NON-PROLIFERATION AND SAFEGUARDS ASPECTS OF ALTERNATIVE FUEL CYCLE CONCEPTS *

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Abstract

Timely visibility on the development, evaluation and optimization of fuel cycle concepts with respect to nonproliferation characteristics should be emphasized in the early stage of planning a civilian nuclear power program, by fuel cycle developers, reviewers and decision makers. Fuel cycle technologies have inherently differing levels of nonproliferation characteristic profiles. Institutional and/or multi-national arrangements have been effective in reducing the nonproliferation concerns. The implementation of international safeguards further reduces these concerns by the timely detection of a possible physical diversion of SNM from fuel cycle facilities. Fuel cycles are safeguardable, but the nonproliferation characteristics of fuel cycle concepts differ significantly with consequent impacts on the international level of technical safeguards measures. The paper comments on characteristics of some of the fuel cycle concepts for the purpose of exploring the need to develop advanced nonproliferation and safeguards measures.

1. INTRODUCTION

The international commercial deployment of nuclear fuel cycle systems for electricity generation has essentially followed the evolutionary extension of the consensus arrived at in the 1980 INFCE study [1]. The technical study focused on the importance of preventing nuclear proliferation by the misuse of fuel cycle technologies, facilities, and materials for the purpose of developing nuclear weapons. Several countries have proposed the recycling of spent fuel without the separation of plutonium from uranium and fission products. The concepts are alternatives to either direct long-term storage or the Purex reprocessing of spent fuels.

Some of the fuel cycles being investigated include the dry-recycle processes such as the direct use of reconfigured PWR spent fuel assemblies into CANDU reactors (DUPIC), and the low-decontamination, single-cycle co-extraction of the fast reactor fuels in a wet-Purex type of reprocessing. The nonproliferation advantages usually associated with these non-separation processes are:

- The highly radioactive spent fuel presents a barrier to the physical diversion of the nuclear material from the fuel cycle;
- The need to dissolve and chemically separate the plutonium from the uranium and fission products; and
- The spent fuel isotopic quality of the plutonium vector is further degraded.

Although high radiation levels and the need for reprocessing may be perceived as a barrier to terrorists or other subnational groups, international proliferation concerns are addressed primarily by the material accountancy and verification activities which are the international safeguards measures of fundamental importance, with containment and surveillance as important complementary measures.

Consequently, the non-separation fuel cycle concepts have to be evaluated on the basis of the impact that the fuel cycle processes may have on nuclear materials accountancy. Safeguards R & D would have to address the implementation of advanced non-destructive assay and accountancy methods for dry-processing systems having concept specific holdup characteristics (measurable and non-measurable).

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The purposes of this paper are:

- To profile the proliferation characteristics of some of the fuel cycles concepts
- To suggest that the nonproliferation concerns be introduced into the early stages of a development program; and
- To perhaps aid in the more effective implementation of international nonproliferation initiatives and safeguards methods.

2. CANDU / PWR CYCLE

The residual reactivity in the spent fuel of a PWR cycle can be used to extend the fuel burnup capability in the high neutron economy of heavy water reactors. The direct use of spent PWR fuel in CANDU reactors (DUPIC) has the potential of reducing the natural uranium resource requirements, and of reducing the overall spent fuel arisings by refabricating spent PWR fuel into CANDU reactor fuel bundles for power generation [2,3].

The DUPIC fuel cycle concept utilizes dry-bulk-processing techniques. The dry process involves the mechanical dismantling, segmenting, and decladding of the PWR fuel elements, and the grinding of the U/PuO_2 spent fuel into powder. The spent fuel oxide powder is then subjected to cycles of oxidation/reduction processes, sintered into pellets and configured into CANDU fuel bundles. The process removes a high fraction of gaseous and volatile fission products. The remaining fission products with high gamma and neutron radiation levels necessitate that refabrication and fuel assembly handling be shielded and automated.

