Analysis and Measurement of Loss of Radioactive Contents of a Type-B(U) Package Design for Transport of Cobalt 60

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INTRODUCTION

The International Atomic Energy Agency's Regulations for the Safe Transport of Radioactive Material (IAEA 1990a) rule the international transport of such material and provide the basis for domestic transport regulations in Argentina. The document establishes the technical, operational, and administrative requirements which shall be accomplished to carry out the transport of radioactive material (RAM). In order to achieve an appropriate level of safety during transport, the Regulations, *inter alia*, specify shielding and containment performance requirements for each type of package.

This paper considers compliance assurance with the maximum level of loss of radioactive contents (LRC) established by the Regulations for a Type B(U) package design used for the transport of 12.95 PBq of ^{60}Co, as a special form radioactive material. In particular, paragraph 548 of the Regulations establishes the following acceptance criteria when the package is subjected to the tests to withstand:

normal conditions of transport, the LRC is restricted to $\leq 10^{-6}$ A_2/hour, and (1)
accident conditions of transport, the LRC is restricted to $\leq$ A_2/week for ^{60}Co. (2)

According to the Regulations, the structural and thermal performance of the special form RAM is high enough to ensure containment under both normal and accident conditions in transport. However, due to the very high specific activities of ^{60}Co involved (about a maximum of 8 TBq.g^{-1} from a CANDU Type Reactor in Argentina), if a few milligrams of ^{60}Co in the form of aerosolized material were released from the containment system into the environment, this would imply an important LRC with its associated risk. Taking into account the above concepts, the authors of this paper have assumed that the evaluations of package design compliance for leakage testing are primarily based on assuming both the failure of a special form RAM during the transport of packages and the possibility of noncompliance, during their manufacture, with the acceptance criteria specified in the leaching and volumetric leakage assessment methods. For such purpose, different scenarios were considered so as to verify package containment compliance with the Regulations' requirements.

On the one hand, an explanation is given of how the decision was made for the selection of methods used, applying ANSI N14.5 (ANSI 1987), AECP 1068 (AECP 1992), and ISO/DIS 12807 (ISO 1995) to evaluate leakage rate under normal conditions of transport. Thereafter, the tests developed and the results obtained thereof are briefly described. Also, a description is provided on how LRCs in accident conditions of transport were evaluated. An assessment by means of calculation was performed by the applicant, while its verification was carried out by the Argentine Competent Authority. Additionally, the calculation process and the figures obtained are briefly illustrated.

Finally, it is concluded that in both normal and accident conditions of transport, compliance assurance related to the containment performance of the Type B(U) package design [Competent Authority Identification Mark RA/0072/B(U)-85] is verified with a high level of reliability.

DESCRIPTION OF THE PACKAGE AND OF ITS RADIOACTIVE CONTENTS

Type B(U) package, named GURI 01, includes the packaging and its authorized radioactive contents. Its external dimensions are 1.5 m in diameter and 1.7 m high. Its mass is 9,400 kg. In turn, the packaging includes three demountable parts: a main assembly, a fireshield, and a base (López Vietri and Novo 1995).

The authorized radioactive contents consist of 12.95 PBq of ^{60}Co generating 5.4 kW of heat energy and comprise up to 86 sealed capsules or nondispersible solids of ^{60}Co, whose overall individual dimensions are about 8 mm in diameter and between 285 and 450 mm in length. The maximum activity per source is between 370 and 518 TBq.

ANALYSIS OF LOSS OF RADIOACTIVE CONTENTS DURING DESIGN

In the analysis of the LRC in the GURI 01 package model during design, consideration was given, among others, to a publication related to closures and seals compiled by the Sandia National Laboratory (Warrant and Ottinger 1989), and to ISO/DIS Standard 12807 (ISO 1995). Below is a summary of the analysis performed.

(a) The properties and the physical shape in which the radioactive contents —^{60}Co as a special form RAM— are located imply that the actual or potential radiological risk, under any condition of transport, is essentially that of external irradiation.

