Internal dosimetry of gamma emitting radionuclides at CNE Cernavoda

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ABSTRACT

CNE Cernavoda developed a comprehensive dosimetry program, including internal exposures. Despite a careful planning for radioactive source control, the release of radionuclides in working environment could lead, infrequently, to radioactive material intake by workers. Various respiratory protection equipment are used by workers performing radioactive contamination risk work, as required by Radiation Work Permit.

Internal contamination of workers may occur due to intakes of radionuclides as a result of several activities, mainly during undressing or when the airborne contamination is unexpected. The most common route of entry of a radioactive contamination into the body of a worker is by inhalation of airborne radioactivity. A strict control of contamination events allow to promptly identify gamma radionuclide intakes and initiating bioassay procedures for internal dose calculation.

Two internal contamination events are presented in this paper, one by inhalation of ^{95}Zr -^{95}Nb and the other one by percutaneous transfer of ^{137}Cs. IMBA Professional Plus code is used in present to calculate internal doses due to gamma emitting nuclides intakes. Dose calculation results are presented for both events.

1.0 INTRODUCTION

Cernavoda NPP has two CANDU 6 reactors in commercial operation, first since December 1996 and the second one since November 2007.

For a CANDU 6 type reactor the major contributor to the external dose is gamma radiation (about 90%). Tritiated heavy water (DTO) is the major contributor to the internal dose of professionally exposed workers contributing with up to 40% of the total effective collective dose.

The main purpose of Individual Dosimetry Program design and implementation is monitoring, evaluation and recording all the significant individual radiation doses received by an individual during activities performed at Cernavoda NPP from both external, Hp(10), and Hp(0.07) and internal, E50, exposures and providing support to maintain ALARA all radiation exposures.

Health Physics Department provides individual dosimetric surveillance for both external and internal exposure for all the personnel entering radiological controlled areas: Cernavoda NPP employees, contractors, short-term atomic radiation workers, and visitors. Individual dose monitoring is provided by our dosimetry laboratory licensed by Romanian regulatory body, National Commission for Nuclear Activities Control (CNCAN).

Radiation Protection Program for Cernavoda NPP is designed insomuch as legal dose limits, established by our national regulatory body, for atomic radiation worker and for public, will not be exceeded.

Cernavoda NPP Dose Monitoring, Evaluation and Recording program is based on the latest ICRP recommendations: ICRP publications 75, 60, 66, 68, 78, 103 and also, on the requirements of national laws and regulations.

2.0 INTERNAL DOSIMETRY PROGRAM

CANDU is a Canadian design pressurized heavy water reactor - PHWR, which uses natural uranium fuel and heavy water as a neutron moderator and primary heat transport agent.

Activation of deuterium by thermal neutron flux is the major mechanism of tritium production in a PHWR reactor but other nuclear reactions could also produce tritium (ternary fission, re-conversion of ^{3}He to ^{3}H by thermal neutron reaction).

Tritiated heavy water (DTO) which is present at many work locations as water vapors is the major contributor to internal dose of professionally exposed workers at Cernavoda NPP.

Minor contributors to the internal doses could be:

1) activation products as ^{95}Nb and ^{95}Zr (corrosion products from the zirconium alloys in fuel sheath and pressure tubes) and ^{60}Co (corrosion product from steel alloys reaching the active zone). Other activation products which could be present in PHT are ^{51}Cr, ^{54}Mn, ^{59}Fe, ^{113}Sn, ^{124}Sb.

2) fission products as ^{131}I, ^{133}I, ^{135}I and ^{137}Cs.

Radiation protection programs provide adequate basis theoretical, and instrumental for exposure control designed to minimize the combined external and internal dose i.e., total effective dose equivalent. As related to internal dosimetry, the radiation protection program includes the following elements: job specific / area scaling factor, estimates of intake and assessment of dose. Biological retention and excretion models are provided by internal dosimetry software – LUDEP 2.0 or recently IMBA.

