it can be accommodated in existing plants with little difficulty.

Thorium fuels

Short term options here would not include recycled U233/Thorium, but rather either ThO_2 (with no added fissile component, for the "once through thorium cycle"), or ThO_2 mixed with enriched UO_2.

Highly Advanced Core (HAC)

This is a fuel cycle (Ref. 2) with 3.2 % enrichment for the Highly Advanced Core CANDU reactor that was developed for EPDC. It uses a unique fuel bundle with 61 elements ,which is still compact enough to fit into the standard CANDU fuel channel.

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[1] Natrual uranium
[2] Light Water Reactor
[3] Pressurized Water Reactor

Actinide Burning

These are specialized fuel cycles intended for the disposal waste actinides produced during normal fuelling operations in either LWR or CANDU.

Some of the cycles described above, such as SEU and HAC, use once-through CANDU cycles and others such as MOX, DUPIC and RU use a tandem LWR - CANDU cycle. These high burnup fuel cycles are capable of achieving core average burnups up to 40 GWd/tU, which is about five times the burnup of the 37 element NU CANDU 6 bundles.

The CANFLEX[1] fuel bundle, while not a specific fuel cycle , is a fuel bundle design that is intended to be used for various fuel cycles to achieve burnups about 21 GWd/tU.

Other advanced fuel cycles are intended for waste disposal. The waste disposal cycles such MOX and actinide burning may also employ a tandem LWR - CANDU cycle.

Table 1
Characteristics of Some of the Advanced Fuel Cycles

FUEL CYCLE	PURPOSE	ENRICHMENT % Fissile	BUNDLE DESIGN	REACTOR	FUELLING RATE Bundle/EFPD[2]
SEU	burnup /power	0.9%-1.2 % U235	37 Element 43-CANFLEX	C-6, C-8	6 -10
MOX (ex LWR)	burnup /power	0.9%-1.2 % Pu239	37 Element 43-CANFLEX	C-6, C-8	6 -10
Pu disposition MOX	waste disposal	2 -3 % Pu239	37 Element	C-8	9-16
DUPIC	burnup /power	1.5% (U235+Pu239)	43-CANFLEX	C-6	9
HAC	burnup /power	3.2% SEU	HAC 61 Element	HAC-640	10
Actinide burning	waste disposal	60%(Pu239+ Pu241) 40% Non-Fissile actinides	37 Element	C-6, C-8	20-80 Depends on Mass of Ac
NU natural uranium (for comparison	power	Natural 0.7%	37 Element and 28 Element	C-6, C-8	17

FUELLING RATES

Many of the advanced fuel cycles require fuelling rates that are not much different from that employed for the natural uranium fuel in current CANDU stations. For example MOX fuel can be burned in the Bruce A reactors at a rate slightly less than the natural uranium now used.(Ref. 7)

[1] CANFLEX® - CANDU FLEXible - Registered trademark
[2] Effective Full Power Day

However, some fuel management schemes required for fuel designed for high burnup such as the HAC 61MK4 has some significant effect on the fuelling machine duty cycle. Although the high burnup fuel requires a lesser total throughput than natural uranium fuel, (e.g. 7 bundles per EFPD for the 640 channel HAC reactor compared to approximately 17 bundles per EFPD for the 380 channel CANDU 6), the fuel is added to the reactor in single bundle shifts rather than the 8 or 4 bundle shifts used currently on CANDU stations. Thus the number of channel visits per day (7) is approximately double that required for natural uranium. This has implications on both operations and maintenance.

The number of channel visits is the major contributor to the duty cycle times of the fuel handling system. This was proven out in calculations done for the HAC reactor.

OPERATIONS AND MAINTENANCE

The CANDU 6 fuelling requirements for operations and maintenance are easily handled within a regular straight days work week. In the HAC, a requirement for fuelling 7 channels per EFPD would result in round-the-clock fuelling approximately 5 days a week and possibly 7 depending on fuel management needs. This would require 5 fuel handling operators crews on 12 hour shifts rather than one crew on 8 hour shifts. This considered the most reasonable alternative, requiring the minimum of physical changes to the system.

