Scientific Review of the Canadian Used Nuclear Fuel Bundles Storage and The Associated Radiation and Heat Hazards

A brief summarized presentation and review of the fission and activation by-products associated with the used fuel bundles storage in regards of the CNSC (July 2003) and NWMO (Nov.2003) reports.

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Part-1

CANDU REACTOR AND NUCLEAR FUEL

1 - NUCLEAR REACTOR

Nuclear or atomic reactor is an assembly of equipments (system) in which a nuclear reaction (fission or fusion) can be initiated, sustained , maintained and controlled . The nuclear chain reactions produce large quantities of heat which can be converted into other energy forms, commonly steam. The latter is used to generate electricity via steam turbines. Sometimes other terms such as atomic pile and nuclear pile are used as substitute for reactor.

The essential components of the nuclear reactor are :

- A pressure vessel with thermo-hydro dynamic characteristics
- A core with fissile fuel such as Uranium - 235 and/or Plutonium- 239
- A neutron sources or generators
- A moderator such as graphite, light water or heavy water
- A coolant such as liquid (light and heavy water) and/or gas(helium and carbon dioxide)
- A set of control rods (usually made of cadmium or boron metals), which absorb neutrons and stop the chain reaction when there is a danger of its going out of control.
- A reflector which is a layer of material surrounding a reactor core to reflect into the core many neutrons that would otherwise escape
- A thermal shield which is a layer of high density material located inside the reactor vessel to reduce radiation heating.

1) **Types of Reactors**:

Most of the power reactors currently in service or under construction are thermal reactors. The many types of thermal reactors depend largely on the selection of the coolant and moderator material. A majority of reactors in the United States use water as coolant and moderator material. Great Britain played a pioneering role in the development of gas-cooled (CO 2) and graphite-moderated reactors. Canada specialized in reactors cooled and moderated by heavy water. In nuclear power terminology, ordinary water, in contrast with heavy water , is termed light water. The following are the major reactors in use around the world :

1- *BOILING WATER REACTOR*: A reactor in which water, used as both coolant and moderator, is allowed to boil in the core.

2- *BREEDER REACTOR* : A reactor that produces fissionable fuel as well as consuming it, especially one that creates more than it consumes.

3- *CONVERTER REACTOR* : A reactor that produces some fissionable material but less than it consumes. In some usages,a reactor that produces fissionable material different from the fuel burned, regardless of the ratio.

4- *FAST BREEDER REACTOR* : A reactor that operates with fast neutrons and produces more fissionable material than it consumes.

5- *FAST REACTOR* : A reactor in which the fission chain reaction is sustained primarily by fast neutrons rather than by thermal or intermediate neutrons.

6- *GAS COOLED REACTOR* : A nuclear reactor in which a gas (CO2, He...) is the coolant.

7- *INTERMEDIATE REACTOR* : A reactor in which the chain reaction is sustained mainly by intermediate neutrons.

8- *ORGANIC COOLED REACTOR* : A reactor that uses organic chemicals as coolant.
9- *POWER REACTOR* : A reactor designed to produce useful nuclear power, as distinguished from reactors used primarily for research or for producing radioisotopes and / or fissionable materials.
10- *PRESSURIZED WATER REACTOR* : A power reactor in which heat is transferred from the core to a heat exchanger by water kept under high pressure to achieve high temperature without boiling in the primary system. Steam is generated in a secondary circuit.
11- *RESEARCH REACTOR* : A reactor primarily designed to supply neutrons or other ionizing radiation for experimental purposes.
12- *SODIUM-GRAPHITE REACTOR* : A reactor that uses liquid sodium as coolant and graphite as moderator.
13- *SUPERCRITICAL REACTOR* : A reactor in which the effective multiplication factor is greater than one (1) - consequently, a reactor that is increasing its power level to a designed and approved limit.
14- *THERMAL REACTOR* : A reactor in which the fission chain reaction is sustained by thermal neutrons.

2) **Types of the fuel moderator assembly:**

a) **Heterogeneous** : A reactor in which the fuel is separated from the moderator and is arranged in discrete bodies, such as fuel elements.
b) **Homogeneous** : A reactor in which the fuel is mixed with or dissolved in the moderator or coolant (i.e. dilute solution of highly enriched Uranyl Sulfate,UO2SO4, in light or heavy water.)

2-CANDU POWER REACTOR DATA
(Darlington Power Station)

a) **Reactor Core Data** :

1- Power : Net output power is 620 MW

2- Fuel : Natural Uranium Dioxide (UO2).

3- Moderator : Deuterium oxide (D2O) known as heavy water.

4- Coolant: Pressurized heavy water.

5- Reactor vessel (Calandria): A horizontal, stepped cylinder comprising main shell, two subshells and two annulus plates.

6- Main shell dimensions : - Inside diameter = 8.46 meters.
- Length = 5.95 meters
- Thickness = 3.17 centimeters
- Material - Austentic stainless steel.

7- Calandria end shields : Integral with calandria shell, provide support for an alignment of fuel channels and shutdown shielding of reactor faces.

b) **Reactor Fuel Elements** :

1- **Fuel Pellet** : The smallest solid fuel entity. It is manufactured by compacting and sintering UO2 powder into cylindrical shape and grinding to required size.
Pellet size : 2 cm long X 0.84 cm dia. or 1.108 cubic centimeter
Pellet weight : 24 grams of UO2
Pellet density = 17.59 grams U - Nat / Cubic centimeter
= 21.66 grams UO2 / Cubic centimeter

2- **Fuel Bundle** : A set of a specific number of stainless tie tubes assembled togather in horizontal position.
Number of tubes in a bundle = 37
Number of UO2 pellets in each tube = 24
Number of pellets in each bundle = 24 X 37 = 888 pellets of UO2 / Bundle

3- **Fuel Channel** : A pipe of specific material designed to enclose the fuel bundles. The combination of a fuel bundles and fuel channels is called a core fuel assembly.
Fuel channel dimensions - Length = 5.95 meters
- Inside diameter = 12.9 centimeters
- Wall thickness = 1.35 centimeters
- Material - Zircaloy- 2 seam welds

Number of Calandria fuel channels (pipes) = 480
Number of fuel bundles in each channel = 13
Number of bundles in the core of calandria = 480 X 13 = 6240 bundles
Number of UO2 pellets in the reactor core = 6240 X 888 = 5 541 120 Pellets

4- **Neutron Sources** : A combination of two elements, one is a heavy radioactive (i.e. Th-228) and the other is light stable element (i.e. Be-9). The neutron source to initiate a chain reaction for reactor start up is

$_{90}Th^{228}(\alpha,n)\ _{4}Be^{9}$

$_{90}Th^{228} \longrightarrow\ _{88}Ra^{224} +\ _{2}He^{4} +\ 5.50$ Mev

$_{2}He^{4} +\ _{4}Be^{9} \longrightarrow\ _{6}C^{12} +\ _{0}n^{1} + 945$ Mev (Thermal neutron)

Several Thorium - Beryllium start- up sources are located within the reactor core. They are positioned vertically in the reactor by "fit up " in a slot (or pin) in the upper grid and a hole in the lower core support plate. The source materials are entirely enclosed in a stainless cladding with an outside diameter of approximately 1.7 centimeter.

5- **Neutron Flux** : A measure of the intensity of neutron radiation. It is the number of neutrons passing through one square centimeter of a given target in one second.
The initial flux of the neutron source = 1.48×10^{4} neutrons / sec/curie
Half Life of neutron source = 1.91 years
(1 Curie = 3.7×10^{10} disintegrations / second)
Neutron Emission = 2.5×10^{7} n/sec/curie
Maximum thermal flux in fuel = 1.32×10^{14} neutrons/ cm^{2}/second
Neutron speed (fast) = 42 000 Kilometers / sec
Slow neutron speed = 3 Kms / sec.