Dose assessment from bioassay generally relies firstly on intake calculation for a radionuclide either from direct measurements with a Whole Body Counter – WBC or by indirect measurements, e.g. urine, faeces or working area contamination samples. Predicted values of the internal residual quantities for unit intake are estimated by using ICRP biokinetic models and these values are used to estimate the intake (ICRP, 1997b). The effective dose resulting from a particular intake is then calculated using ICRP dose coefficients.

2.1 Internal dosimetry for minor contributors

The most frequent source for internal contamination is due to the presence of loose contamination with ^{95}Nb / ^{95}Zr, when primary heat transport system is opened for maintenance activities.

Routine WBC monitoring program is implemented as follows:

- The fuel handling / fueling machine personnel are monitored once a month, and the rest of Fuel Handling staff four times a year.
- Nuclear operators, maintenance services workers, radiation control service technicians, chemical lab technicians and Non Destructive Examination - NDE laboratory technicians are monitored once a year.
- Employees which usually are not involved in activities in contaminated areas are monitored every three years. New employees are monitored at the very beginning of activity in the radiological zone.

In case of a job with significant risk of internal contamination, every worker involved is monitored at the Whole Body Counter prior the beginning of work and immediately after the end of that special activity. WBC monitoring is also required after a personal contamination event (skin or clothes).

Calculation method of committed dose E_{50} due to intake of beta – gamma emitting particulates is based on ICRP recommendations.

2.2 Instrumentation

Internal contamination with gamma emitting nuclides at Cernavoda NPP is measured by using the Whole Body Counters - WBC Fastscan, and Accuscan II Canberra USA.

FASTSCAN whole body counter is designed to quickly and accurately monitor people for internal contamination of radionuclides with energies between 300 keV to 2000 keV. The system includes two large sodium iodine detectors [NaI(Tl)] that typically provide a prior Lower Limit of Detection of approximately 150 Bq for ^{60}Co with a count time of one minute for a person with normal ^{40}K internal activity. This dual detector system provides uniform or flat (±15%) response along the longitudinal axis from the thyroid of the tallest 99th percentile male to the lower gastrointestinal tract of the shortest female. For a counting time of 3-5 minute range, the detection limits are about 50 Bq for ^{137}Cs and about 60 Bq for ^{60}Co.

The ACCUSCAN-II is a high resolution, stand-up WBC. It is designed to identify and quantify radionuclides with energies between 100 keV and 2000 keV in complicated combinations. The ACCUSCAN-II also provides information on the location of the radioactive materials found in the body through its scanning mechanism and the system's ABACOS software. Count time is the 3-5 minute range. The detection limit for uncontaminated person (count time 30 minute) is about 81 Bq for Cs-137 and about 76 Bq for Co-60.

2.3 Estimates of Intake and Assessment of Dose

Investigative whole body counts provide a timely and direct measure of the deposition of gamma emitting radionuclides in the body. An estimate of the intake of gamma emitting radioactivity is determined from these whole body count measurements and applicable intake retention fractions.

$$I = \frac{A(t)}{IRF(t)}$$

where:

I – estimate of intake in Bq

A(t) - the bioassay measurement obtained at time t in Bq

IRF(t) - intake retention fraction corresponding to the nuclide, solubility class, mode of intake, time after intake, and type of bioassay measurement

The committed effective dose (CED) from gamma emitters can be calculated using the estimates of the intake (I) and the Dose coefficients in the ICRP:

$$CED = e_{50} \times I \ (mSv)$$

where e_{50} is the dose coefficient, i.e. the committed effective dose per unit acute intake calculated for 50 years, for adults in Sv/Bq.

2.4 Work control

Routine monitoring of workplaces is intended to demonstrate that the working conditions allow continuing the activities and there have not been changes that compel modification of the working procedures or protective measures.

Routine program includes monitoring of:

- beta, gamma and neutrons dose rates;
- tritium in air concentration;

- aerosols (alpha, beta, gamma);
- iodine in air concentration;
- surface contamination level.

An electronic database HAZARDINFO is available for plant staff, RP technicians and workers, containing information about all significant radiological hazards in accessible areas.
For particular jobs with known contamination risk preventive actions intended to prevent the spread of contamination on the surrounding areas and internal contamination of workers are mentioned in Radiation Work Permit: set-up of rubber areas / rubber change areas, installing ventilated tents with HEPA filers, using adequate individual respiratory protection equipment, continuous monitoring of air borne radioactivity.