Consideration has been given to innovative solutions such as two fuelling machines on each bridge or simultaneous bi-directional single ended fuelling on different channels from opposite ends of the reactor. Neither of these alternatives have been investigated in detail.

Two fuelling machines per bridge would require major complex changes to the fuel handling computer control system to prevent collisions. It would probably also require a duplicate new fuel and irradiated fuel transfer system on the opposite end of the reactor face.

All CANDU reactors are fuelled in multiples of 2 bundles at each channel visit, i.e., by 4,8 or 10 bundle shifts. The fuelling machine magazine normally carries fuel bundles in pairs. To perform single bundle shifts for a HAC reactor some operations and control procedures and sequences will have to be modified. For example the magazine may have to be loaded with single bundles in the magazine fuel tubes. Alternatively a scheme could be worked out using the separators on the upstream fuelling machine. This would be unusual since the separators are normally used only on the downstream fuelling machine.

The maintenance interval and the life cycle for fuelling machine heads are directly correlated to the number of channel visits because of wear to the ram ballscrews and nuts, the snout clamping mechanism and the pressurisation cycles on the pressure vessel. The maintenance demands on the fuel transfer system are more related to the total number of fuel bundles and may benefit from the use of high burn up fuel. Advanced fuel cycles requiring more frequent channel visits will require significant adjustments to the maintenance scheme.

The obvious approach to maintenance is to provide additional spare fuelling machines. Current CANDUs use two fuelling machines in service per reactor with sufficient spare fuelling machines and spare rams to maintain capacity factor. To accommodate the fuelling demands of the HAC 640 channel reactor, for example, a total of five fuelling machines would be required. Between annual outages, after approximately 2500 channel visits, two fuelling machines would be in service, two fuelling machines would be in maintenance and one fuelling machine would be ready for immediate installation in the event of an unplanned failure of one of the in-service machines. Current maintenance records for fuelling machine rams suggest that this interval between outages can be achieved. The capital investment in these fuelling machines would reduce unplanned outages and replacement power costs.

NEW FUEL HANDLING

For the plutonium dispositioning study the radiation fields from new fuel were compared to fields from natural uranium fuel. Measures to limit occupational radiation exposure in handling and inspection of new fuel were assessed. Gamma fields for the "weapons grade" MOX fuel are about four times higher than for natural uranium. In addition the plutonium would also have a 5 mrem/hr neutron field.

The special packaging designed for the shipping and handling of MOX fuel would reduce radiation exposure by means of steel sleeves and water-expanded polyester packaging. The fuel would stay in the packing until immediately prior to transfer into the new fuel loading mechanism. Although it has not been studied in detail, it is conceivable that there would be increased labour and space usage costs associated with the special packaging scheme.

Other fuel cycles such as DUPIC present new fuel with much higher gamma fields, comparable to irradiated fuel. This fuel would be shipped and handled in shielded casks. Studies have shown that, in existing plants, reverse fuelling through the irradiated fuel bay is feasible without major plant modifications. The system would be labour intensive and would reduce the capacity of the irradiated fuel bay. Currently, equipment such as the FARE tool and modified shield plugs has been loaded into fuelling machines from the irrradiated fuel bay through the spent fuel port

For a new plant intended for DUPIC fuel a completely re-designed new fuel loading system could be devised with sufficient shielding and remote operation,

SECURITY AND SAFEGUARDS

Ordinarily, fresh CANDU natural uranium fuel is not subject to extraordinary security and safeguards measures because it is not readily converted to weapons material. Irradiated CANDU natural uranium fuel contains significant amounts of Pu and thus is carefully surveyed and monitored by the IAEA from the time of discharge from the reactor throughout the transfer and storage cycle. These systems are now well established for CANDU reactors.

Some of the fuels being studied in the advanced fuel cycles such as MOX and actinide burning are particularly sensitive to weapons diversion and unauthorized appropriation. These fuels in the unirradiated condition contain significant amounts of fissile material that can be chemically separated. Some of these fuels may be handled occasionally in their normal state without extraordinary radiation protection measures which makes unauthorised diversion possible without risk of personal injury. Fresh DUPIC fuel also contains sufficient fissile material to be a safeguards concern.