Although the gamma radiation and neutron emission levels could be perceived as a layered barrier to deter subnational theft or diversion, the radioactivity does not present a layered barrier to the national diversion and the international level of proliferation concerns. The proliferation resistance characteristics address the barriers to accessing the material, and the barriers to converting the nuclear material for uses other than for power generation. International proliferation concerns require that stringent safeguards in nuclear material accountancy and validation be implemented throughout the dry-bulk process. The radiation barriers could compromise the efficacy of the accountancy and validation measures.

In the dry-bulk process, the nuclear material forms, inventory, and flow are such that current nondestructive assay (NDA) methods may be limited. Research and development would have to address specific measurement methods and validation standards to directly assay the nuclear materials in the two major waste streams from the mechanical dismantling, segmenting, and decladding processes of PWR fuel assemblies and from the oxidation/reduction, sintering/pelletizing processes. Dry-bulk powder processes have characteristically high holdup inventories and excessive nuclear material holdup could be expected in the DUPIC dry-bulk-processing plant.

With respect to barriers in converting the nuclear material to non-fuel uses, the softer neutron spectrum in the CANDU reactors generates a plutonium isotopic vector with greater concentrations of the even plutonium isotopes (Pu-240 and -242) than in the initial PWR spent fuel feed. The fresh fuel DUPIC plutonium isotopic composition for a 35GWD/T PWR power operation, is transmuted into a plutonium isotopic composition for a 16GWD/T DUPIC once-through power cycle, as listed in Table I. This results in increased specific neutron emission rates by factors of two or more than in the initial PWR or CANDU spent fuel arisings, maintaining the plutonium more unattractive for non-fuel uses.

TABLE I. DUPIC PU ISOTOPIC COMPOSITION (W/O)

Isotope	Fresh Fuel (35GWD/T)	Once-Through (16 GWD/T)
238	0	0
239	60	38
240	26.6	42.7
241	8.35	6.68
242	4.48	12.2

The advantages of the DUPIC cycle are outlined as follows:

- No wet-processing is required
- The geological disposal requirements of the spent PWR and CANDU fuels are greatly reduced; and
- The natural uranium requirements for the CANDU phase of the fuel cycle would also be greatly reduced.

The early stages of a feasibility exploration program would have to include early design considerations which address the following:

- Proliferation characteristics based on the radiation levels of the fuel assemblies as being within a subnational level threat or an international level of proliferation concern;
- Geologic repositories would still be needed for the once-through DUPIC fuel assemblies; and
- The impact on the IAEA materials accountability measurement methods for establishing dry-process holdup and recoverability of the plutonium/uranium mixture.

3. FAST REACTOR SINGLE-CYCLE CO-EXTRACTION

The fast-reactor advanced-fuel-recycle concept is based on the characteristic neutron energy spectra of fast reactors [4]. The complete separation of plutonium and uranium is a sufficient condition for fast reactor power systems, but is not necessary. Since the fast reactor fuel cycles are capable of operating with a high concentration of nuclear material impurities, there is a reduced need for the purification cycles beyond the initial co-extraction stage of the Purex wet-separation process. Decontamination factors of 10^3 or less are acceptable in the fast reactor fuel cycle for power generation. The Pu/U/fission product stream retains the radiation barrier to the subnational theft or diversion. The fast reactor single-cycle co-extraction concept has many of the attributes outlined in the dry-cycle process. However, the coprocessing and the fabrication aspects of the concept address only the subnational level of proliferation. The elimination of the purification stages greatly reduces the size of the conventional Purex process. The integration of reprocessing and fabrication processes into a single unit fuel cycle plant would reduce the nonproliferation concerns by the contraction of the transportation links between the fuel cycle facilities.

The international aspect of nonproliferation concerns must depend on direct nuclear materials accounting, validation and verification measures. International safeguards R & D should address the development of accountancy techniques to measure directly the plutonium inventories and flows in the severe gamma and neutron radiation fields of the fission products.