Various respiratory protection equipment are available for workers performing radioactive contamination risk jobs depending on working area particular conditions, as required by Radiation Work Permit.

Internal contamination of workers may occur due to intakes of radionuclides as a result of several activities, mainly during undressing or due to unexpected airborne contamination or unintended contact with contaminated equipment. The most common route of entry of a radioactive contamination into the body of a worker is by inhalation of airborne radioactivity.

After few years of increasing number of internal contaminations, most of them with doses below the recording level of 0.1 mSv/month, a root cause analysis performed in 2010 identified two main causes for these contaminations: spreading of radioactive particles from contaminated protective equipment (tyvek hoods) during undressing, followed by inhalation, and temporary removal of individual respiratory protection equipment (air supplied / particulate filter half mask) in order to communicate with co-workers, followed by putting the mask back on the mouth and nose.

Procedures for undressing tyvek hoods used during activities with high risk of contamination were improved with the requirement provide assistance to workers during undressing protective clothes.

Wireless ear-phones were purchased in order to allow communication without removing the mask.

A strict control of contamination events allow to promptly identify gamma radionuclide intakes and initiating bioassay procedures for internal dose calculation. Since the moment of intake is very important for an accurate calculation of internal doses, when the risk of contamination is identified prior performing the job, workers must be monitored at whole body counter before and immediately after the work. WBC requirement is documented in the Radiation Work Permit, and the workers are informed during pre-job briefing.

3.0 RESULTS AND DISCUSSIONS

Despite a careful planning for radioactive source control, the spread of radioactive contamination in working environment could lead, infrequently, to radioactive material intake by workers.

Most of them involved activities of the radionuclide close to the MDA of the WBC and probably are external contamination or particles retained in the superior air ways, taking into consideration that the activity is not identified on measurements performed after taking a shower or blowing the nose, in the same day or in the next morning.

Two confirmed internal contamination events are presented in this paper, one by inhalation of ^{95}Zr - ^{95}Nb and the other one by percutaneous transfer of ^{137}Cs. IMBA Professional Plus is used in present to calculate internal doses due to gamma emitting nuclides intakes. Dose calculation results are presented for both events.

3.1 Inhalation of ^{95}Zr -^{95}Nb

During Unit 2 planned outage, on May 21st 2015 a welder had to replace a defective segment of a tubing line on a Primary Heat Transport system auxiliary. Prior the welding activity the pipe needed to be dried by blowing with argon and an argon shield had to be maintained in the pipe during the welding. Since the activity was performed in a narrow space and tritium concentration was low, the welder didn't wear plastic suit. The operating experience for similar jobs did not reveal the hazard of airborne contamination spreading during this step of the job, the worker did not wear other respiratory protection. While exiting reactor building he was found contaminated and internal contamination was confirmed at the full body counter.

Whole body counting was performed by using NaI(Tl) detectors FASTSCAN system designed to quickly monitor people for internal contamination of radionuclides with energies between 300 keV to 2000 keV. ^{95}Zr and ^{95}Nb are a parent-daughter pair in a transient equilibrium. The two radioisotopes have gamma radiation with energy 724 and 758 keV for ^{95}Zr respectively 765 keV for ^{95}Nb which are not resolved by NaI(Tl) detectors. A contamination of 18 kBq ^{95}Nb was initially measured. After removing external contamination by repeated showers the remaining activity of 7300Bq was measured, the first day after intake, an 1921 Bq in the second day which was taken into consideration to start calculating the internal dose.

Contamination samples from surfaces of equipment in working area were measured by gamma ray spectrometry. ^{95}Zr and ^{95}Nb were identified as main contributors, but other radionuclides such as ^{51}Cr, ^{54}Mn, ^{59}Fe, ^{60}Co, ^{113}Sn, ^{124}Sb having activities lower with several order of magnitude were identified as shown in the Table 1, below.

