THE UTILIZATION OF RUSSIAN WEAPONS PLUTONIUM IN CANADIAN CANDU REACTORS: A FEASIBILITY STUDY

E.G. KUDRIAVTSEV
MINISTRY FOR ATOMIC ENERGY OF RUSSIAN FEDERATION (MINATOM)

E.I. TYURIN
SPECIALIZED STATE DESIGN INSTITUTE MINATOM RUSSIAN FEDERATION

L. PETROVA
SPECIALIZED STATE DESIGN INSTITUTE MINATOM RUSSIAN FEDERATION

A.I. TOKARENKO
ALL-RUSSIA DESIGN AND SCIENTIFIC RESEARCH INSTITUTE OF COMPLEX POWER TECHNOLOGY (VNIPIET)

R.D. GADSBY
AECL CANADA

L.R. JONES
ZIRCATEC PRECISION INDUSTRIES CANADA

J.I. SAROUDIS
AECL CANADA

E.G. BAZELEY
ONTARIO HYDRO CANADA

ABSTRACT

Between 1994 and 1996, AECL in cooperation with Ontario Hydro and Zircatec Precision Industries undertook a series of studies funded by the United States Department of Energy to determine the feasibility of utilizing weapons Plutonium, surplus to military needs, as Mixed OXide (MOX) fuel in Canadian CANDU reactors. The Bruce A N.G.S. was used as the reference station for the study. One of the conclusions of these studies was that the CANDU option allowed for the possibility to also utilize Russian surplus plutonium and thus offered the two nuclear powers the possibility of symmetric drawdown of their surplus stockpiles.

Starting in the spring of 1996, the Canadian Government funded a similar study on the feasibility of manufacturing CANDU MOX fuel in Russia and safely transporting this fuel to the Bruce site. The study was undertaken by a joint Canadian/Russian team comprised of AECL, Ontario Hydro, Zircatec Precision Industries, the Ministry for Atomic Energy of the Russian Federation (MINATOM) and several of its institutes and was concluded in the spring of 1997.

This paper presents some of the key findings of the joint Russian/Canadian study.

1. INTRODUCTION

In the wake of the increased mutual commitment to nuclear arms reduction, Russia and the United States have been conducting a broad range of studies designed to provide the information necessary to evaluate methods for the long-term disposal of excess plutonium from military stockpiles. The U.S. Department of Energy (DOE) has conducted an in-depth evaluation of all credible options, and announced a Record of Decision in January 1997 indicating preferred directions for eliminating important stockpiles of plutonium. One of the main options is the conversion of plutonium into mixed-oxide (MOX) fuel for consumption in commercial nuclear reactors.

Canada participated in this evaluation process by conducting a full-scale feasibility study for DOE that demonstrated the attractiveness of converting the excess plutonium from US warheads into MOX fuel for Canadian CANDU reactors. The 1994 DOE study has shown that the CANDU MOX fuel variant is essentially similar to the natural uranium fuel currently used, and that a large scale program to consume up to 100 tonnes of plutonium in 25 years can be implemented rapidly at Ontario Hydro's Bruce A nuclear power station without changes to the reactor core design and only minor changes to the fuel handling systems.

As a complement to an extension of the DOE study, Canada and Russia undertook in 1996 a joint Plutonium Utilization Study to provide information to Canadian and Russian decision makers on the technical, environmental and economical feasibility of fabricating CANDU MOX fuel in Russia using Russian weapons plutonium and transporting it safely to Bruce A for consumption there.

The results of the Russia/Canada Study are important for supporting the CANDU option in the overall evaluation program. The CANDU option's attractiveness stems partly from the fact that it offers a unique opportunity for both Russia and the United States to contribute in equal measures to a parallel plutonium consumption program hosted by a third, non-nuclear weapons state with a strong non-proliferation policy.

Joining the Canadian team of AECL, Ontario Hydro and Zircatec Precision Industries was the Russian Ministry for Atomic Energy (Minatom). Its main Nuclear Department acted as the coordinator for the institutions listed below:

- The Specialized State Design Institute (SSDI) is the designer of all types of reactors and fuel production facilities in Russia; it provided its expertise for studying modifications to an existing fuel fabrication building at PO Mayak which it originally designed, and for the conceptual design of a new building /and plant, also at PO Mayak.
- The Bochvar Institute (VNIINM) has been responsible for all new fuel developments in Russia and has extensive MOX expertise; it is participating in the initial CANDU MOX fuel testing program (Parallex program) and would be involved in the design of the new MOX manufacturing facility with SSDI, especially with regard to processing conditions.
- The Machinery Plant, Electrostal, is a large-scale manufacturer of nuclear fuel in the Russian Federation. Their involvement in the production of CANDU MOX fuel components will include all the required depleted UO_2, and the natural uranium and poison fuel pellets which will be supplied to the fuel manufacturing facility.
- The Production Association, PO Mayak is the production complex that will supply the plutonium oxide for this MOX program. The proposed CANDU MOX fuel fabrication facility would be located at Mayak to eliminate the problems associated with transportation of the plutonium oxide. The Study assessed the suitability of upgrading an existing building at Mayak or erecting a new building on the same site.
- The All-Russian Design and Scientific Research Institute of Complex Power Technology (VNIPIET) contributed its expertise in the design of shipping containers, nuclear fuel transportation and national and international regulatory issues.