In general, fast reactor fuel management should address separately the core nuclear materials and the blanket materials. Spent radial blanket assemblies contain weapons-grade plutonium, and consequently, nonproliferation concerns suggest that the blending of the radial blanket materials with core materials be completed as far upstream as possible for the conventional (blanketed) fast reactor power cycle. The moderate (non-radial blanket) plutonium burner operations does reduce the plutonium isotopic quality compared to the conventional operating mode. In the integral fuel element design, the axial upper and lower blanket sections and the core sections are mechanically separated and simultaneously dissolved in the dissolution tank.

Although co-extraction may mitigate international proliferation concerns compared to existing conventional fast-reactor fuel cycles, safeguards methods must be developed to minimize fuel handling and processing operations for spent blanket assemblies in and out of the reactor environment.

The inaccessibility of co-extracted fuel Pu/U/ fission product streams (dry-bulk or single-cycle) is not necessarily to be construed as a lesser proliferation concern. The radioactivity will decay over 30 to 100 or more years to a level where it no longer deters subnational threats. International safeguards measures designed for this phase of the fuel cycle should ensure irreversibility. The high mass throughput of fissile material in the fast reactor cycle requires emphasizing containment and surveillance methods.

4. THORIUM - URANIUM FUEL CYCLES

The thorium-uranium fuel cycle is being pursued on a limited scale by several countries. The primary incentive for the thorium-uranium fuel cycle would be to utilize indigenous nuclear material resources in conventional commercial thermal and fast reactor power systems. The exploitation of thorium resources is essentially a long-term, large-scale energy-generation option [5,6].

The denatured uranium (i.e. low enrichments in U-235 or U-233) fuel cycle systems should be assessed in the context of established international proliferation criteria. The U-233 produced in the Th-U cycle is as fissionable and perhaps as radiotoxic as Pu-239. Although systems have been proposed in which U-233 is denatured with U-238, even the denatured Th-U/U-233 introduces nonproliferation concerns. The suggested cycles include U-233/U enrichment levels ranging from three to twelve percent or more.

The thorium-uranium fuel cycles have certain nuclear characteristic features which persist through all stages of the fuel cycle process and consequently may strongly influence the design of IAEA safeguards.

Two fundamental invariant characteristics in the denatured uranium-thorium fuel cycle are:

1. Chemical reprocessing is a necessary phase of the fuel cycle, and

2. The U-233 and the plutonium isotopes are in combination throughout the back end of the cycle.

    (1) The separation of the uranium-thorium and plutonium is necessary for reactor systems in a symbiotic power complex operating at high conversion ratios with only denatured uranium being used in the front end of the cycle. The assessment of the impact on safeguards considerations should include the following:

        a) The fissile isotope identification, materials balance, and accountability will involve U-233, significant concentrations of plutonium and, depending on the total reactor deployment strategy, U-235;

b) Safeguarding techniques should be introduced for continuous surveillance and mass flow accountability of the plutonium streams, and safeguarding the reconfiguration and casting of the separated plutonium for storage (retrievable and nonretrievable) and the consequent long-term safeguarding of the storage facilities.

(2) In consideration (a), the spent fuel of the denatured U-233/U-238/Th cycle contains significant amounts of plutonium (about one-fourth to one-third) of the plutonium content in the spent fuel of the uranium/plutonium fuel cycle. The safeguards concerns between these two cycles are therefore of equal significance. However, an added safeguards problem arises in that discharged denatured fuel contains a significant amount of U-233, and the fissile accountability must now be applied to the uranium, thorium, and plutonium process streams through all phases of the fuel cycle. On the international level of safeguards concern, gas-centrifuge enrichment technologies and the electromagnetic isotopic separation technology (EMIS) calutrons make the isotopic separation of the denatured uranium enrichment levels a relatively low-level effort. The safeguards concerns would have to be emphasized at the front-end of the denatured fuel cycle.