Table 1 Radionuclides in contamination sample from PHT system tubing replacement in Unit #2 planned outage in 2015 May 21st

Radionuclide	Activity (Bq)	Relative uncertainty	Ratio to ^{95}Nb activity
^{51}Cr	1.98E+01	25.45%	3.57E-02
^{54}Mn	1.25E+01	5.76%	2.24E-02
^{59}Fe	2.23E+01	6.07%	4.02E-02
^{60}Co	2.09E+01	4.12%	3.76E-02
^{95}Nb	5.56E+02	3.18%	1.00E+00
^{95}Zr	2.86E+02	2.48%	5.15E-01
^{113}Sn	5.41E+00	20.95%	9.74E-03
^{124}Sb	1.92E+00	25.33%	3.45E-03

In January 12th 2016 he was found with 180 Bq Nb^{95} on **FASTSCAN** whole body counter, and no contamination was found on January 25th.

An effective committed dose of 0.04 mSv was calculated by: IMBA Professional Plus, Issued in Dec 13, Version number 4.1.47, based on following parameters:
Initial intake: 14402 Bq of indicator nuclide Nb^{95} and 34% Zr^{95} associated nuclide;
Intake regime: acute inhalation
Absorption to blood: Type S (Slow)
Aerosol/deposition parameters were: ICRP Defaults
AMAD = 5 µm
GSD = 2.4977233
Density = 3g/cc
Shape Factor = 1.5
Worker Type = light
Total effective dose from indicator nuclide: 0.0207 mSv
Total effective dose from associated nuclide: 0.0189 mSv

3.2 Percutaneous transfer of Cs^{137}

On January 23rd 2015, a fuel handling operator had been contaminated on the skin during preventive maintenance of spent fuel handling tools in Unit #1. Gamma spectrometry performed on liquid waste resulted from handling tools decontamination identified other radionuclides besides ^{137}Cs (as shown in Table 2 below, but the whole body counting performed after the contamination event identified ^{137}Cs only.

Table 2 Radionuclides in fuel handling tools decontamination liquid waste sample, Unit #1 in 2015 January 26st

Radionuclide	Activity (Bq)	Relative uncertainty	Ratio to ^{95}Nb activity
^{54}Mn	1.45E+03	6.18E-02	2.70E-02
^{59}Fe	1.22E+02	3.26E-01	2.27E-03
^{60}Co	2.58E+03	3.86E-02	4.80E-02
^{95}Nb	5.38E+04	3.12E-02	1.00E+00
^{95}Zr	2.43E+04	3.68E-02	4.52E-01
^{137}Cs	8.37E+01	1.16E+00	1.56E-03
^{144}Ce	8.44E+02	6.09E-01	1.57E-02

Since no radioactive aerosols were identified in working area during and after the job by continuous air monitor - CAM, and also, no contamination was found on operator face, around the nose and/or mouth, the only hypothesis remained that the intake of Cs was only possible by absorption through the intact skin. Percutaneous absorption of cesium has been demonstrated in 1 and 2 hr in vivo exposures of rats. In 2 hr experiments the blood concentration of cesium reached its maximum 38–45 min after its application. [Richard H. Guy et al., 1999]

IMBA do not calculate internal doses based on absorption through skin and bioassay data after intake fits inhalation / ingestion and / or injection model. Cesium is readily and almost quantitatively absorbed in the GI tract and widely distributed throughout the human body, mainly in the soft tissues. Excretion appears to be bimodal: an average 10% of a single oral dose is excreted within 1–2 days, but the major part has a half-life of 50–150 days. ^{137}Cs was measured to have a physical half-life of 30 years and a biological half-life (the retention half-time corrected for radioactive decay) of 102 days. The distribution of radiocesium throughout the body and the β and γ radiation from its decay result in essentially whole-body irradiation. [ICRP Publication 78]

On September 16th 2015 the fuel handling operator was found with a ^{137}Cs body burden of 265 Bq on **FASTSCAN** whole body counter, and no internal contamination higher than the detection level of 50 Bq was found on October 7th.