To protect against unauthorized diversion of these fuels effective procedural and physical barriers will have to be put in place. New structures may have to be built to accommodate this fuel in a secure manner These measures could turn out to be quite costly to retro-fit at existing plants

MECHANICAL INTERFACE

The fuel bundles for the various advanced fuel cycles are designed to pass through the CANDU reactor fuel channels without modification. That is, their diameter and are the same as a conventional natural uranium CANDU fuel bundle. The bearing pads are placed in the familiar position (with some minor adjustments to control bundle end plate droop).

The major mechanical differences in the fuel bundles for the advanced fuel cycles, as they interface with the fuelling machines, is the smaller size of the outer pencils and the larger outer diameter of the endplates. See Figure 1.

Through the fuel channel and most of the fuel handling system this difference has no effect. However, when the fuel string is being supported by the fuelling machine separator sidestops these differences become important and must be closely examined.

<u>Geometry - Endplate Interference</u>
Since the CANFLEX endplate is larger compared to the original CANDU 6 fuel bundle the question arises whether the bottom point of the separator will interfere with the endplate. This situation could be worsened by the bundle conditions such as droop and severe bearing pad wear. Recently extensive calculations were done for the CANFLEX bundle prior to testing to ensure that this interference would not occur with the worst case of fuel bundle geometry.

<u>Load Sharing</u>
The HAC 61 bundle has twenty-four 9.5 mm elements in the outer ring. When the separators' interaction was examined it was found that the axial load due to hydraulic drag on the fuel string supported by the separators during the refuelling process was shared by too few elements.

If the separator engagement is too little, element eccentric loading is increased and thus the stresses on the fuel sheath.

Several design solutions were evaluated and a bottom stop was proposed to be included in the design with the conventional sidestops.

IRRADIATED FUEL STORAGE

Generally, the irradiated fuel from advanced fuel cycles can be handled in the same manner as current CANDU natural uranium fuel. Immediately after discharge from the reactor it does not have significantly higher radiation or thermal output. Thus, no special cooling systems are required in the FM head or the fuel transfer system. However, heat loads from high burnup fuels over the long term are higher than those of natural uranium fuel. See Figure 2. This would have implications on long term storage beyond the 7-10 year period when CANDU fuel is normally put into dry storage. The requirements for bay capacity will also have to be considered.

CRITICALITY

Natural uranium CANDU fuel has no potential for criticality in conditions of light water flooding in either its fresh or irradiated states (Ref. 8). Such is not the case for some of the advanced fuel cycles.

Criticality control measures for the storage and transfer of new fuel may include special packaging (see Figure 3) and procedures. The packaging is designed to provide physical separation of the fuel bundles and neutron absorption.

Criticality of the new fuel in the fuelling machine head was examined specifically for the MOX fuel cycle. The fuel configuration was found not to be critical in this case. This situation would have to be studied for each advanced fuel cycle including non-routine fuel handling scenarios such as mixed fresh and irradiated fuel in the fuelling machine.

Some of the fuel cycles may produce irradiated fuel that present a concern about criticality. Then criticality control measures in the irradiated fuel bay would have to be designed. The case of new fuel being discharged to the irradiated fuel bay also has to be considered. These techniques are well known in LWR stations and would have to be adapted to CANDU.

CONCLUSION

The CANDU fuel is sufficiently adaptable to accommodate advanced fuel cycles in one way or another in new or existing CANDU reactors.