2.0 SCOPE OF THE STUDY

The study focused on the following aspects:

- MOX fuel supply: sources of feedstock materials and the design of the MOX facility to be located in Russia;
- Safeguards, Security, Packaging and Transportation;
- Safety, Licensing and Environmental Assessment: the team studied the impact of Russian MOX fuel on Bruce A operations and identified the Russian regulatory agencies responsible for the environmental impact assessment;
- Bruce A station modifications;
- Disposal of spent MOX fuel;
- Implementation scenarios.

This paper will present the key results in the areas of MOX fuel supply and packaging and transportation to Canada.

3.0 REFERENCE FUEL DESIGN

The basic CANDU MOX fuel design based on the Bruce A 37-element bundle configuration was developed in the course of the 1994 study for DOE. A CANFLEX MOX bundle was also developed in 1994. These designs were subsequently revised in 1996 to allow for enhanced throughput of plutonium and thus reduce the Pu utilization mission time. This feasibility study used the 1994 fuel design as a reference.

Table 3-1 compares the nuclear characteristics of the 37-element bundle MOX fuel design with those for the standard 37-element natural fuel design. In CANDU reactors, fission is caused by thermal neutrons entering the fuel channel from the moderator. Fuel elements in the third ring are shielded from these thermal neutrons by the elements in the outermost ring, i.e., ring 4. This reduced neutron flux level results in a much lower power output in ring 3 as compared to that in ring 4. The power output of the entire fuel bundle is often limited by the maximum allowable power rating for an individual fuel element. Therefore, it is desirable to design a fuel bundle such that all fuel elements operate at comparable power ratings.

In the 37-element MOX Fuel Design, the Pu content of the elements in the third ring is 2%, which is higher than the 1.2% Pu content in the fuel elements of the fourth ring. The higher enrichment level in ring 3 is designed to compensate for the reduced neutron flux level. This enrichment grading scheme enables the elements in ring 3 to operate at a power level comparable to that in ring 4 in spite of the reduced neutron flux level. This allows the fuel bundle to operate at a high power level without exceeding the maximum allowable power rating for individual fuel elements.

The neutron flux level in the central seven elements, which contains 0.2% depleted uranium, 5% dysprosium and no plutonium, is so low that these elements do not produce any significant amount of power as compared to the MOX elements in the two outer rings. Hence, all the power in the MOX bundle is effectively produced by 30 fuel elements instead of 37. This requires the MOX fuel bundles to operate at a lower maximum bundle power limit than that for natural fuel bundles. The 2-bundle shift fuelling scheme chosen for the MOX core flattens the radial and axial power distributions such that the maximum channel and bundle powers in the MOX core, 7000 kW and 780 kW respectively, are lower than those in the natural uranium core, 7200 kW and 950 kW respectively.

The maximum fuel element burnup of the MOX fuel is calculated to be 15,500 MWd/te, which is essentially the same as the maximum fuel burnup attained by natural fuel elements in Bruce A. The MOX fuelling rate is 15.5 bundles per full power day, which is lower than the present fuelling rate of 18 bundles per full power day with natural uranium fuel.

The major difference between the natural uranium fuelled reactor and the MOX fuelled reactor is the reactivity effect during a hypothetical Loss of Coolant Accident. Full core LOCA reactivity in Bruce A is estimated to be +11 mk for the natural uranium reactor and -4.7 mk for the MOX reactor. The transition from a natural uranium CANDU reactor to a MOX reactor can be achieved without hardware modifications to the existing control and safety systems.

Table 3-2 compares the uranium and plutonium content in the natural fuel with that in the Reference MOX fuel. Fresh natural fuel contains 133 g of U-235 per bundle. At discharge, each bundle contains 38.7 g of U-235 and 51.1 g of fissile plutonium (Pu-239 and Pu-241). Each fresh MOX fuel bundle contains 36.8 g of U-235 and 218.3 g of fissile plutonium. At discharge, each MOX bundle contains 17.4 g of U-235 and 92.0 g of fissile plutonium. Although the nuclear characteristics of the MOX fuel are different from those of natural uranium fuel, a fuel management scheme has been devised for the MOX fuel to ensure that the performance of the MOX core is comparable to that of the natural uranium core in the areas of fuel power rating, control and safety.