An effective committed dose of 0.089 mSv was calculated with IMBA Professional Plus, Version number 4.1.47, based on following parameters:
Initial intake: 12893 Bq of indicator nuclide ^{137}Cs and no associated nuclide;
Intake regime: acute inhalation
Absorption to blood: Type M (Medium)
Aerosol/deposition parameters were: ICRP Defaults
AMAD = 5 µm
GSD = 2.4977233
Density = 3g/cc
Shape Factor = 1.5
Worker Type = light

The figure below presents the measured and calculated by IMBA whole body activity of ^{137}Cs.

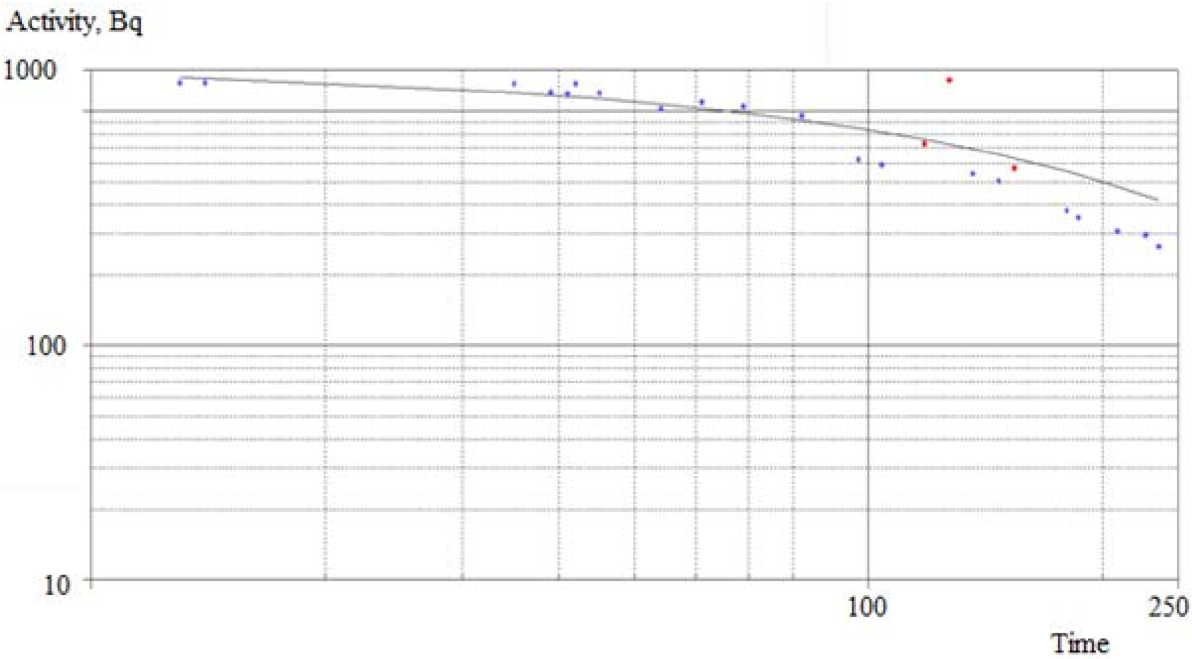

Figure 1. ^{137}Cs measured whole body activity and calculated by IMBA

4.0 CONCLUSIONS

Internal contamination hazard must be carefully controlled during maintenance activities which could spread radioactive contamination in working area. Individual monitoring for intakes of radionuclides for professional exposed workers is critical to provide valuable information to be used with biokinetic models in order obtain an assessment of the committed effective dose. This is necessary to demonstrate compliance with managerial and regulatory requirements and to contribute to the contamination hazard control during maintenance and operation of the plant ant to contribute to design improvement.

At Cernavoda NPP the operational radiation protection programs correlates assessment of workplace conditions, contamination control measures and individual internal exposures monitoring in a way that allows us to meet these objectives and, first of all to prevent as much as possible internal contaminations with beta / gamma and alpha radionuclides. Since 1996, when operation of Unit 1 started till 2013 most of internal exposures excepting tritium, were below the recording level of 0.1

mSv and, only very few internal contaminations led to doses above this value. Since 2014 till now no internal contamination led to recordable doses.

References

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