Studies in isotopic separation processes (electromagnetic isotope separations) have indicated that the separation of U-233 is greatly facilitated in comparison to the isotopic separation of U-235 in the low enrichment U-235/U cycle [7]. Estimates indicate that the effort level to enrich U-233/U fuels can be lowered by factors of 3 to 20 in comparison to the re-enrichment of 3% U-235/U. The ease of the isotopic separation is a consequence of the mass difference of five between U-233 and U-238 as compared to three for the U-235 and U-238, the higher concentration levels of the U-233/U fuel, and the lowered inventory fuel requirements to achieve significant-quantity mass levels. These considerations would have to be integrated into the evaluation of the nonproliferation characteristics of the thorium/uranium cycles.

The anticipated impacts on safeguards of the thorium-uranium fuel cycles are speculative, since sustaining fuel management strategies have not yet been detailed. The source of the U-233 for startup, the disposition of the plutonium generated in the denatured fuels because of the presence of U-238, and the precise composition of the U-233/U fuel should be evaluated as the fuel cycles are developed further. The safeguards assessment of the U-233/U/Th fuel cycles would involve the layout of symbiotic systems to establish the somewhat unique aspects of the fuel:

- Feed sources of U-233 would be necessary since the denatured cycles may not be self-sufficient in flow and inventory of fissile material;
- The impact on safeguards relating to the differences in the enrichment properties and capacity requirements between U-233 and U-235; and
- The impact on IAEA safeguards methods resulting from the radioactivity of the daughter products of the U-232;
- Proliferation concerns be addressed at the front-end of the fuel cycle.

The safeguards problems introduced into the nuclear material accountability methods by the denatured thorium-uranium cycle will require research and development programs in implementing advanced chemical analytical measures and NDA techniques.

5. EXCESS PLUTONIUM DISPOSITION CYCLES

The disposition of excess weapons plutonium from disarmament programs has been explored in many studies and by many countries in the past few years. There appears to be a general consensus and commitment for the continued study of two major options: use in reactors, and immobilization [8]. The reactor alternative involves the use of MOX fuel as a fuel source for commercial reactors (LWR's, WWER's, CANDU's, and Fast Reactors) [9-11]. The immobilization alternative involves the vitrification of plutonium in a matrix log inserted within a canister containing radioactive material (can-in-canister). The consensus also included the time lines: the plutonium disposition program is to be initiated in approximately 10 years, and the program should be completed in 25 to 30 years thereafter.

5.1. Thermal reactor fuel cycle (LWR, WWER)

In the case of the MOX fuel burning in thermal reactors, the once-through fuel cycle operation degrades the weapons-grade plutonium into a form that is as unattractive and inaccessible for weapons use as that of plutonium contained in the spent fuel from current commercial reactors (Spent Fuel Standard) as listed in Table II.

TABLE II. NOMINAL PLUTONIUM ISOTOPIC COMPOSITION (W/O)

Pu-Isotopes	Weapons Grade	LWR, Spent Fuel Standard (33-36 GWD/T)	LWR,WWER, MOX Once-through (40-45 GWD/T)	Fast Reactor Once-through (100 GWD/T)	CANDU Once-through (10 GWD/T)	CANDU Inert Matrix Once-through (733 GWD/T)
Pu-238	0.01	2	0	0.1	0.0	0.0
Pu-239	93.6	55	52	85.5	51.6	14
Pu-240	5.9	26	29	13.2	37.9	46
Pu-241	1.4	10	15	1.1	8.5	20
Pu-242	0.1	7	4	0.1	2.6	20

The specific neutron emission rate from the even-plutonium isotopes, "equivalent" to Pu-240, is expected to be comparable for the reference spent fuel standard (SFS) and the once-through fuel cycle of the LWR/WWER MOX loading. The "Pu-240 equivalence" defines the weighted neutron emission rates of the even-plutonium isotopes.