(b) The capacity and the conditions of the containment system for ^{60}Co, whose $A_2 = 0.4$ TBq, are such that, during transport, the LRC shall not exceed:

$$A_N = 1.11 \,.\, 10^{-10}\ \text{TBq.s}^{-1} \text{ in normal conditions, and} \qquad (3)$$
$$A_A = 6.61 \,.\, 10^{-7}\ \text{TBq.s}^{-1} \text{ in accident conditions,} \qquad (4)$$

that manometric working pressures shall not exceed 700 kPa and that the design is made for environmental temperatures between -40°C and +38°C. In order to be realistic, it was assumed that the leakage contains one of the cobalt oxides, Co O, since, during normal transport, the rods are at a temperature of 400°C and, consequently, cobalt oxides shall aerosolize rather than pure cobalt. On the basis of IAEA's Safety Series 37 (IAEA 1990b), it was conservatively assumed that the specific activity of cobalt is $4.18 \,.\, 10^4$

TBq.kg^{-1} (density 8.9 . 10^{3} kg.m^{-3}). Taking into account that the density of Co O is 6.45 . 10^{3} kg.m^{-3} and that the ratio between the molecular weights of Co and Co O is 0.786, the specific activity of Co O is:

$$a_{Co\,O} = 3.3 \;.\; 10^{4}\ \mathrm{TBq.kg^{-1}} \qquad (5)$$

(c) The containment surfaces are affected by their own finish (rugosity, undulation, direction of the dominant pattern, spotted irregularities). The type of closure shall provide a uniform strength for the containment to maintain the LRC authorized by the IAEA in any condition of transport. A bolted closure was selected for the containment, with a carefully machined finish of the contact surfaces of the main body and cover.

(d) The closing seals must be plastically deformable in their surface and with an elastic inner part; under compression, material fatigue must vary very slightly with time and must not be affected by thermal changes; they must not be porous nor shall they be easily torn or broken under compression; and their physical properties shall not be degraded by their contact with the closure material, nor shall this cause corrosion in their surfaces. The seal shape and size and its compression strength are the factors establishing the width of the seal-closure contact area and the most stressed area. After a thorough analysis of this matter, a 5 cm wide and 0.5 cm thick viton seal was selected.

(e) The way in which the leakage occurs through the closure and the seal is also important: permeability, in case of radioactive gases, or passage through either sonic or nonsonic ducts (laminar, turbulent or molecular flow, sealing or a combination among them). LRCs are caused by vibrations, accelerations, or vibrational resonance during routine transport or by drops and fires in the case of incidents or accidents. Aerosol leakage is overestimated if considered as a leakage of gas or liquid, because the actual release occurs through multiple small openings rather than through one single equivalent opening; particles may settle, agglomerate, or adhere to the contents or to the inner walls of the containment, thus not finding the leak-free path. Besides, particles in the leak-free path are retained by the latter's geometry, rugosity, settlement by gravity, changes in the flow direction, or Brownian diffusion. Conservatively, it was assumed that the LRC occurs in the form of a gas, since this assumption involves an overestimation of the actual leakage (aerosol).

EVALUATION OF THE GURI 01 DESIGN

At present and in the near future, the development of Type B(U) packages in Argentina is oriented specifically to the transport of ^{60}Co for medical and industrial purposes. Almost 100% of the ^{60}Co contents in such packages is considered to comply with the IAEA's Regulation for special form RAM, since the material is a containment system in itself and, therefore, radiological risk during transport in any condition is due to external irradiation. This is why a nonfixed contamination of both the outer surfaces of the special form RAM and the inner surfaces of the containment vessel was considered.

Following the IAEA's Regulation, the special form RAM must comply with the following acceptation criterion: "... the activity in the water from the leaching tests specified in paras 612 and 613 would not exceed 2 kBq" (equivalent to a leakage of 10^{-5} Pa.m^{3}.s^{-1}), while the IAEA's Safety Series 37 defines nonleachable material as that in which 0.01% of the total activity may be dragged in 0.1 L of still water at 20°C in 48 hours. When the package contains ^{60}Co, the maximum specific activity may be 8 $\mathrm{TBq.g^{-1}}$, which might imply a loss of activity into the environment exceeding the limits established in the Regulations [see equations (3) and (4)].

On the other hand, working pressure in the GURI 01 model in normal conditions does not exceed 300 kPa. Such overpressure is caused by the vaporization of the water remaining in the containment after a wet loading operation, since the gas temperature in the inner containment is 290°C, which brings along the generation of a significant dragging force from the containment to the environment. In order to disregard the remaining water, the GURI 01 model's Operation Manual (INVAP SE 1994) requires a careful drying of the containment by means of argon gas flow and counterflow.

A tentative aerosolization of the nonfixed contamination of the containment's inner surface does not show significant values of radioactive material leakage, since the surface is washed and dried with argon gas, thus eliminating most of the contamination. Besides, if consideration is given to the fact that the containment closure is a maze and has a viton seal between the adjacent closure faces, the probability for all the formed aerosol to reach the leak free path is scarce. Considering the above, it may be inferred that a fraction of the radioactive contents would leak into the environment in the form of an aerosol.