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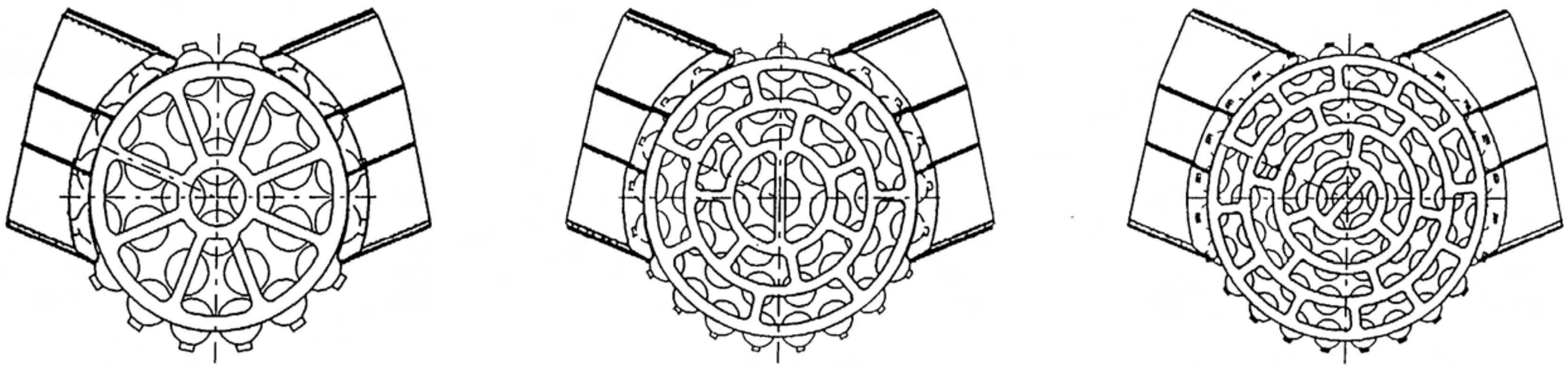
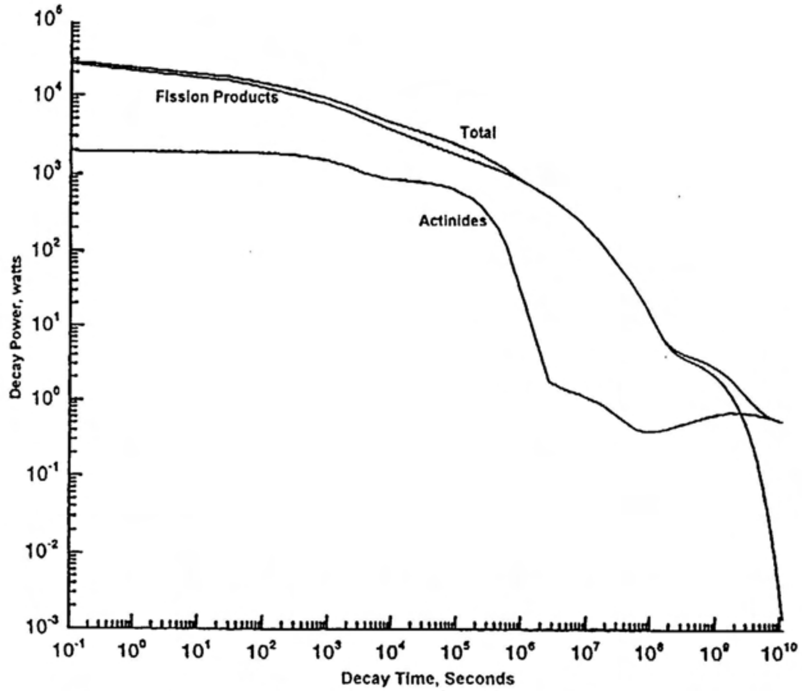
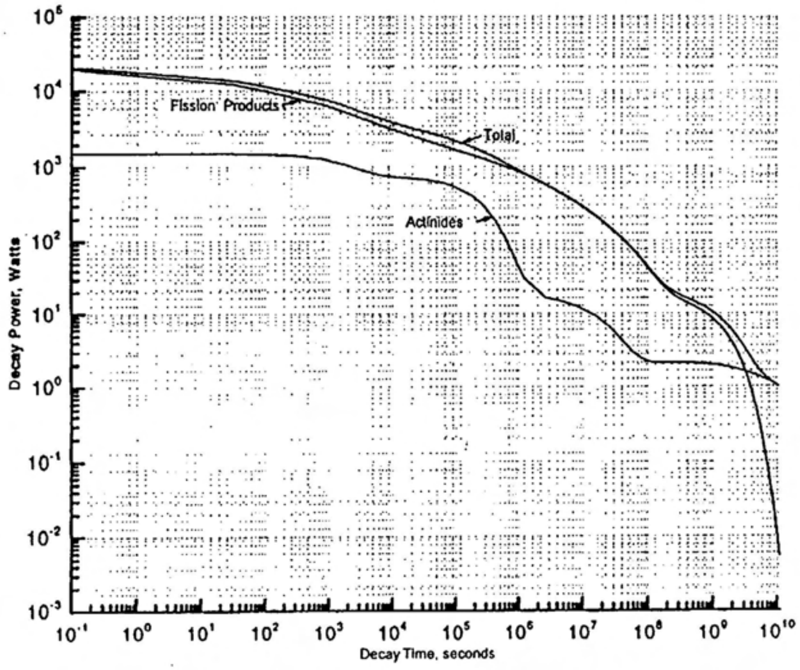