3- USED NUCLEAR FUEL AND DECAY PROCESSES

In a nuclear-powered electricity generating station, heat is produced by fission, which occurs in a fuel bundle when a neutron is absorbed by certain heavy elements (such as uranium-235 or plutonium-239).

In the CANDU system used in Canada, each fuel bundle contains about 19 kg of natural uranium, in the form of high-density uranium dioxide ceramic pellets. These pellets are sealed inside zirconium alloy tubes, about 0.5 m long, arranged in a circular array 10 cm in diameter (Fig. 1). Heat is removed by passing liquid heavy water over the many bundles in the reactor. In turn, the heavy water coolant passes through boilers which transfer the heat to ordinary water, producing steam. The cooled heavy water is then pumped through the reactor again in a closed loop in order to retain the heavy water. The steam from the boilers drives a turbine generator, producing electricity.

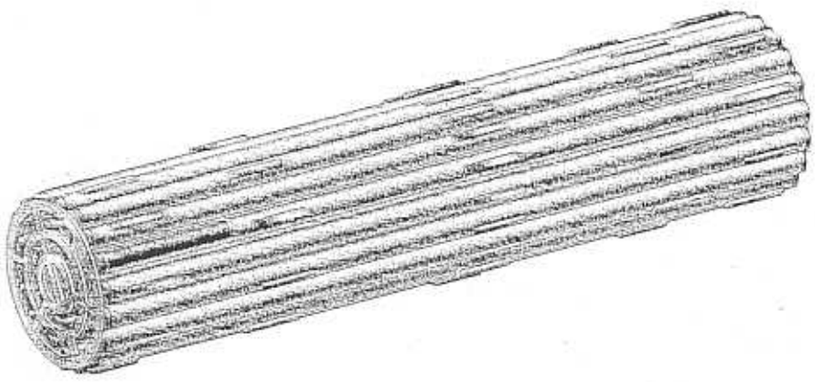

Fig.1- CANDU Nuclear Fuel Bundle

When a U-235 atom is split and neutrons are released, one neutron goes on to split another atom, and so on, keeping the nuclear reaction going

1) $_{92}U^{235} + {}_{0}n^{1} \dashrightarrow {}_{56}Ba^{141} + {}_{36}Kr^{92} + 3\,{}_{0}n^{1} + 200$ Mev

2) $_{92}U^{235} + {}_{0}n^{1} \dashrightarrow {}_{55}Cs^{140} + {}_{37}Rb^{93} + 3\,{}_{0}n^{1} + 200$ Mev

3) $_{94}Pu^{239} + {}_{0}n^{1} \dashrightarrow {}_{56}Ba^{142} + {}_{38}Sr^{95} + 3\,{}_{0}n^{1} + 198$ Mev

4) $_{94}Pu^{239} + {}_{0}n^{1} \dashrightarrow {}_{55}Cs^{141} + {}_{39}Y^{96} + 3\,{}_{0}n^{1} + 198$ Mev

A second neutron is absorbed by the non-fissionable materials in the fuel and the reactor core to form a radioactive fissionable material (Pu-239).

1) $_{92}U^{238} + {}_{0}n^{1} \longrightarrow {}_{92}U^{239} + \gamma$

2) $_{92}U^{239} \longrightarrow {}_{93}Np^{239} + {}_{-1}e^{0}$

3) $_{93}Np^{239} \longrightarrow {}_{94}Pu^{239} + {}_{-1}e^{0}$

A third neutron is absorbed by $_{1}H^{2}$ (deuteron) to form radioactive hydrogen atom $_{1}H^{3}$ known as tritium.

$$_{1}H^{2} + {}_{0}n^{1} \longrightarrow {}_{1}H^{3} + 4.34 \text{ Mev}$$

As the process continues, the concentration of fission products increases until their neutron absorption capacity becomes so large that the nuclear reaction begins to be impeded. At this stage, after about 18 months, the fuel is removed both because of the partial depletion of the fissile material as well as the build-up of neutron-absorbing fission products and actinides.

a) **Fission Products**: Fission products are formed when neutrons hit and split uranium 235 atoms. In the splitting process, several dozen different isotopes are formed. The most significant fission products, along with their half lives are listed in table 1. Fission products generate large of radiation and heat, so fuel bundles must be handled remotely, and they must be shielded and cooled when first removed from the reactor.

Table 1-**Significant Fission Products**

Fission Product	*Half-Life (Years)*
Krypton-85	11
Strontium-90	29
Technetium-99	213 000
Tin-126	234 000
Iodine-129	17 200 000
Cesium-135	2 300 000
Cesium-137	30

The following are the Radioactive disintegration processes of the fission products:

1) $_{36}Kr^{85} \longrightarrow {}_{37}Rb^{85} + {}_{-1}e^{0} + 0.67$ Mev

2) $_{38}Sr^{90} \longrightarrow {}_{39}Y^{90} + {}_{-1}e^{0} + 2.27$ Mev

3) $_{43}Tc^{99} \longrightarrow {}_{44}Ru^{99} + {}_{-1}e^{0} + 0.29$ Mev

4) $_{50}Sn^{126} \longrightarrow {}_{51}Sb^{126} + {}_{-1}e^{0} + 1.9$ Mev

5) $_{53}I^{129} \longrightarrow {}_{54}Xe^{129} + {}_{-1}e^{0} + 0.85$ Mev

6) $_{55}Cs^{135} \longrightarrow {}_{56}Ba^{135} + {}_{-1}e^{0} + 0.21$ Mev

7) $_{55}Cs^{137} \longrightarrow {}_{56}Ba^{137} + {}_{-1}e^{0} + 1.18$ Mev

b) **Actinides**: Actinides are nuclides of heavy elements in the series beginning with actinium in the periodic table of the elements. Some absorb neutrons but do not split. The main actinides in used fuel are listed in table 2.

Table 2- **Main Actinides in used fuel.**

Actinides	*Half-Life (Years)*
Uranium-235	710 000 000
Uranium-236	23 000 000
Uranium-238	4 500 000 000
Plutonium-239	24 000
Plutonium-240	6 600
Plutonium-242	360 000
Neptunium-237	2 100 000
Americium-241	460
Thorium-232	14 000 000 000

The following are the disintegration of the above actinides:

1) $_{92}U^{235} \longrightarrow {}_{90}Th^{231} + {}_{2}He^{4} + 4.56$ Mev

2) $_{92}U^{236} \longrightarrow {}_{90}Th^{232} + {}_{2}He^{4} + 4.5$ Mev

3) $_{92}U^{238} \longrightarrow {}_{90}Th^{234} + {}_{2}He^{4} + 4.2$ Mev

4) $_{94}Pu^{239} \longrightarrow {}_{92}U^{235} + {}_{2}He^{4} + 5.15$ Mev

5) $_{94}Pu^{240} \longrightarrow {}_{92}U^{236} + {}_{2}He^{4} + 5.16$ Mev

6) $_{94}Pu^{242} \longrightarrow {}_{92}U^{238} + {}_{2}He^{4} + 4.9$ Mev

7) $_{93}Np^{237} \longrightarrow {}_{91}Pa^{233} + {}_{2}He^{4} + 1.73$ Mev

8) $_{95}Am^{241} \longrightarrow {}_{93}Np^{237} + {}_{2}He^{4} + 5.5$ Mev

9) $_{90}Th^{232} \longrightarrow {}_{88}Ra^{228} + {}_{2}He^{4} + 4.01$ Mev

Table 3- **Actinides neutron absorption processes**

1) $_{92}U^{236} + {}_{0}n^{1} \longrightarrow {}_{92}U^{237} + \gamma$

2) $_{92}U^{238} + {}_{0}n^{1} \longrightarrow {}_{94}Pu^{239} + 2\ {}_{-1}e^{0}$