4.0 CANDU MOX PLANT IN RUSSIA

The complete fabrication of CANDU MOX fuel at the Mayak site, starting from metallic plutonium processing, is to be divided between two plants.

Plutonium Conversion Facility (Facility No. 1)

Facility No. 1 will be a new building for the metallic plutonium conversion facility. It will be located on the territory of an existing fuel fabrication plant in the military zone of the Mayak complex; its proposed dimensions are equal to 75 x 30 x 20.4 metres.

The following operations are to be carried out at Facility No. 1:

- metallic Pu dissolution in a mixture of nitric and hydrofluoric acids;
- purification of plutonium nitrate solution by extraction;
- Pu oxalate precipitation from nitrate solution, drying and calcining to Pu dioxide;
- completion of batches and packaging of Pu dioxide;
- reprocessing of "rich" solid wastes;
- reprocessing of raffinate and washing solutions and their transfer for further reprocessing at other existing fuel fabrication facilities;
- collection of Al- and F-containing solid wastes and their transfer for cementation; shipment of Am- and Pu-containing solid wastes for storage.

A flowsheet of the process proposed for facility No. 1 is shown in Figure 4-1.

CANDU MOX Fuel Fabrication Facility (Facility No. 2)

Fabrication of CANDU MOX fuel elements and fuel assemblies is to take place at Facility No. 2, a newly designed building to be located on the undeveloped territory adjacent to Building 300 (or in an unoccupied area of the operating RT plant). Its proposed dimensions are equal to 120 x 45 x 15.3 m.

The following operations are to be carried out at Facility No. 2:

- line for formation of plutonium oxide and depleted uranium oxide master blend (20% mass Pu);
- line for pellet fabrication and fuel element fabrication with 1.2% mass Pu enrichment;
- line for pellet fabrication and fuel element fabrication with 2% mass Pu enrichment;
- line for fuel element sets completion;
- section for fuel bundle assembly, inspection and storage;
- facility for liquid and solid radioactive wastes cementation and transfer for disposal.

A flowsheet of the process to be used in Facility No. 2 is shown in Figure 4-2.

Figure 4-3 shows schematically the process for manufacturing CANDU MOX fuel and its utilization in the Bruce A reactors as compared to an equivalent throughput of natural uranium fuel.

5.0 PACKAGING AND TRANSPORTATION

Both the air and the sea shipment options were considered in the study. In the case of air transport, the new 1996 IAEA regulations require a type C (air crash resistant) package to transport more than four fuel bundles, or the fuel itself must be qualified as Low Dispersible Material. A thorough review of available packages was conducted and it was concluded that there is no existing package suitable to transport large shipments of CANDU MOX fuel bundles in a cost-effective manner.

A new package design was proposed that can satisfy the above regulations. It would be a double walled cylindrical container designed to transport 18 CANDU MOX fuel bundles stored in two stacking baskets. Individual tubes separated by spacer plates receive one fuel bundle each. Shielding would be provided first by 5 to 6 cm of concrete poured between the steel walls of the container, and also by individual shielding sleeves surrounding each fuel bundle. Leak tightness would be provided by a seal and verified by a verification device provided on the container cover. A schematic of the package proposed by VNIPIET appears in Figure 5-1.

The possible modes of transportation from Russia to Canada are by sea or by air. The Russian study assessed the respective advantages of each transportation mode, and more precisely of specific transportation routes that were ranked by a weighted comparison of all relevant criteria.

The transportation route analysis considered for example costs, which are higher for air than for sea, while transportation time is shorter. The shorter transportation time would minimize security and safeguard concerns. Direct air shipment from Russia to Canada would also eliminate jurisdictional interfaces of other countries. From a security of supply point of view, the sea shipments could be considered the primary option with air transport as the back-up option.

Examples of the various transport modes and routes are as follows:

i) Mayak to "Izotop" storage facility in St-Petersburg by rail; to St-Petersburg seaport by truck; to Canadian seaport by sea vessel; to Bruce by truck.

ii) Mayak to "Izotop" storage facility in St-Petersburg by rail; to "Pulkovo" airport, St-Petersburg by truck; to Canadian airport (civilian or military) by chartered air cargo plane; to Bruce by truck.

iii) Mayak to "Koltsovo" airport, Ekaterinburg by truck; to Canadian airport by chartered air cargo plane; to Bruce by truck.

The team concluded that transportation of CANDU MOX fuel from the manufacturing facility at Mayak to the Bruce site is feasible and cost-effective.

6.0 IMPLEMENTATION SCENARIOS

The study team evaluated the time frame within which such a program could be implemented. A level 1 schedule is presented as Figure 6-1. The concept presented is one under which some of the Bruce A units begin operation with the 37-element CANDU MOX fuel design and then switch to the CANFLEX design once the fuel qualification program for the latter is completed. Basically, a first Bruce A unit could be in operation with MOX fuel from a Russian facility within about 6 years of the start of the program.

