DETEC

Dose Assessment of the Ion Mobility Spectrometer Containing Ni^{63}

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Summary

The IMS (Ion Mobility Spectrometer) is used in a system to be manufactured in Canada and sold in the US at a predicted rate of 50 units a year. Each IMS unit will contain 3.3 mCi of Ni^{63}, a β emitter with an endpoint energy of 67 keV. Hence, the instrument must comply with US federal regulations, notably table 32.28 of 10CFR32.27 which provides annual dose equivalent limit for various organs for internal and external exposure to the radioactivity. In this work, established Monte Carlo techniques and published fluence to dose conversion coefficients are used to assess the dose risk in a situation of normal use of the IMS and in an accident situation where the source is outside its shielding enclosure. In all situations, under reasonable assumptions, it is demonstrated that the dose limits set by 10CFR32.27 are not exceeded.

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1.0 Introduction

The IMS (Ion Mobility Spectrometer) is used in a system to be manufactured in Canada and sold in the US at a predicted rate of 50 units a year. Each IMS unit will contain Ni^{63}, a β emitter with an endpoint energy of 67 keV. Hence, the instrument must comply with US federal regulations, notably table 32.28 of 10CFR32.27 which provides annual dose equivalent limit for various organs for internal and external exposure to the radioactivity.

The annual equivalent dose limits are listed in table 32.28 of 10CFR32.27. It lists 3 categories of radiation exposure in 3 columns. Column I is concerned by the dose to organs caused by the ingestion or inhalation of radioactive material. Column II give dose limits which are unlikely to be exceeded. We view these as representing dose limits during the normal operation of the IMS. In column III, very high dose limits are given for which there is a negligible risk of exceeding. We view these as dose limits for accident situations. Dose limits in all 3 columns are specified according to exposure to the extremities, the whole body and other organs.

Using Monte Carlo techniques and some reasonable assumption, it will be demonstrated that the IMS complies fully with the dose limits set by 10CFR32.27.

2.0 Parts of the IMS' life cycle covered by CFR-30.27

The activity in the IMS consists of 3.3 mCi source of Ni^{63} electroplated on a Ni disk, 50 μm in thickness and 0.95 cm in diameter. The disk is mounted inside a cylindrical aluminum housing which consists of two parts. The outside diameter is about 6 cm and the total length is 4 cm. The aluminum thickness is near 1 cm for the side and one end wall. It is thinner (.25 cm) at the end nearest to the source location. In this way, the Ni^{63} source is essentially enclosed in a tamper proof shielding enclosure.

Special assembly components are used during production at the manufacturing location in Canada which prevent opening the cylinder in the field. For servicing and disposal, the unit must be returned to the manufacturer outside the US. Hence, this report is an analysis of the potential radiological risk of the device while in normal use and in accident situations while the instrument is located in the US . It does not cover the radiological risk posed by the manufacture of the IMS.

2.1 The IMS from a radiological protection point of view

It is safe to assume that the current IMS design will be used in the medium term for all systems produced. It is then worth doing a detailed analysis of the ionizing radiation which "leaks" from the aluminum enclosure either in the form of energetic electrons and photons.

The model assumed for the analysis is shown on Figure 1. It shows the relative location of the various components but it is not to scale. In particular, the Nickel disk and the steel screen would be vanishingly small in a realistic schematic.

Ni^{63} is a β emitter with endpoint and average energies of 67 keV and 17 keV respectively. The spectral shape used in this work is from [1]. Potential radiation risk is due to the source β particles and x-ray photons. These photons result from the interaction of the β particles with the surrounding materials, especially the higher Z elements such as the Ni plate and those contained in the steel mesh and they are in the form of bremstrahlung or line radiation. From the geometry shown on Figure 1, it is anticipated that the hottest location will be "A" where the Nickel plate acts as a β to X-ray converter and is located near the thinnest wall of the enclosure.