3) $_{94}Pu^{239} + {}_{0}n^{1} \longrightarrow {}_{94}Pu^{240} + \gamma$

4) $_{94}Pu^{240} + {}_{0}n^{1} \longrightarrow {}_{94}Pu^{241} + \gamma$

5) $_{94}Pu^{241} + {}_{0}n^{1} \longrightarrow {}_{94}Pu^{242} + \gamma$

6) $_{94}Pu^{242} + {}_{0}n^{1} \longrightarrow {}_{94}Pu^{243} + \gamma$

7) $_{93}Np^{237} + {}_{0}n^{1} \longrightarrow {}_{93}Np^{238} + \gamma$

8) $_{95}Am^{241} + {}_{0}n^{1} \longrightarrow {}_{95}Am^{242} + \gamma$

9) $_{90}Th^{232} + {}_{0}n^{1} \longrightarrow {}_{90}Th^{233} + \gamma$

c) **Activation Products**: The third and final category of radioactive materials in spent fuel comprises the radioactive isotopes resulting from neutron reactions with materials in the fuel cladding as distinct from the fuel itself. They are called activation products since they arise from non-radioactive materials

that have been made radioactive(activated) by fission neutrons.Some of them are shown in table 4

Table 4 - Activation products in fuel

Isotopes	*Half-Life (Years)*
Carbon - 14	5 700
Chlorine-36	300 000
Zirconium- 93	1 500 000

Radioactive disintegration of the activation products:

1) $_{6}C^{14}$ ----------> $_{7}N^{14}$ + $_{-1}e^{0}$ + 0.156 Mev

2) $_{17}Cl^{36}$ ----------> $_{16}S^{36}$ + $_{+1}e^{0}$ + 0.71 Mev

3) $_{40}Zr^{93}$ ----------> $_{39}Y^{93}$ + $_{+1}e^{0}$ + 0.063 Mev

At the time of removal of the used fuel bundles from the reactor, about 67% of the Uranium-235 in the fuel bundles has been consumed. Table 5 provides an overall comparison between the composition of fresh and spent CANDU fuel. The major change between fresh and used fuel is the transformation of about two thirds of the uranium-235 to fission products. There is also an intermediate reaction in which a small amount (less than 1%) of the uranium-238 absorbs a neutron and transforms to plutonium-239, of which about half subsequently fissions (splits) to produce additional fissile isotopes. About 30% of the energy derived from the fuel bundles is derived from the fissioning of plutonium.

Table 5- Composition of fresh and spent Candu Fuel

Component	*Composition of Fresh Fuel %*	*Composition of Used Fuel %*
Uranium-235	0.72	0.23
Uranium-236	0	0.07
Uranium-238	99.28	98.58
Plutonium-239	0	0.25
Plutonium-240	0	0.10
Plutonium-241	0	0.02
Plutonium-242	0	0.01
Fission Products	-	0.74

4- RADIOACTIVITY AND HEAT EMISSION FROM THE USED FUEL BUNDLES

a)**Radioactivity** :

Radioactivity is the spontaneous decay or disintegration of an unstable atomic nucleus, usually accompanied by the emission of ionizing radiation. The unstable nucleus is called a radioactive isotope or radioisotope , that decays or disintegrates spontaneously, emitting radiation.

Unstable nuclei may exist in nature or may be produced by nuclear reactions and may undergo radioactive decay by several different processes . In each of these processes , the sumof the masses of the resultant particles is less than the mass of the parent nucleus. The following are the main forms of the radioactivity emissions :

1- **Alpha particle decay** : Alpha particle is a fast moving positively charged particle emitted by certain radioactive elements. It is identical with the nucleus of a helium atom . For example, Uranium-238 decays by alpha particle emission to thorium-234 and a specific amount of energy is liberated and associated with the decay process

$$_{92}U^{238} \dashrightarrow {}_{90}Th^{234} + {}_{2}He^{4} + 4.25 \text{ Mev}$$

2- **Beta particle decay** : Beta particles are negatively (negatron) or positively (positron) charged electrons that have been expelled from the nucleus. Negative beta emission converts a neutron into a proton. For example, neon - 23 illustrates this process

$$_{10}Ne^{23} \dashrightarrow {}_{11}Na^{23} + {}_{-1}e^{0} + 4.39 \text{ Mev}$$

Positive beta emission converts a proton into a neutron. For example, carbon-11 illustrates this process

$$_{6}C^{11} \dashrightarrow {}_{5}B^{11} + {}_{+1}e^{0} + 0.96 \text{ Mev}$$

3- **Gamma ray or photon** : Gamma ray is an electromagnetic radiation emitted by atomic nuclei and produced when the nucleus returns to a lower energy state. The energy of the gamma rays correspond to the energy difference between two of the energy levels of the nucleus. For example ,barium-137 and protactinium-91 illustrate this process

$$_{56}Ba^{137} \dashrightarrow {}_{56}Ba^{137} + \gamma + 4.80 \text{ Mev}$$

$$_{91}Pa^{234} \dashrightarrow {}_{91}Pa^{234} + \gamma + 6.14 \text{ Mev}$$

Disintegration energy : It is the energy carried by any process in which a nucleus sends out one or more particles (including photons) either spontaneously or on being hit or bombard. This energy is measured with Mev (million electron- volt).

Electron :It is the negatively charged particle (charge $e = 1.6 \times 10^{-19}$ Coulomb , mass $m = 9.11 \times 10^{-28}$

gram) which forms a constituent of all atoms, its positively counterpart of equal mass and charge being called positron. However, the word electron is often used to include both negative electrons(negatrons) and positive electrons (positrons).

Electron-volt (eV):It is a unit of energy equal to the kinetic energy acquired by an electron when accelerated through a potential difference of 1 volt (1 eV = 1.6×10^{-12} ergs)

Million electron volt (Mev) or 10^6 ev: It is a unit of disintegration energy used to measure the radioactive transformation and associated heat emanation.

Curie : The basic unit used to describe and measure the intensity of radioactivity in a sample of radioactive material. The curie is equal to 37 billion disintegrations per second (3.7×10^{10} dps).

Half - life : The half-life of a radioisotope is the period of time required for the activity to decrease to half of its original value and disintegrate to another nuclear form.

The uranium-238 is the main radioactive element in the used fuel bundles (98.58%) and it is a source of alpha particle and gamma ray decay. The radioactive decay continues when the used fuel is removed from the reactor, causing emission of radiation and heat at decreasing rates proportional to half life value and changing composition over time.

b) **Heat**: Heat is energy being transferred (Energy Transfer /Heat Flow) It occurs between bodies when they are at different temperatures. The radioactive thermal energy of a substance is the total of translational kinetic energies of all atoms and molecules in the substance.

When the used fuel bundles are removed from the reactor, they are placed in water filled pools where they cool. The surface temperature of the used fuel bundles is measured by the heat generated per unit time. The heat generated or lost by the used fuel bundles is constant and continuous for long period of time and is equal to the heat removed or gained by coolant, and it can be calculated from the following formula

$$H = W\, Cw\, (T_{PO} - T_{Pi})$$

Where H= Heat removed by coolant, in calories
W= Coolant mass flow rate, in grams /sec.
Cw= Specific Heat capacity of water at constant pressure, in calories/ gram/degree Celsius
T_{PO} = Temperature of the pool outlet, in degrees Celsius
Tpi = Temperature of the pool inlet, in degrees Celsius

Specific Heat Capacity: It is that quantity of heat required to increase the temperature of a system or substance one degree of temperature. It is expressed in calories per gram per degree Celsius.

Calorie: It is a unit to measure heat quantity. It is the quantity of heat required to raise the temperature of one cubic centimeter of water by one degree Celsius.