MEASURING LEAKAGE IN NORMAL CONDITIONS

For the calculation of the leakage in normal conditions, a conservative estimation shows:

(i) Activity leakage (86 rods) = $2\ \mathrm{kBq}\ .\ 0.1\ \mathrm{L}\ .\ (0.01\%)^{-1}\ .\ 2\ \mathrm{L}^{-1}\ .\ 86$ rods

$$Ab = 86\ \mathrm{MBq} \tag{6}$$

(ii) Since $Sc = 15{,}000\ \mathrm{cm}^2$ in the inner surface (the drainage and venting duct surfaces are disregarded) and assuming that the nonfixed contamination of the containment's inner surface is 10 times the limit for the contamination of the packages' outer surface required by the IAEA's Regulations, 4 $\mathrm{Bq.cm^{-2}}$, the leakage of activity shall be:

$$Ac = 0.6\ \mathrm{MBq} \tag{7}$$

(iii) The leakage of activity caused by permeability is not considered because the gas dragging the Co O particles is not radioactive.

Therefore, the total estimated leakage of activity in normal conditions, A_{TN}, is:

$$A_{TN} = Ab + Ac = 87\ \mathrm{MBq} \tag{8}$$

Since the containment volume is $Vc = 0.045\ \mathrm{m}^3$, the average activity in the containment is:

$$C = A_{TN} / Vc = 1.9\ .\ 10^{-3}\ \mathrm{TBq.m^{-3}} \tag{9}$$

Consequently, the maximum volumetric leakage rate, L_N, is:

$$L_N = A_N / C = 6.0\ .\ 10^{-8}\ \mathrm{m^3.s^{-1}} \tag{10}$$

Since the maximum pressure in normal conditions is $P_N = 300$ kPa, the leakage rate, Q_N, is:

$$Q_N = L_N \, . \, P_N = 1.8 \, . \, 10^{-2} \, Pa.m^3.s^{-1} \qquad (11)$$

Following ISO/DIS Standard 12807 (ISO 1995), Knudsen's equation —modified for transient (viscous and molecular) gas flows— is used, while the leak-free path is modeled considering that the leakage occurs through a single circular cross-section capillary tube, thus overestimating the leakage. In order to calculate the most restrictive diameter of the capillary tube, D_N, the Q_N value is used, considering that the flow is estimated for a range between 10^{-8} $Pa.m^3.s^{-1}$ and 1 $Pa.m^3.s^{-1}$ in Knudsen's equation.

$$Q_N = 0.0123 \frac{D_N^4}{\mu.a}\left(P_u^2 - P_d^2\right) + 1.204 \frac{D_N^3}{a}\sqrt{\frac{T}{M}}\left(P_u - P_d\right) \qquad Pa.m^3.s^{-1} \qquad (12)$$

Where:

Q_N = leakage rate in normal conditions, in $Pa.m^3.s^{-1}$.
Pu = pressure within the containment = $3.039 \, . \, 10^5$ Pa.
Pd = pressure outside the containment = $1.013 \, . \, 10^5$ Pa.
μ = flow's dynamic viscosity = $2.92 \, . \, 10^{-5}$ Pa.s, for air at 290°C (573 K).
μ = fluid's dynamic viscosity = $1.85 \, . \, 10^{-5}$ Pa.s, for air at 25°C (298 K).
a = length of the leak free path = 0.05 m.
T = air temperature = 290°C = 573 K.
M = air molecular weight = 0.029 $kg.mol^{-1}$.

By applying equation (12), we obtain $D_N = 7.1 \, . \, 10^{-5}$ m. As from this D_N value and using equation (12), the standard leakage rate, $Q_{N(SLR)}$, may be calculated; that is, the leakage rate for dry air at 25°C (298 K), with Pu = $1.013 \, . \, 10^5$ Pa y Pd = 0.0 Pa, which results to be:

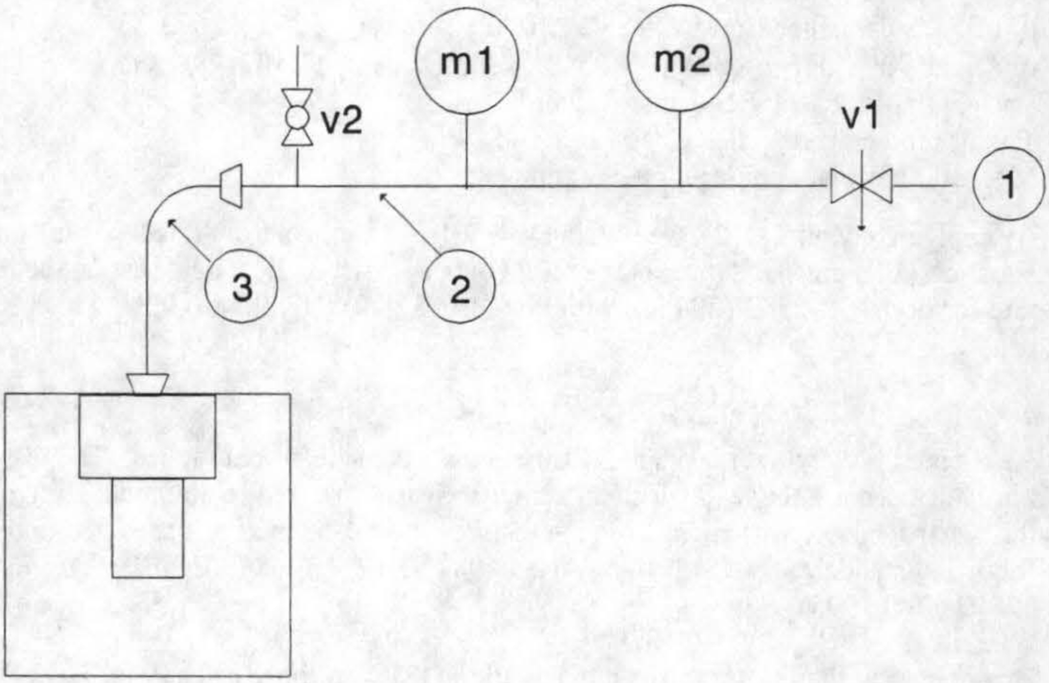
$$Q_{N(SLR)} = 3.56 \, . \, 10^{-3} \, Pa.m^3.s^{-1} \qquad (13)$$

As a general rule, direct leakage measurement is considered impractical. The test methods normally used are those in which an activity release is related to a nonradioactive leak. In this regard, advice was taken from the testing criteria and methods specified in the following standards: ANSI N14.5 (ANSI 1987), AECP 1068 (AECP 1992), and ISO/DIS 12807 (ISO 1995).

By comparing the $Q_{(SLR)}$ obtained in equation (13) with those in Table A_1 —Leakage test sensitivities— in Standard ISO/DIS 12807, it may be seen that, as far as the GURI 01 package design is concerned, both quantitative and qualitative leakage testing methods may be used. In this case, taking into account the item to be tested, "a single non-pressurized container with a plane viton o-ring sealing" and the sensitivity of each leakage test procedure specified in the mentioned standards, a quantitative test "gas pressure drop," whose nominal test sensitivity (NTS) is between 10^{-2} $Pa.m^3.s^{-1}$ and 10^{-6} $Pa.m^3.s^{-1}$, and a qualitative "soap bubble" test, whose NTS is 10^{-4} $Pa.m^3.s^{-1}$, were selected by the applicant in agreement with the Argentine Competent Authority. Both methods were applied during the tests performed before the first shipment.

The leakage test method is based on a pressurization and measuring device that is coupled to the tested package through the venting hole (see Figure 1). The operation involves filling 2 liters of demineralized water into the package, injecting dry and clean air at 686.5 kPa through piping t_1, closing globe valve v_1, applying a soapy solution to the cover closures, drain plug, and device couplings, and keeping v_1 closed for 15 minutes. After such period, one must verify that the pressure drop at manometers m_1 and m_2 does not exceed 5.88 kPa and that no leakages appear through the soapy solution. Should both criteria be fulfilled, the package must be kept under pressurization for 2 more hours, after which the absence of leakages through the soapy solution must be verified again, while the pressure drop should not exceed 19.62 kPa and the water volume must not have decreased more than 15 mL. When these three latter requirements are fulfilled, the package is accepted as leak-free and ready for use. If the opposite occurs, the package must be repaired and tested again. When the testing is finished, the pressurization device's venting valve v_2 is opened in order to relieve the containment. Both manufactured specimens passed this test and, consequently, the Argentine Competent Authority verified their compliance with their leakage requirements for normal conditions, equation (3).

Figure 1. Outline of the Pressurization and Measuring Device



GURI 01: specimen of Type B(U) package submitted to testing.
m_1 and m_2: manometers used for measuring pressure drops.
v_1: globe valve for blockage.
v_2: spherical valve for depressurization.
(1): air supply.
(2): galvanized steel piping and couplings - diameter = 1.27 cm.
(3): copper tube - diameter = 0.95 cm.