5.2. Fast reactor fuel cycle

The burning of weapons plutonium or MOX in fast reactors with conversion ratios of less than unity, results in a plutonium composition vector, for the once-through cycle (open cycle), as listed in the last column of Table II. The isotopic degradation does not differ much from the initial weapons-grade plutonium. For the higher grade weapons-plutonium, the degradation of the plutonium isotopic vector in the fast reactor spectrum can be expected to differ even less [10]. The plutonium isotopes approach the LWR spent fuel standard concentration levels, if an equilibrium feed and discharge fuel recycle mode of operation is utilized in the fast fuel cycle However, the equilibrated fuel cycles would require higher burnups equivalent to some 4 to 5 recycles which would then exceed the time line for completing the disposition program.

5.3. CANDU reactor fuel cycle

The Atomic Energy of Canada Limited (AECL) has proposed options for using excess weapons-plutonium in the CANDU reactor system [12,13]. The CANDU reactor fuel cycles have a characteristic well-thermalized neutron spectra, with a high neutron economy resulting in higher concentration levels of the even-plutonium isotopics (i.e. Pu-240/242) than in the fast-reactor spectra. The AECL studies indicate that the weapons-grade plutonium MOX fuel can be introduced into the CANDU reactor fuel cycles as a full MOX core in a once-through mode. The plutonium isotopic composition of the CANDU spent MOX fuel is listed in Table II, for burnups of about 10GWD/T. The specific neutron emission rate approaches the LWR MOX option and the LWR spent fuel standard (SFS). The neutron emission rates correspond to the "Pu-240 equivalence" isotopic concentration of 43, 34, and 49 by w/o in the CANDU, LWR-MOX, and the LWR-SFS options, respectively.

The AECL studies included the alternative option of introducing weapons-grade plutonium in an inert-matrix (non-fertile) fuel material. With anticipated long burnups of 733 GWD/T, the plutonium content was reduced by 80% of the fresh fuel. The resultant spent fuel plutonium isotopics vector is listed in Table II. The "Pu-240 equivalence" for neutron emission rates is 86 percent, which is almost a factor 2 greater than in the spent fuel plutonium of the CANDU- and the LWR-MOX options, and the LWR-SFS.

5.4. Safeguards measures

The need for advanced safeguards development in direct plutonium accountability measures exists in all of the proposed disposition options. NDA and DA systems development for the dry-bulk processes should be advanced:

- To enhance the transparency of the weapons-plutonium flows and inventories
- To improve material accountability
- To directly establish isotopic compositions, and
- To ensure that the weapons material are indeed unattractive and inaccessible, and irreversible, for uses other than the nuclear power fuel cycle.

6. SUMMARY

Fuel cycle technologies have inherently differing levels of proliferation characteristic profiles. Institutional and/or multi-national arrangements have been effective in reducing proliferation concerns. The implementation of international safeguards further reduces proliferation concerns by allowing the timely detection of a diversion of SNM from fuel cycle facilities. The proliferation characteristics of different fuel cycles could differ significantly, with consequent impacts on the required level of technical safeguards measures. The nonproliferation considerations should include:

- Generation/disposition of fissile materials
- Development of high burnup fuels
- Transparency of fissile material flows and inventories
- Balancing supply and demand of fissile materials, and
- International safeguards and institutional arrangements.

Advanced NDA and DA methods for direct plutonium accountability, being developed in many analytical chemistry laboratories, should be explored for implementation on an engineering scale in on-line processing operations.

The reduction of radioactive hazards has both short- and long-term concerns. Hazards-analysis addresses the consequence of exposure, whereas risk analyses requires the modeling of radionuclide dispersion and intrusion into the biosphere. These two analyses are expected to impact differently on the site selection and design of the geologic repositories. Waste repositories will be needed for all fuel cycle concepts and consequently should be a continuing development program. Fuel cycle developments should include waste management as an integral phase of the concept. Institutional and/or regional consortia involving fuel cycle options and fuel cycle services will be influenced by the long-term nonproliferation and health hazards concerns as well as the utilization of nuclear energy resources.

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