7.0 CONCLUSIONS

The joint Russian/Canadian feasibility study on the utilization of Russian weapons plutonium surplus to defense requirements concluded that it is feasible to manufacture CANDU MOX fuel in Russia to Canadian specifications and to safely and reliably transport this fuel to Canada for use in the Bruce A reactors. The considerable capacity of the Bruce reactors to consume plutonium offers a unique opportunity for the United States and Russia to simultaneously draw down their stockpiles of surplus plutonium in a relatively short period of time by using only the Bruce reactors.

Alternatively, the CANDU option could complement other initiatives and still offer the possibility of significantly reducing the mission time. For example, Canada and Russia are in the process of completing a study on the feasibility of expanding the scope of a proposed French/German/Russian MOX project designed to manufacture MOX fuel for VVER 1000 PWR reactors and BN-600 fast reactors in Russia to also manufacture CANDU MOX fuel.

TABLE 3-1 COMPARISON OF NATURAL FUEL AND MOX FUEL CHARACTERISTICS

	Existing 37-element NU Bruce-A Station		37-element MOX-Fuelled Bruce A Station	
Fuel Bundle Dimension	102 mm (4.02") dia. 495 mm (19.5") long		Same as existing Natural UO_2 fuel bundle	
Pellet Material Composition (% based on weight of heavy metal in fuel)	Natural UO_2 in all rings (37 pins)		Ring 4 (18 pins) Ring 3 (12 pins) Ring 2 (6 pins) Ring 1 (1 pin) All rings have 0.2%	1.2% Pu 2% Pu 5% Dy 5% Dy U^{235}
Bundle Material Composition (fuel material only)	U^{235} U^{238} O_2 TOTAL:	0.13 kg 18.67 kg 2.53 kg 21.33 kg	Pu U^{235} U^{238} Dy O_2 TOTAL:	0.23 kg 0.04 kg 18.36 kg 0.17 kg 2.53 kg 21.33 kg
Average Burnup	8,300	MWd/te	9,700	MWd/te
Maximum Burnup	15,000	MWD/te	15,500	MWd/te
Bundle/FPD	18		15.5	
Fuel Management Scheme	2, 4, 8	mixed bundle shift	2	bundle shift
Maximum Channel Power	7,200	kW	7,000	kW
Maximum Bundle Power	950	kW	780	kW
LOCA Void Reactivity	11	mk	-4.7	mk

TABLE 3-2
ACTINIDE INVENTORY FOR NATURAL U AND REFERENCE MOX FUEL BUNDLE (G/BUNDLE)

	Fresh		Exit-Burnup	
	Natural U	MOX	Natural U 8300 MWd/teHE	MOX 9700 MWd/teHE
^{235}U	133	36.8	38.7	17.4
^{238}U	18,670	18,360	18,534	18,276
^{239}Pu		218	46.8	78.8
^{240}Pu		13.5	20.6	57.6
^{241}Pu		0.317	4.32	13.2
^{242}Pu		0.051	1.28	3.75
*M.A.	0	0	2.5	1.6
*F.P.	0	0	155	181
TOTAL	18,803	18,629	18,803	18,629