LEAKAGE MEASUREMENT IN ACCIDENT CONDITIONS

Leakage evaluation and measurement for accident conditions was performed analytically and considering some tentative scenarios in which a fraction of the radioactive contents, in the form of Co O, may leak from the containment into the environment. These hypothetical scenarios were selected taking into account that, although this is not frequent, there are possibilities for the transport of sealed sources or nondispersible solids suffering leaks due to defects or failures in their manufacture or handling. This leads to taking into account both the leaks considered in equations (6), (7), and (8) and those due to the release of special form RAM through weldings or fissures in the capsule material. In the latter cases, consideration must also be given to the potential risk of external irradiation and internal contamination during transport.

During the thermal analysis required by the IAEA's Regulation, the designer calculates that the maximum temperature of gas in the containment is 373°C (646 K), while internal pressure could reach 700 kPa.

The occurrence of the following accident scenarios is considered as probable: (1) leakage of 10 mg of Co O within the containment due to failures in the ^{60}60 Co rods, which — taking into account equations (5) and (8)— are estimated to be $A_{TA1} = 0.33$ TBq; (2) a 30 mg leakage, that is $A_{TA2} = 1$ TBq; and (3) a 3 g leakage, that is $A_{TA3} = 100$ TBq (equivalent to 1% of the authorized radioactive contents). By applying a similar calculation method as that used for normal conditions, the volumetric leakage rate, L_A, the leakage rate, Q_A, the capillary tube diameter, D_A, and the standard leakage rate, $S_{A(SLR)}$, are calculated for each hypothetical scenario and the leakage test method or methods are selected. A summary of calculated values can be seen in Table 1.

Table 1. Leakage Test Methods in Accident Conditions of Transport

A_{TA}	$C=A_{TA}/V_C$	$L_A=A_A/C$	$Q_A=L_A.P_A$	D_A	$Q_{A(SLR)}$	**Test**
TBq	$TBq.m^3$	$m^3.s^{-1}$	$Pa.m^3.s^{-1}$	m	$Pa.m^3.s^{-1}$	**method**
0.33	7.33	$9 \, . \, 10^{-8}$	$6.3 \, . \, 10^{-2}$	$6.40 \, . \, 10^{-5}$	$2.34 \, . \, 10^{-3}$	**(1)**
1.00	22.22	$3 \, . \, 10^{-8}$	$2.1 \, . \, 10^{-2}$	$4.90 \, . \, 10^{-5}$	$8.13 \, . \, 10^{-4}$	**(1)**
100.00	2222.22	$3 \, . \, 10^{-10}$	$2.1 \, . \, 10^{-4}$	$1.54 \, . \, 10^{-5}$	$8.55 \, . \, 10^{-6}$	**(2)**

(1) Take into account nominal test sensitivity of Table A1, ISO/DIS 12807; it is applicable to any quantitative test method (gas pressure drop or pressure rise, gas filled or evacuated envelope) or qualitative test method (gas bubble techniques, soap bubble, tracer gas).

(2) Take into account nominal test sensitivity of Table A1, ISO/DIS 12807; it is applicable to any quantitative test method but only the tracer gas qualitative test method.

On the basis of the results obtained, the Argentine Competent Authority verified the performance of the GURI 01 package in accident conditions; an indication of its compliance with the loss limit established in the IAEA's Regulations is seen in equation (4).

CONCLUSIONS

The analysis and the measurement of the loss of radioactive contents from the Type B(U) package, named GURI 01, allow for the following relevant conclusions:

- Due to the design of the package's closure and sealing and to the special form RAM of the radioactive contents, a radioactive material leakage above the limits established by the IAEA's Transport Regulations is highly unlikely, in both normal and accident conditions of transport.

- In the case of the posed hypothetical loss scenarios, based on the leakage of special form radioactive material within the containment due to material failures or defects, demonstrating the capacity of the containment for bearing accident conditions through the application of quantitative leakage test methods is considered as sufficient, since the latter are sensitive enough to detect the assumed leakage values.

- Considering the broad international acceptance reflected by the unanimous affirmative votes of the ISO member countries when they approved the draft of the ISO/DIS 12807 standard (ISO 1995), as well as the favorable results reached during the evaluation performed by the Argentine Competent Authority, that Standard shall be enforced in Argentina in the near future for regulating the analysis and the measurement of radioactive loss from Type B(U) packages.

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