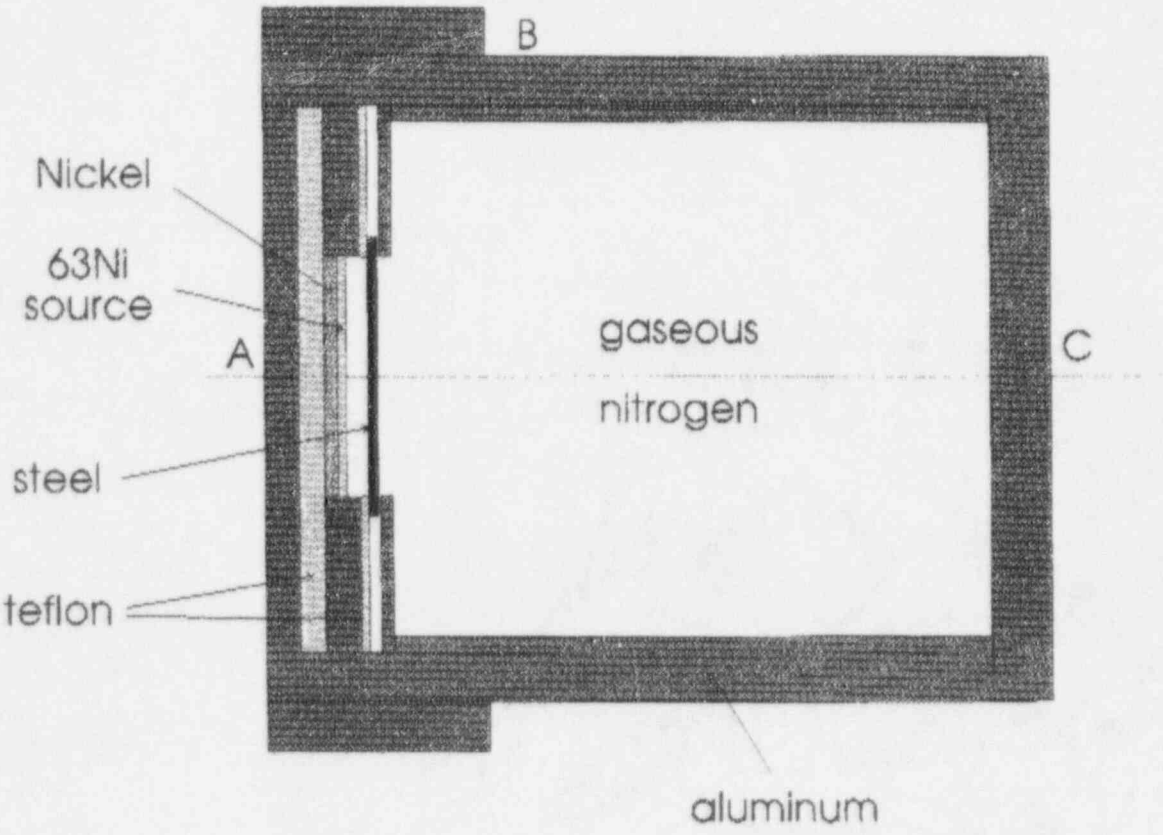

Figure 1: Schematic of the geometry of the IMS used for the purpose of external radiation calculations. Its shows the relative placement of the components but is not to scale. In particular, the thickness' of the nickel plate and the steel mesh are exaggerated.

3.0 Dose rate estimation

3.1 Beta particles

The ranges of β particles in aluminum for energies E from 0.010 MeV to 3 MeV are given by the following empirical equation [2].

$$R = 0.412E^{n} \text{ gm/cm2} \qquad (1)$$
$$n = 1.265 - 0.0954 \ln E$$

The maximum energy electron from Ni^{63} (0.067 MeV) has a range of 25 μm in aluminum. The thinnest wall of the IMS is 100 times thicker than the electron range. We conclude that β particles will not contribute to the external dose during routine use and handling of the IMS.