Conclusion: It is concluded that the heat emanation or emission from the used fuel bundles is a function of radioactive decay, and it is directly proportional to the liberated disintegration energy. The physical relationships and mathematical linkages between radiation and heat energy of radioactive material are exchangeable. Each disintegration is charged with a specific amount of energy. This energy is associated with radiation and heat emanations. The radiothermal energy is a general expression to combine the radioactive and thermal energy, in which radioactive energy is expressed by Mev unit, and thermal energy by calorie. The unit for measuring radioactive energy (Re) is a Million Electron Volt (Mev), and the unit for measuring heat energy (He) is a calorie (Cal). The Mev and Calorie are exchangeable units. The unit of radioactive energy can be used to measure heat energy, and vice versa, the unit of heat energy can be used to measure radioactive energy. Therefore

$$1 \text{ Mev} = 3.83 \times 10^{-14} \text{ Calories} \quad (1)$$

$$1 \text{ Calorie} = 2.62 \times 10^{13} \text{ Mev} \quad (2)$$

$$1 \text{ Watt} = 0.626 \times 10^{13} \text{ Mev/sec} \quad (3)$$
$$= 0.239 \text{ Calorie/sec} \quad (4)$$

$$He(cal) = 3.83Re \times 10^{-14} \quad (5)$$

$$Re(Mev) = 2.62He \times 10^{13} \quad (6)$$

$$Eh(Cal/sec) = 4.184Er \times 10^{13} \quad (7)$$

$$Er(Mev/sec) = 3.817Eh \times 10^{-14} \quad (8)$$

Where He = heat energy, in calories

Re = Radiation energy, in Mev

Eh = Rate of heat energy, in calories/second

Er = Rate of radiation energy, in Mev/second

Table 6-The Radioactive Disintegration of the U-238 in the Used Fuel Bundles

Disintegration Reaction	*Half-Life*	*Symbol*
1) $_{92}U^{238}$ ------> $_{90}Th^{234}$ + $_{2}He^{4}$ + 4.2 Mev	4 500 000 000 y	U = uranium
2) $_{90}Th^{234}$ ------> $_{91}Pa^{234}$ + $_{-1}e^{0}$ + γ + 0.47 Mev	24.1 d	Th= thorium
3) $_{91}Pa^{234}$ ------> $_{91}Pa^{234}$ + γ + 6.14 Mev	1.18 m	Pa=protactinium
4) $_{91}Pa^{234}$ ------> $_{92}U^{234}$ + $_{-1}e^{0}$ + 1.97 Mev	6.66 h	" "
5) $_{92}U^{234}$ ------> $_{90}Th^{230}$ + $_{2}He^{4}$ + 9.485 Mev	250 000 y	U = uranium
6) $_{90}Th^{230}$ ------> $_{88}Ra^{226}$ + $_{2}He^{4}$ + 9.297 Mev	80 000 y	Th = thorium
7) $_{88}Ra^{226}$ ------> $_{86}Rn^{222}$ + $_{2}He^{4}$ + 9.554 Mev	1620 y	Ra =Radium
8) $_{86}Rn^{222}$ ------> $_{84}Po^{218}$ + $_{2}He^{4}$ + 5.48 Mev	3.825 d	Rn = Radon
9) $_{84}Po^{218}$ ------> $_{85}At^{218}$ + $_{-1}e^{0}$ + 6.0 Mev	3.05 m	Po=polonium
10) $_{85}At^{218}$ ------> $_{86}Rn^{218}$ + $_{-1}e^{0}$ + 13.35 Mev	1.3 s	At = astatine
11) $_{86}Rn^{218}$ ------> $_{82}Pb^{214}$ + $_{2}He^{4}$ + 2 $_{-1}e^{0}$ + 7.74 Mev	0.019 s	Rn = Radon
12) $_{82}Pb^{214}$ ------> $_{83}Bi^{214}$ + $_{-1}e^{0}$ + γ + 2.13 Mev	26.8 m	Pb = lead
13) $_{83}Bi^{214}$ ------> $_{84}Po^{214}$ + $_{-1}e^{0}$ + γ + 17.04 Mev	19.9 m	Bi = bismuth
14) $_{84}Po^{214}$ ------> $_{81}Tl^{210}$ + $_{2}He^{4}$ + $_{-1}e^{0}$ + 7.68 Mev	0.00016 s	Po=polonium
15) $_{81}Tl^{210}$ ------> $_{82}Pb^{210}$ + $_{-1}e^{0}$ + 1.96 Mev	1.3 m	Tl=thallium
16) $_{82}Pb^{210}$ ------> $_{83}Bi^{210}$ + $_{-1}e^{0}$ + 0.127 Mev	21 y	Pb= lead
17) $_{83}Bi^{210}$ ------> $_{84}Po^{210}$ + $_{-1}e^{0}$ + 6.23 Mev	5 d	Bi= bismuth
18) $_{84}Po^{210}$ ------> $_{81}Tl^{206}$ + $_{2}He^{4}$ + $_{-1}e^{0}$ + 6.105 Mev	138.4 d	Po= polonium
19) $_{81}Tl^{206}$ ------> $_{82}Pb^{206}$ + $_{-1}e^{0}$ + 1.51 Mev	4.2 m	Tl= thallium
20) $_{82}Pb^{206}$ Stable		

5- CRITICAL APPRAISAL OF THE NWMO REPORT

In reviewing the NWMO report of Nov. 2003 I noticed three important points required to be revised and / or modified: The radioactive decay graphs shown in figures 2.2 and 2.3 on page 27, the rate of decreasing the radioactive heat emission (page 27,29 and 68) and the values of the half-lives of certain radioisotopes mentioned in tables 2.1 and 2.2 on page 26.

1) **Radioactive Decay Graphs** :

The rate at which a particular radioactive material disintegrates or decays is a constant factor that is almost completely independent of all physical and chemical conditions. It is an experimental fact that the number of atoms of a given radioactive substance decreases exponentially with time provided that no new atoms are introduced. Half of the material will have decayed at the end of a certain time interval(half-life),which can be determined by mathematical calculations and experimental tests. Half-life is the time required for the activity to be reduced to half its initial value. Each radioactive substance was characterized by a particular half-life and the emission of a particular type of radiation, with definite energy limitations. The experimental investigations showed that the mean life of any group of emitted particles is 1.44 times the half - life. Its relationship to half-life for any emitter is shown in the following graphs(Fig. 2,3.4,5 and 6)

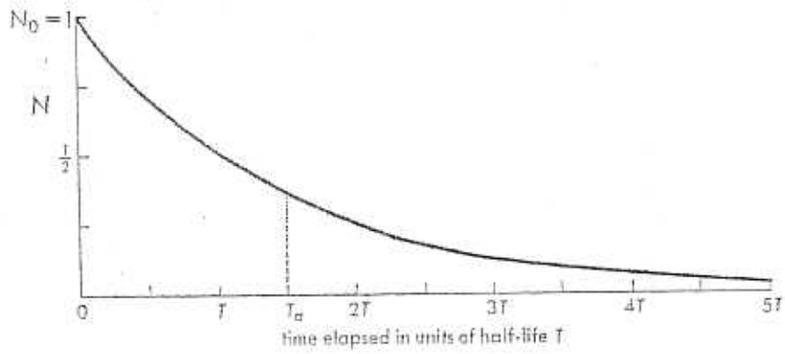

*Fig.2- **Exponential decay of a radioactive element with time***

(Source: Henry Semat- Introduction to Atomic and Nuclear Physics,4th edition, New York 1963 Page 333)