- Minor Actinides and Fission Products calculated with ORIGEN-S

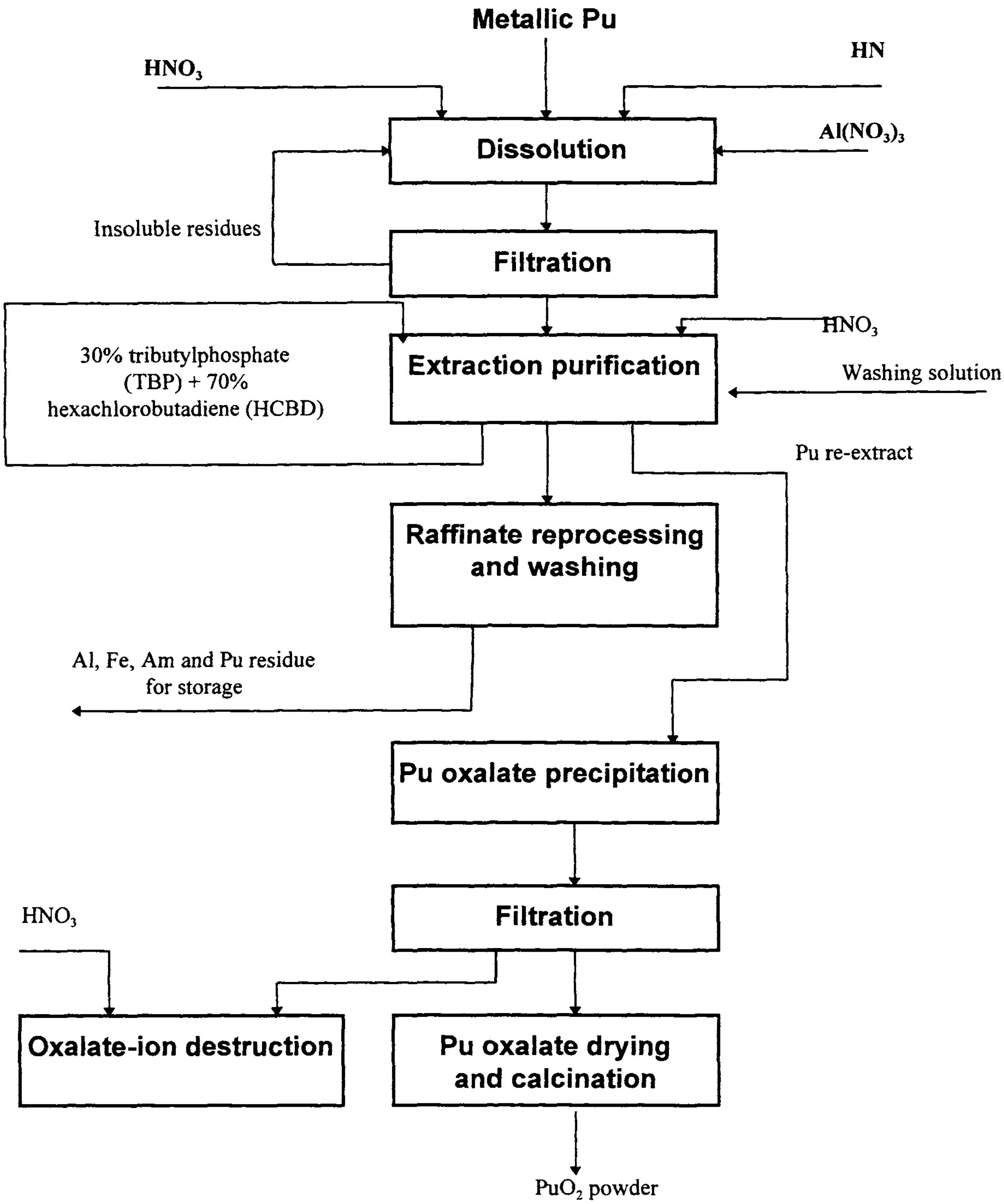

FIGURE 4-1: TECHNOLOGICAL SCHEME FOR PLUTONIUM DIOXIDE POWDER PRODUCTION

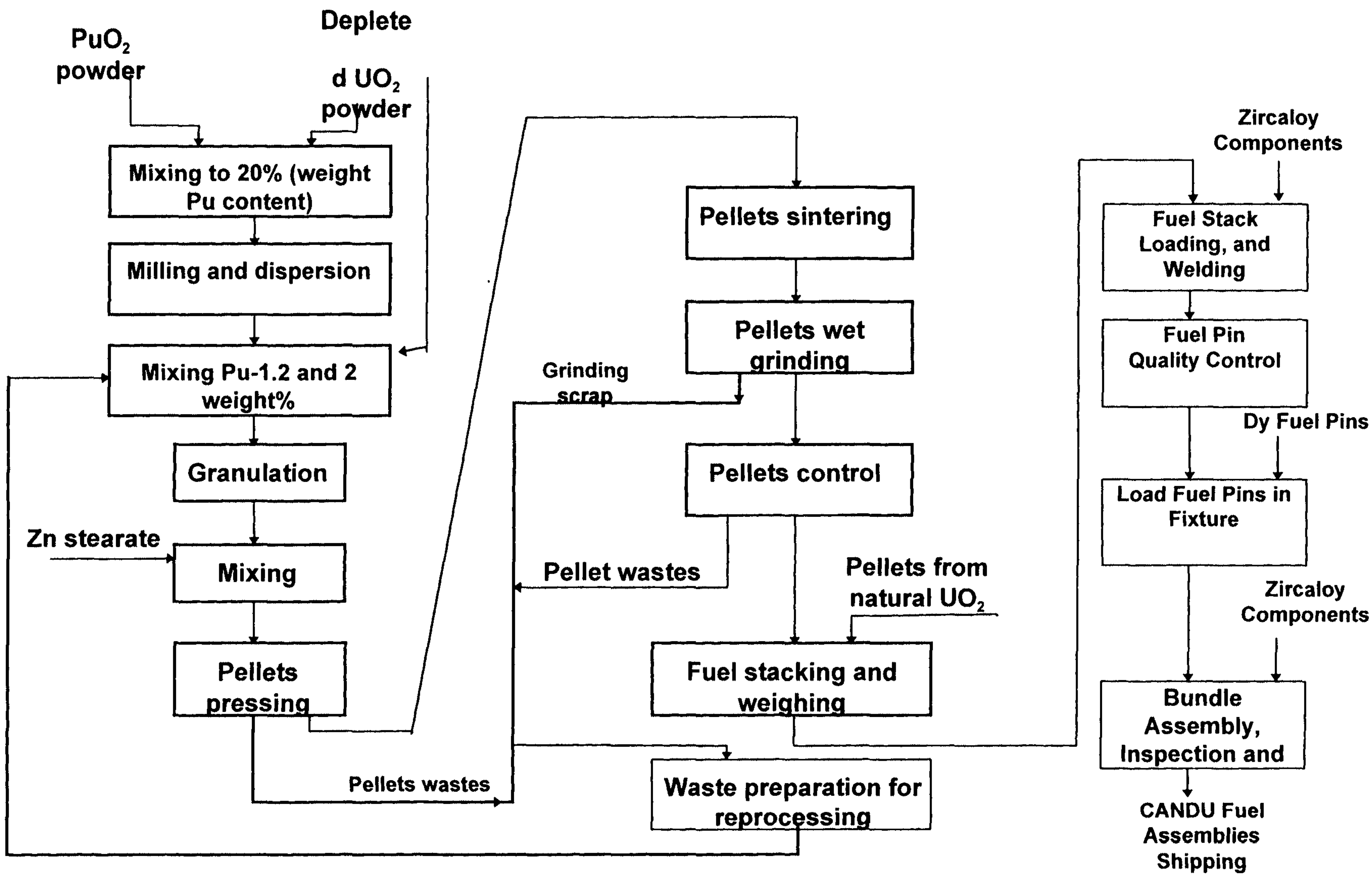

FIGURE 4-2: SCHEMATIC OF P.A. MAYAK PROCESS FOR CANDU MOX PRODUCTION