FIGURE 1 SEPARATOR ENGAGEMENT



Decay Power of 37-Element Natural Uranium Fuel Bundle at Nominal Burnup



Decay Power of HAC61MK3 SEW Fuel Bundle at Nominal Burnup

FIGURE 2 DECAY POWERS

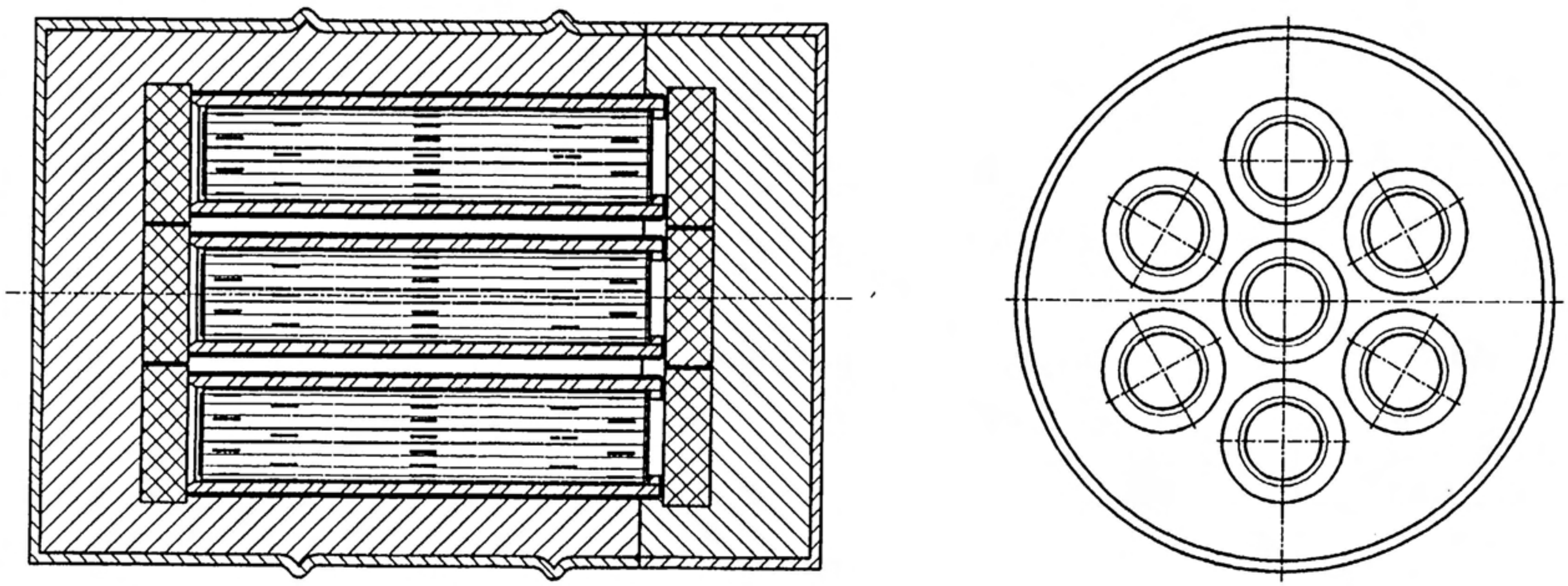


FIGURE 3 NEW FUEL SHIPPING AND STORAGE CONTAINER FOR PLUTONIUM FUEL