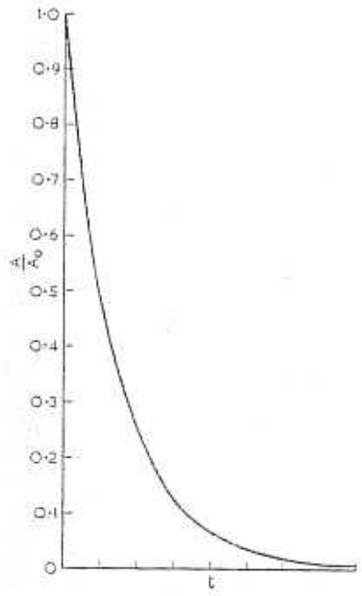

Fig.5- ***Decay curve of single radioisotope (linear plot).***
(Source: R.A. Faires& B.H. Parks- Radioisotope Laboratory Techniques, 2nd edition,London 1964 Page 13)

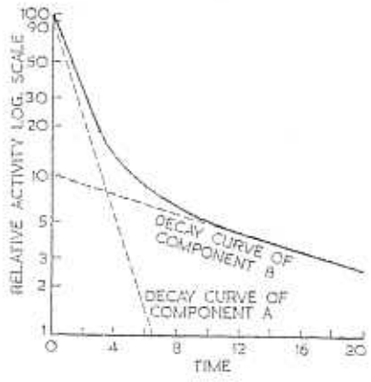

Fig.6- ***Decay curve of two component system .***
(Source: Faires & Parks- Radioisotope Laboratory Techniques,London 1964 Page 15)

From the exponential nature of the decay law which based on the laws of chance or probability,it follows that after two half-lives the activity is reduced to 1/4 , and that after m half-lives it has become $1/2^m$. This fact is of importance in the planning of experiments involving radioisotopes, and in the disposal of radioactive waste. If a nuclide has a half- life of 12 hours, the activity after a week will be $1 / 2^{14}$ Therefore it will be reduced by a factor of 16384. That means one curie (3.7×10^{10} Bequerel) initially will have decayed to about 60 microcuries after one week.

Here it must be strongly emphasized that the curie is a unit of disintegration rate, and not the rate of emission of alpha, beta particles, or gamma photons or other radiations and particles. From the published half - life of an isotope,a decay curve can easily be constructed using linear plot and / or semi-logarithmic plot as shown in the following graphs (Fig.7 & 8)

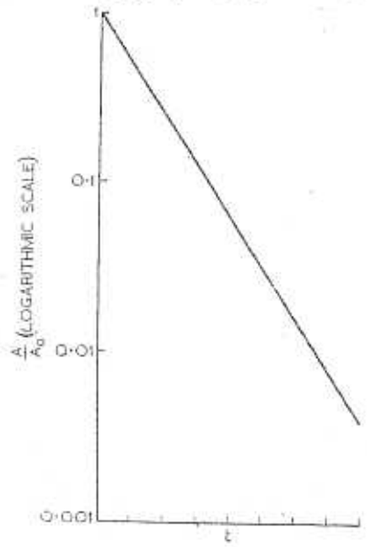

Fig. 7- ***Decay curve of single radioisotope by semi-logarithmic plot.***
(Source: Faires & Parks- Radioisotope Laboratory Techniques, 2nd edition,London 1964 P.13)

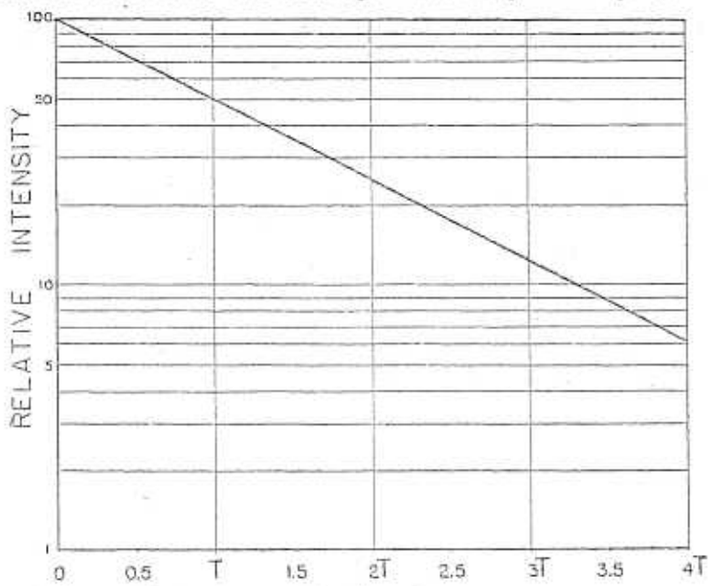

Fig.8- ***The logarithmic decay of radioactive source.***
(Source: James M. Cork- Radioactivity and Nuclear Physics,3rd edition,Princeton NJ 1957 P.24)

To construct the graph it is only necessary to mark 100% at a suitable point on the log scale and to draw a straight line through this and the point where the vertical line through the half-life on the time scale meets the horizontal through 50 %. By choosing suitable time scales,the decay curves of several nuclides may be drawn on the same graph as shown in the following graphs(Fig.9,10 & 11)

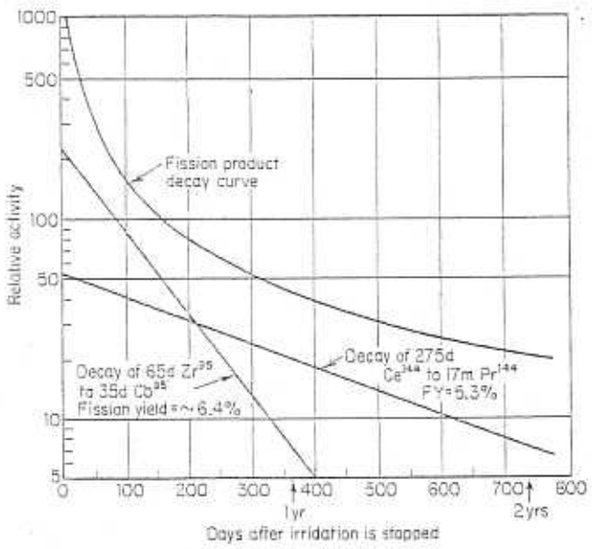

Fig.9- ***Decay of fission product mixture formed during 100 days operation of a nuclear reactor.***
(Source: R.Lapp & H. Andrews- Nuclear Radiation Physics,3rd Edition,London 1963 P.311)

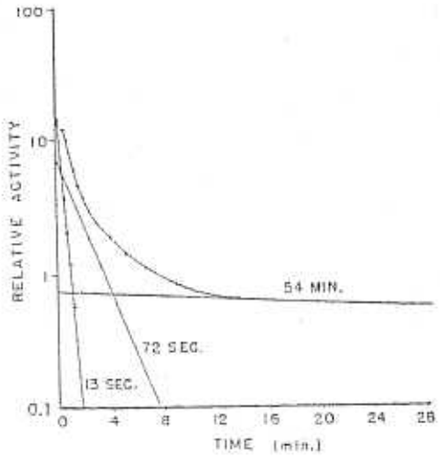

Fig.10- ***The analysis of a composite decay curve into its three components.***
(Source:James M. Cork-Radioactivity and Nuclear Physics,3rd edition, Princeton NJ 1957 P.24)

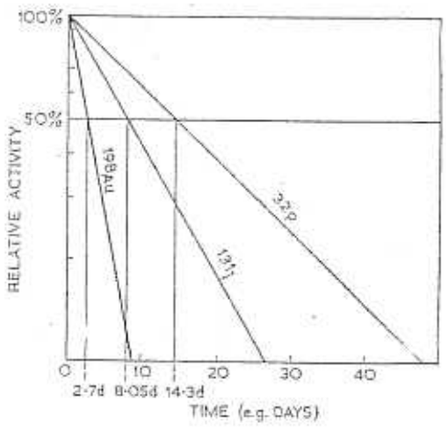

Fig.11- *Typical decay curves of multiple radioisotopes by logarithmic plot.*
(Source: Faires & Parks -Radioisotope Laboratory Techniques,2nd edition,London1964 P.14)

Elements of different atomic number are usually separable chemically. In this way continued investigations revealed the fact that the atom of uranium-238 and atomic number 92 is the parent of an entire series of elements of descending atomic weights. In its continued disintegration one alpha particle and one gamma ray (photon) are emitted in the first step. The final residual atom is a stable isotope of lead of atomic weight 206 and an atomic number 82.(See attached table).The half-life of U-238 is about 4.5×10^{9} years, which means that the disintegration constant is 4.9×10^{-18} per second. Hence a gram of pure uranium-238, which contains 2.53×10^{21} atoms will give rise to $2.53 \times 10^{21} \times 4.9 \times 10^{-18}$ or about 12 400 disintegrations per second.