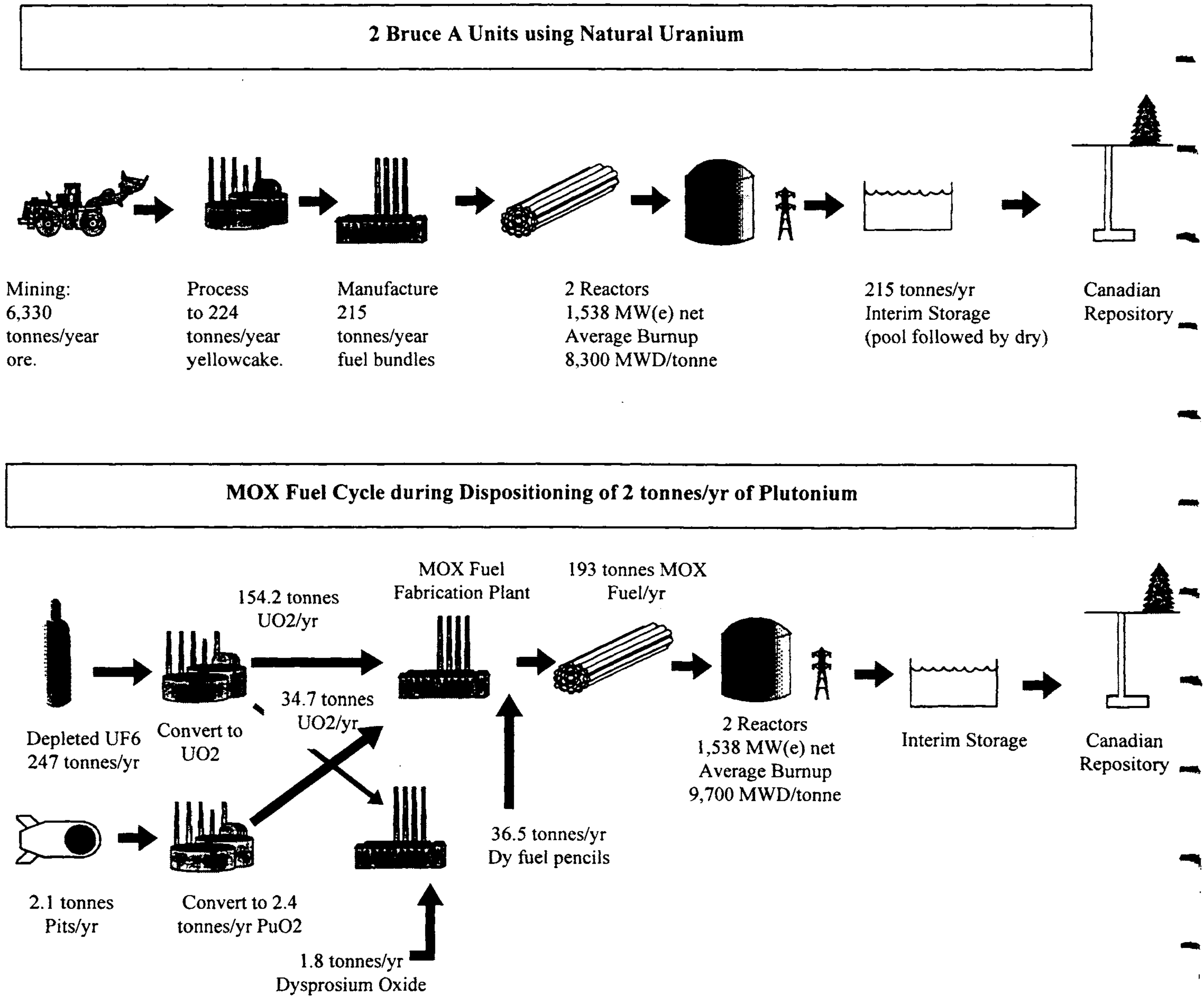

FIGURE 4-3: COMPARISON OF NATURAL URANIUM AND MOX CANDU FUEL CYCLES

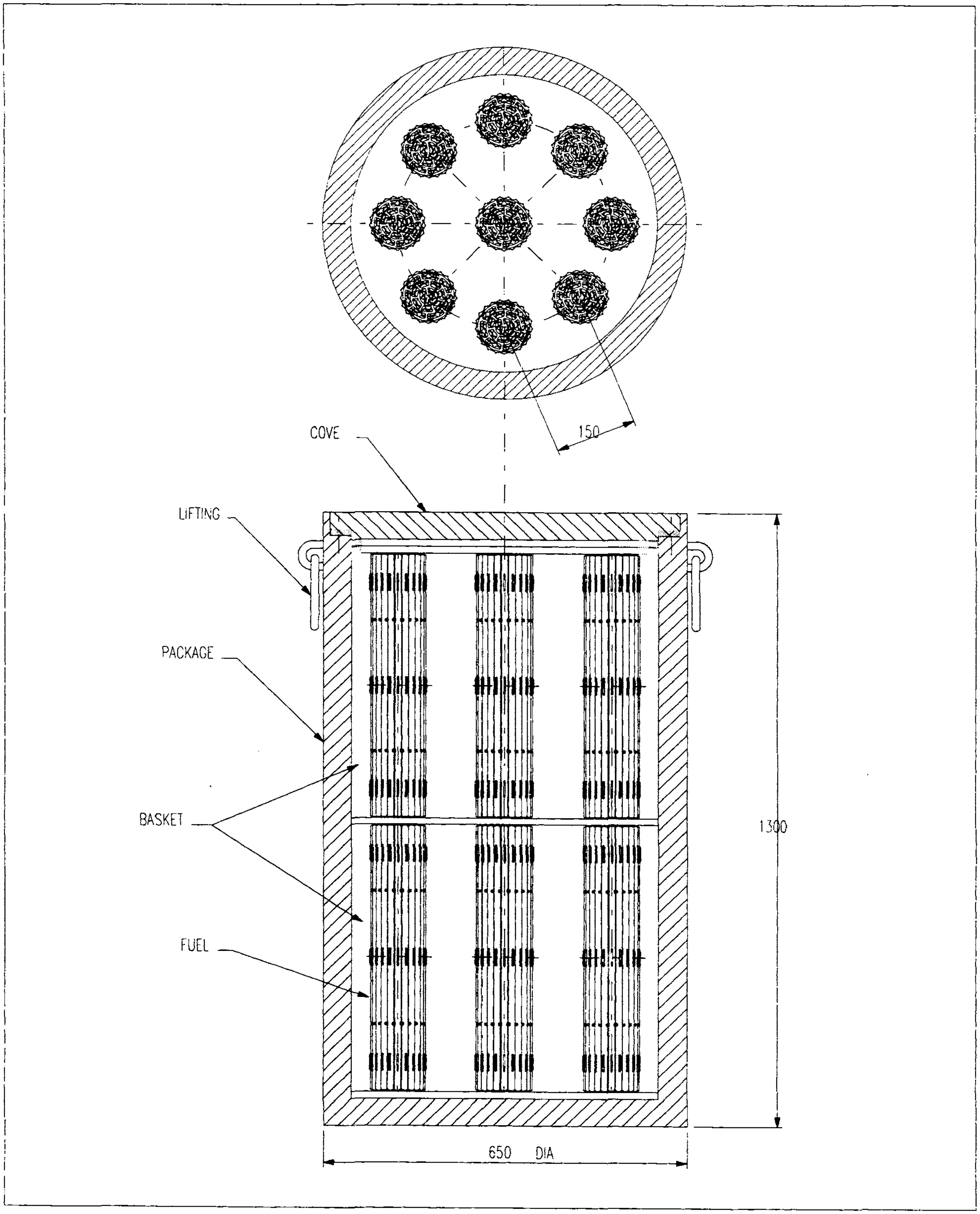

FIGURE 5-1: PROPOSED TRANSPORTATION PACKAGE

Name	Early Start	Early Finish