In examining the published graphs of fig.2.2 and 2.3 of NWMO report page 27, it appears that these graphs are not good representation for the experimental models. The radioactivity of a used fuel bundle over time (logarithmic scale) as represented by the graph of fig.2.2 is not a semi-logarithmic plot nor a linear plot representation. It is not in agreement with the known half-life and disintegration constant data of the U-238 radioisotope or other fission products which are all in the fuel pellets. The same observations are applied to the total radioactivity per bundle of used fuel as represented by the graph of fig.2.3. The graphs of fission products which are all in the fuel pellets,uranium and activation products are not exponential as it should be in the linear scale, nor are straight lines as it should be in logarithmic scale.(See fig.2.2 and 2.3 below)

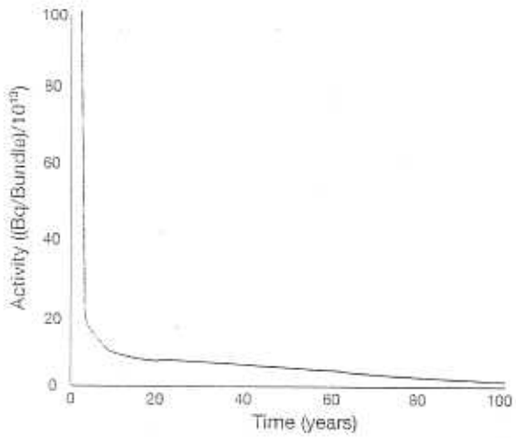

Fig.2.2- ***Radioactivity of a used fuel bundle over time(logarithmic scale)***

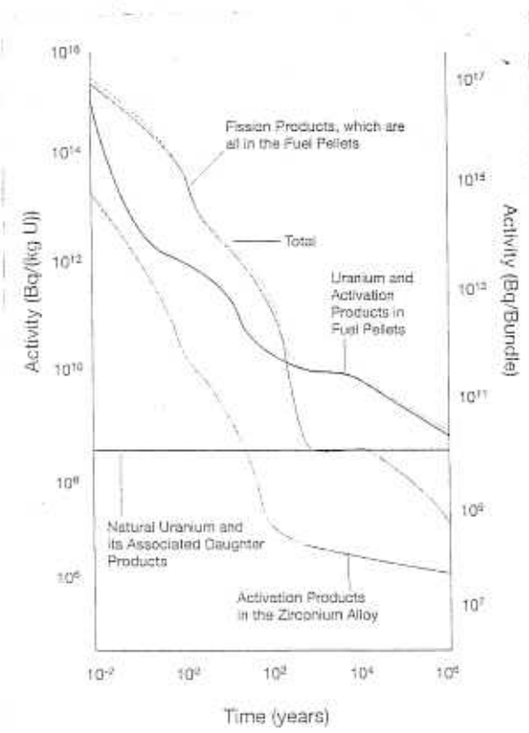

Fig.2.3- ***Total radioactivity per bundle of used fuel (linear scale)***

2-Radioactive Heat Emission:

NWMO report mentioned the radioactive heat emission from the used fuel bundles in the following statements :

1)-"*As shown in figures 2.2 and 2.3 , the level of radioactivity declines rapidly at first, then tails off. Activity declines to that of material uranium and its associated radioactive decay products after about one million years. These decay characteristics are well established, having been both observed in nature (radioactive decay has gone on continuously since the earth formed) and modeled theoretically " p.27*

If the level of radioactivity declines to that of natural uranium after about one million years, then surely it can not be described as " declines rapidly ",then the theoretical model showed in the graph of fig.2.2 is not an accurate representation of the observed and tested facts of the radioactive decay.

2)-"*...Solid nuclear waste is placed in an excavated cavity or a deep borehole. Radioactive heat generated by the waste would increase, melting the surrounding rock and dissolving the radionuclides in a growing sphere of molten material " P.68*

The rock melting required a tremendous amount of radioactive heat, which means the used fuel bundles are not rapidly cooled in the water-filled pools.

3)- " *Radioactive decay continues when the used fuel is removed from the reactor, causing emissions of radiation and heat at decreasing rates, and changing composition over time. Some 350 different isotopes are present, of which about 200 are radioactive " P.27*

Radioactive decay of the used fuel is a continuous process. The removal of the used fuel from the reactor has no physical or chemical effect on the radioactive decay or disintegration, nor on the heat emission which is associated with the value of the half-life of the radioactive material.

4)-" *When used fuel bundles are removed from a reactor, they are extremely hot, each bundle gives off more than 25 500 watts of energy- the equivalent of 250 light bulbs (100 watt) in one concentrated bundle. In this initial period the heat, alone , emanating would cause injury upon direct exposure. " P.29*

That means each used fuel bundle produces 25 500 watts X 0.239 calories / sec =6094.5 cal / sec. This radioactive heat rate is steady and continuous. It is directly related to the radioactive disintegration without any local effect.

All the mentioned statements, so far, are in full agreement with observed and tested data of the radionuclide's decay charts.

5)- " *When the fuel bundles are removed , they are placed in water - filled pools where they cool quite rapidly. After about an hour, they emit about 35 % of the original heat, after a day, it is 12 %, after a year, about 0.2 % . At this time, the heat emanating from one bundle is roughly equivalent to a 60 watt light bulb." P.29*

The CNSC report of July 2003, admitted that the temperature of the inner carbon steel liner of DSC is 98^0 C. In order to sustain this temperature, a continuous source of heat is required.

Bundles lost heat = (inner Carbon steel) liner gained heat

$$m_b\ c_b\ (t_2 - t_1) = m_1\ c_1\ (t_2 - t_1)$$

My detailed calculations mentioned in my second report to the CNSC (September 12th 2003) showed that millions of calories are required to sustain that temperature.

3- **The Values of The Half-Lives:**

In reviewing the values of the half lives of the radioisotopes published in the tables 2.1 and 2.2 the following values should reviewed and /or corrected:

	Radioisotope	H.L NWMO Published value	Scientific Accepted Value
Table 2.1	Technetium- 99	210 000 y	213 000 y
	Tin- 126	210 000 y	234 000 y
	Iodine- 129	16 000 000 y	17 200 000 y
Table 2.2	Thorium- 232	1 400 000 000 y	14 000 000 000 y

(Source: David R. Lide - Editor- in- chief, Handbook of Chemistry and Physics, 82nd edition 2001-2002 CRC Press- New York, 2001.)

Part-2

STORAGE AND DISPOSAL METHODS OF NUCLEAR FUEL

Appendix - 1

Canadian Nuclear Generating Stations (NWMO Report P.32)

SITE	REACTORS	OPERATOR	LOCATION (SEE MAP ABOVE)
Bruce-A	4 x 825 MW	Bruce Power Inc.	Kincardine, ON *(1)*
Bruce-B	4 x 915 MW	Bruce Power Inc.	Kincardine, ON *(1)*
Pickering-A	4 x 540 MW	Ontario Power Generation	Ajax-Pickering, ON *(2)*
Pickering-B	4 x 540 MW	Ontario Power Generation	Ajax-Pickering, ON *(2)*
Darlington	4 x 880 MW	Ontario Power Generation	Bowmanville, ON *(3)*
Gentilly-2	1 x 635 MW	Hydro-Québec	Trois-Rivières, QC *(4)*
Point Lepreau	1 x 635 MW	New Brunswick Power	Saint John, NB *(5)*

Appendix - 2

Canadian Research and Isotope - producing Reactors (NWMO report P.32)

LICENSEE	REACTORS	LOCATION (SEE MAP ABOVE)
McMaster University (Pool-type research reactor)	5 MWt	Hamilton, ON *(6)*
Ecole Polytechnique (SLOWPOKE-2)	0.02 MWt	Montreal, QC *(7)*
Ecole Polytechnique (Subcritical Assembly)	0 MWt	Montreal, QC *(7)*
Dalhousie University (SLOWPOKE-2)	0.02 MWt	Halifax, NS *(8)*
Saskatchewan Research Council (SLOWPOKE-2)	0.02 MWt	Saskatoon, SK *(9)*
University of Alberta (SLOWPOKE-2)	0.02 MWt	Edmonton, AB *(10)*
Royal Military College of Canada (SLOWPOKE-2)	0.02 MWt	Kingston, ON *(11)*
AECL (Maple 1)	10 MWt	Chalk River, ON *(12)*
AECL (Maple 2)	10 MWt	Chalk River, ON *(12)*
AECL (NRU)	135 MWt	Chalk River, ON *(12)*
AECL (ZED-2)	0.0002 MWt	Chalk River, ON *(12)*

MWt represents thermal power, which applies to non-power reactors

Appendix - 3

Storage of Used Nuclear Fuel in Canada (as of December 31, 2002)
(NWMO report P.33)

STORAGE LOCATION *(SEE MAP OPPOSITE)*	LICENSEE	FUEL BUNDLES IN REACTOR	USED-FUEL BUNDLES IN WET STORAGE	USED-FUEL BUNDLES IN DRY STORAGE	TOTAL FUEL BUNDLES
ONTARIO					
Bruce A *(1)*	Bruce Power Corporation	0	354,567	0	354,567
Bruce B *(1)*	Bruce Power Corporation	24,679	356,519	0	381,198
Pickering *(2)*	Ontario Power Generation	36,756	393,690	99,106	529,552
Darlington *(3)*	Ontario Power Generation	24,960	211,932	0	236,892
Douglas Point *(13)*	AECL	0		22,256	22,256
Chalk River Laboratories *(12)* (used fuel from Rolphton Nuclear Power Demonstration)	AECL	0		4,853	4,853
QUEBEC					
Gentilly 1 *(14)*	AECL	0	0	3,213	3,213
Gentilly 2 *(4)*	Hydro-Québec	4,560	37,181	48,000	89,741
NEW BRUNSWICK					
Point Lepreau *(5)*	New Brunswick Power	4,560	40,482	52,920	97,962
MANITOBA					
Whiteshell Laboratories *(15)* (used fuel from Douglas Point and non-standard waste)	AECL	0		360	360
TOTAL		95,515	1,394,371	230,708	1,720,594

Appendix - 4

Estimated Future Used Fuel Inventory (NWMO report P. 34)

RESPONSIBLE	FACILITIES WHERE USED FUEL BUNDLES ARE LOCATED	NUMBER OF USED FUEL BUNDLES AS OF 31 DECEMBER 2002 (FROM TABLE 2.7)	ESTIMATED FUTURE USED FUEL BUNDLES
OPG	Bruce A	354,567	3,300,000 (1)
	Bruce B	381,198	
	Pickering	529,552	
	Darlington	236,892	
AECL	Chalk River Laboratories	4,853	4,853 (2)
	Douglas Point	22,256	22,256 (3)
	Whiteshell Laboratories	360	360 (3)
AECL	Gentilly 1	3,213 (3)	3,213 (3)
Hydro-Québec	Gentilly 2	89,741	133,000 (4)
NB Power	Point Lepreau	97,962	111,480 (5)
TOTAL		1,720,594	3,575,162

(1) Reference - OPG Report W-CORR-00531-0052, "Revised Plan and Cost Estimates for Management of Used Fuel", October 2002, submitted to the CNSC.
This report provides OPG's projected total inventory of 3.3 million bundles assuming all of the reactors operate for 40 years.

(2) This is a research facility that no longer produces used CANDU fuel.

(3) These are decommissioned facilities that no longer produce used CANDU fuel.

(4) Reference – Attachment to Hydro-Québec Document H08-1374-003, "Preliminary Decommissioning Plan for G-2 Nuclear Generating Station", April 2001, submitted to the CNSC. This document refers to an estimate of 133,000 bundles to be produced by 2013. The assumed Gentilly-2 station design life is 30 years. No decision has been taken yet regarding the refurbishment of Gentilly-2. If the refurbishment is approved, the operation of Gentilly-2 would be extended and the estimated bundles will be revised accordingly.

(5) Reference - Attachment 1 of August 2003 letter from NB Power submitted to the CNSC. The attachment to this letter refers to an irradiated fuel inventory of approximately 111,480 bundles at the end of NB Power's current Power Reactor Operating Licence (March 31, 2006). If the operation of Point Lepreau is extended beyond March 2006, the estimated bundles will be revised accordingly.

Appendix - 5

Nuclear Terminology : Disposal , Storage and Treatment (NWMO report P.61 - 62)

1) **Used Nuclear Fuel**
Irradiated fuel from a commercial or research reactor that has served its intended purpose (for instance, for generation of electricity) and has been removed from the reactor.

2) **Method**
A technology, technique, technical process or procedure for handling used nuclear fuel.

3)**Management Approach**
A strategy for the long - term care of used nuclear fuel which encompasses a particular technical method or sequence of methods, and all of the conditions necessary for its successful implementation.

4) **Disposal**
A method of isolating used nuclear fuel from humanity and the environment; the method must be conclusive and without the intention of retrieval or reuse . Disposal methods may require transporting used nuclear fuel to a centralized location , whether in the home country, to an international repository or to an offshore location .

5) **Storage**
A method of maintaining used nuclear fuel in a manner that allows access , under controlled conditions for retrieval or future activities..Most storage methods rely on engineered barriers, for radiation protection . The used nuclear fuel is placed in engineered facilities (which can be concrete containers, silos or modules). Storage methods require repackaging of the fuel containers over time , and will require transportation if the storage facilities are not located at the reactor site where the waste is created.

6) **Treatment**
Processes applied to used nuclear fuel that change its characteristics. Currently these include processes that reduce the volume of the used nuclear fuel and separate the components for individual treatment (reprocessing, partitioning and conditioning). Treatment methods involve applying chemical and physical processes to the used nuclear fuel, recovering desirable components and separating and treating residual, radioactive and hazardous waste streams . Treatment methods may require that the used nuclear fuel be transported to the treatment facility and recovered components and residual waste streams may need to be transported back.

Appendix - 6

Methods Requiring Review Under The Nuclear Fuel Waste Act
(NWMO report P.62 - 65)

The Nuclear Fuel Waste Act obligates the NWMO to examine, in detail, three management methods,. Countries other than Canada are also actively examining or implementing these methods.

1) **Deep Geological Disposal**
Deep geological disposal involves burying the used nuclear fuel deep underground. This method is currently favored by many countries and by most international agencies. It would require transporting used fuel from interim storage facilities to a disposal facility (wherever it is located).

2) **Centralized Storage**
Long - term storage at a central site requires transporting the fuel from the reactor sites. Storage facilities can be located either above or below ground. Here in Canada, industry has completed a preliminary review of centralized extended storage. Their above - ground alternatives include casks and vaults in storage buildings; and surface modular vaults. Below - ground alternatives include casks and vaults in buried storage containers; and casks and vaults in rock caverns.