ContractStart	7/1/98	7/1/98
AECBReview and Approval	7/1/98	12/31/02
Fuel Qualification(37 element)	1/1/98	12/31/03
Fuel Qualification(CANFLEX)	7/1/98	12/27/05
New fuel storagefacility at Bruce	4/1/99	3/26/03
New MOX Facility (Russia)	1/1/98	9/30/03
Power ReactorDemonstration	10/2/03	6/30/04
FirstUnitOpsPeriod with 37 element MOX	7/1/04	8/1/06
Balance of unitsoperationwith CANFLEX MOX	8/2/06	7/3/29

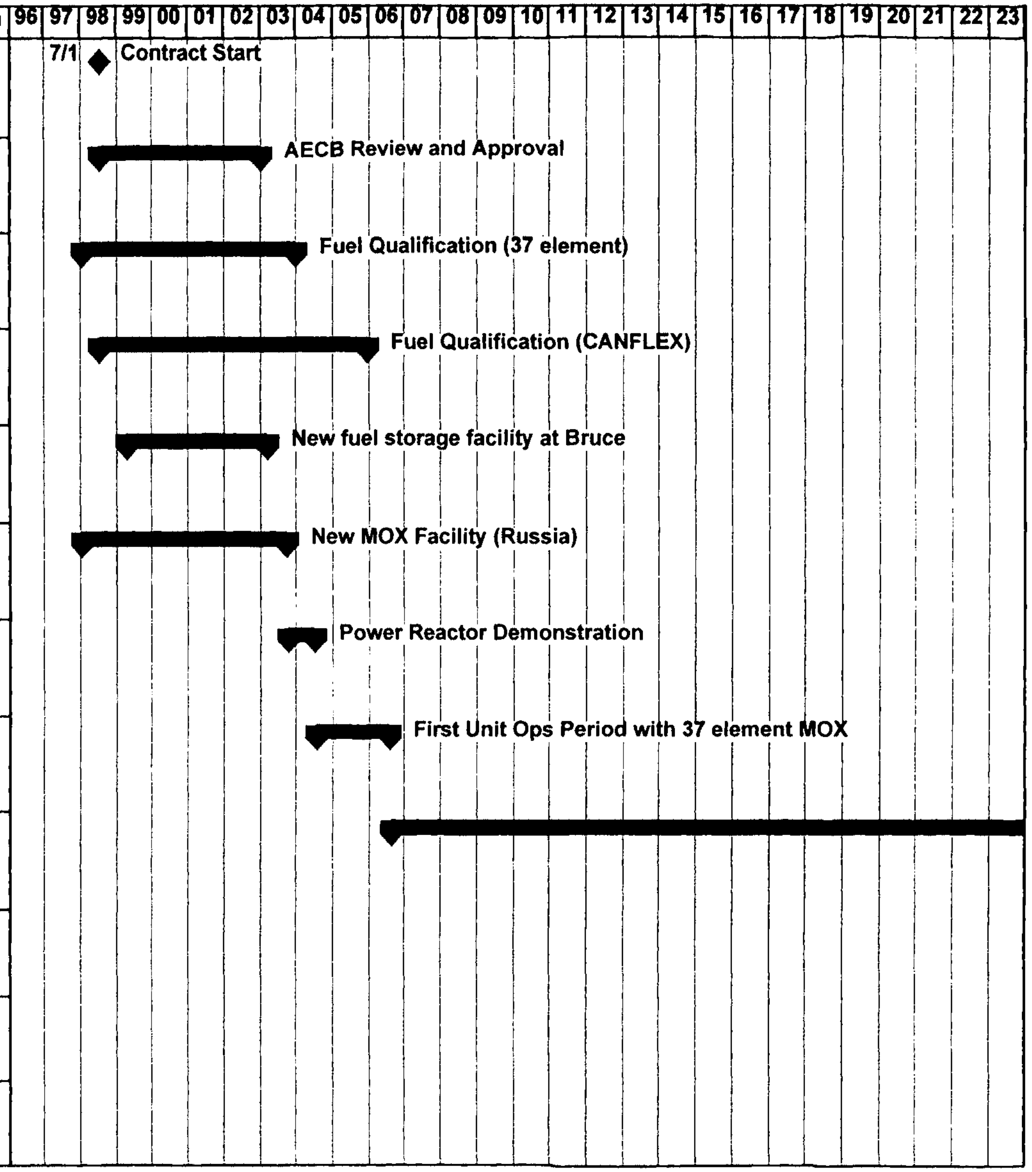

FIGURE 6-1: DETAIL SCHEDULE OF THE RUSSIAN MOX PROJECT IMPLEMENTATION