3) **Reactor - Site Extended Storage**
Both above and below - ground storage alternatives are in use today. Each site has its own distinguishing characteristics, and many conditions must be factored into the design, construction, operation and maintenance processes. One advantage of storing used fuel at the reactor site is that it eliminates the need to transport the fuel to another (centralized) location.

Appendix - 7

Methods Receiving International Attention (NWMO report P.66 - 67)

This discussion looks at additional methods that are being considered in some national programs around the world ,and at methods that are likely to receive some attention in the future.

1) **Processing, Reprocessing, Partitioning and Transmutation**

a- Processing :It is mainly the method or procedure for the preparation of fresh fuel before it goes into the reactor.

b- **Reprocessing** : It is a general term for applying chemical processes to used nuclear fuel for the purpose of recovery and recycling of fissionable isotopes .It takes place after the used nuclear fuel has cooled for a few years. The fuel is moved to a reprocessing facility where it is stored in large lead and steel casks.

c- **Partitioning** : Separation and segregation are the main partitioning processes used to isolate products into different streams, such as useable uranium and plutonium; highly radioactive liquid waste ; and less radioactive solids, liquids, and gases.

d- **Transmutation** : It is a nuclear research process developed and used to transform some radioactive components into non- radioactive elements and vice- versa by using nuclear reactions initiated by neutrons or protons. This process changes one element to another and it is of interest because successful transmutation could significantly reduce the time horizon of risk associated with used nuclear fuel, unwanted nuclear weapons and surplus plutonium.

Examples of Artificial Nuclear Transmutation :

a) - **Artificial Gold Production:**

1- $_{82}Pb^{200} + {}_{0}n^{1} \longrightarrow {}_{79}Au^{197} + {}_{2}He^{4} + {}_{+1}e^{0}$

2- $_{77}Ir^{193} + {}_{2}He^{4} \longrightarrow {}_{79}Au^{196} + {}_{0}n^{1}$

3- $_{80}Hg^{198} + \gamma \longrightarrow {}_{79}Au^{197} + {}_{0}n^{1} + {}_{+1}e^{0}$

b) - **Transmutation of Stable Element into Radioactive one:**

1- $_{5}B^{10} + {}_{2}He^{4} \longrightarrow {}_{7}N^{13} + {}_{0}n^{1}$

2- $_{13}Al^{27} + {}_{2}He^{4} \longrightarrow {}_{15}P^{30} + {}_{0}n^{1}$

3- $_{27}Co^{59} + {}_{2}He^{4} \longrightarrow {}_{28}Ni^{63} + {}_{+1}e^{0}$

c) - **Transmutation of Radioactive Element into Stable one:**

1- $_{12}Mg^{27} + {}_{1}H^{1} \longrightarrow {}_{11}Na^{23} + {}_{2}He^{4} + {}_{0}n^{1}$

2- $_{29}Cu^{64} + {}_{1}H^{2} \longrightarrow {}_{28}Ni^{62} + {}_{2}He^{4}$

3- $_{31}Ga^{73} + {}_{+1}e^{0} \longrightarrow {}_{32}Ge^{72} + {}_{0}n^{1}$

2) **Storage or Disposal at an International Repository**

Any assessment of international storage or disposal would necessarily include all the costs ,benefits and risks of the site and related infrastructure (including transportation), linked to all affected societies and cultures . The design could be either above or below ground . The facility could either be based in another country and accept Canadian waste , or be based in Canada to accommodate its own and other countries' waste. Should this repository method be considered, a complex issue would be choosing a suitable site.

3) **Emplacement in Deep Boreholes**

Some countries, which must dispose of only small quantities of high- level waste, are looking at a method called " emplacement in deep boreholes ". In this method, solid pachaged waste would be placed in deep boreholes drilled to depths of seven kilometres , with diameters of typically less than one metre . The waste containers would be stacked in each borehole and would be separated from each other by a layer of bentonite or cement.

Appendix -8

Methods of Limited Interest (NWMO Report Page 68-70)

Eight methods are included in this category. They have been studied over the past 40 years, but none are being implemented , nor are they the focus of major research effort. Brief summaries are provided here to share information on the broad range of options that have been raised historically .

1- **Direct Injection:** This method involves injecting liquid radioactive waste directly into a layer of rock deep underground. Direct injection requires detailed knowledge of subsurface geological conditions. It does not incorporate any man- made barriers . There would be no control of the injected material after disposal . Retrieval would be impossible.

2- **Rock Melting:** In this method, liquid or solid waste is placed in an excavated cavity or a deep borehole. Heat generated by the waste would increase, melting the surrounding rock and dissolving the radionuclides in a growing sphere of molten material . As the rock cools, it would solidify and incorporate the radionuclides in the rock matrix, dispersing the waste throughout a larger volume of rock .

3- **Sub-seabed Disposal:** In this method, radioactive waste containers are buried in a suitable geological setting beneath the deep ocean floor. The sub-seabed disposal concept involves using missile-shaped canisters called "penetrators" to hold solid waste. The penetrators are dropped from ships, and bury themselves to a depth of a few metres or more in the sediments on the ocean floor.

4- **Disposal at Sea:** This method consists of placing packaged waste on the bed of the deep ocean. The packaging would consist of canisters designed to last for a thousand years or more. The waste would be in a solid form that would release radionuclides into the ocean very slowly when the canister fail.

5-**Disposal in Ice Sheets:** In this method, containers of heat-generating waste would be placed in very thick, stable ice sheets, such as those found in Greenland and Antarctica. Three possibilities have been suggested:

a) In the"**meltdown**" concept, containers would melt the surrounding ice and be drawn deep into the ice sheet, where the ice would refreeze above the wastes, creating a thick barrier.

b) In the "**anchored emplacement**" concept, containers would be attached to surface anchors that would limit the containers' penetration into the ice by melting at around 200-500 metres.

c) In the"**surface storage**" concept, containers would be placed in a storage facility constructed on piers above the ice surface.

6- **Disposal in Subduction Zones:** This method was initially proposed in the 1980s. In theory, it involves placing waste in a subducting (or descending) plate of the earth's crust. Subduction zones are always offshore, so this concept can be considered a variant of emplacement in the sea or beneath the seabed.

7-**Disposal in Space:** The method would permanently remove radioactive waste from earth by ejecting it into outer space. Alternative destinations that have been considered include the sun, orbit around the sun, and ejection beyond the solar system.

8- **Dilution & Dispersion:** The method would involve dissolving the fuel in acid, neutralizing the solution and discharging it slowly down a pipeline into the sea. The discharge site and rate would be such that radiation dose to people never exceed internationally-accepted limits. It differs from all other storage and disposal methods in that there is no containment of the waste or isolation from the environment .It has never been proposed or considered seriously for used nuclear fuel disposal because sea disposal is prohibited by international conventions.

References:

1) Andrews & Lapp -**Nuclear Radiation Physics**, 3rd edition , London 1963

2) Cork , James - **Radioactivity and Nuclear Physics** ,2nd edition,Princeton NJ 1957

3) Faires & Parks - **Radioisotope Laboratory Techniques** ,2nd edition ,London 1964

4) Lide , David - **Handbook of Chemistry and Physics** , 82nd edition ,New York 2001

5) Parker ,Sybil -**Encyclopedia of Physics** ,5th edition , New York 1983

6) Semat, Henry - **Introduction to Atomic and Nuclear Physics**,4th edition,New York 1963

7) CSNC - **EA of the proposed DUFDS project**, Ottawa May 2003

8) CSNC - **EA of the proposed DUFDS project**, Ottawa July 2003

9) NWMO - **Asking the Right Questions?**
The Future Management of Canada's Used Nuclear Fuel, Toronto,November 2003