3.2 X-Ray Photons

In assessing the external dose during routine operation and handling of the IMS, we must keep in mind the categories put forward by the US Nuclear Regulatory Commission in its Rules and Regulations [3], from now on referred to as 10CFR32.27. Specifically, the IMS must comply with the annual extremity dose limit of 7.5 rem and whole body limit of 0.5 rem.

We have opted to assess the external dose rates by the Monte Carlo method. The code used was CYLTRANP of the ITS family of codes [4] developed at the Sandia National Laboratories. These well established coupled electron-photon transport codes are descendants of ETRAN [5], developed at the US National Bureau of Standards. In particular, the CYLTRANP code is well suited for 3-dimensional transport simulation in geometries which have cylindrical geometries. The cut-off energies for both the electron and photons are 1 keV which allows the inclusion of nearly the full β spectrum from Ni^{63}.

Dose rates may be obtained using two methods. The calculations supply the energy spectra of the x-rays which escape from the aluminum cylinder. These may be combined with suitable fluence to dose conversion coefficients [6,7] to yield the dose at any depth in tissue and for any distance away from the IMS. For contact doses, a piece of "standard" human tissue (ICRU tissue: 10.1% {weight fract.} H, 11.1% C, 2.6% N, 76.2% O) is put in contact with the aluminum enclosure and the dose is calculated directly from the energy deposition of photoelectrons in the tissue.

3.3 Potential for Skin (Extremity) Dose

3.3.1 Normal use

In general, particularly for the x-ray energies of interest here, the point of maximum dose is on the surface, as shown by the exposure to dose equivalent conversion factors [7]. The most radiosensitive cells of the skin, if not the whole body, are the germinal or basal layer [8] cells which are located at a mean depth of 70 μm according to ICRP 26 [9] . It also corresponds approximately to the depth of the peak dose for low energy x-ray photons.

At location A, B and C on the IMS (Figure 1), we apply a 1 cm layer of "skin-equivalent" ICRU tissue [10] divided in 3 layers. The first layer, in contact with the IMS, is 70 μm thick and corresponds to the insensitive layer of the skin. The second layer is 20 μm thick and corresponds to the radio-sensitive layer of interest. The rest of the ICRU tissue layer may be thought as a backscattering phantom, roughly the thickness of a finger.

At location "A", the energy deposited below 70 μm in a 6.28 mg mass of ICRU tissue is 1.49×10^{-11} MeV (13% 1 σ) per source β particle. Assuming a quality factor of 1, this is equivalent to 3.80×10^{-17} rem/β. The source has a strength of 3.3 mCi. It emits 4.4×10^{11} β/hour. Hence the skin equivalent dose rate on contact at point "A" is 1.67×10^{-5} rem/hour (13% error).

At location B, the tissue mass in the sensitive layer is put as 36 mg. A 1 cm wide strip of ICRU is applied all around the aluminum cylinder at B. This "simulates" a hand or finger wrapped around the IMS. The deposited energy is 3.6×10^{-13} MeV/β (31%). Repeating the analysis above, this corresponds to 7×10^{-8} rem/hour.

At location C, the tissue mass in the sensitive layer is 6.28 mg. The deposited energy is 1.6×10^{-13} MeV/β (66%). Clearly, in this case the calculation has insufficient statistics to supply a small error. However, it is clear that the highest dose rate is found at "A" and further calculations at C are unnecessary. Nevertheless, this result gives a dose rate of 3×10^{-8} rem/hour.

As expected, the skin dose rate is highest at "A" where the source is closest and the aluminum shielding is the thinnest. At a dose rate of 1.6×10^{-5} rem/hour, a worker cannot exceed the annual extremity dose limit of 7.5 rem even if he is in contact with the source 24 hours a day. In such a case, his total accumulated equivalent dose would be 0.14 rem. This fulfills the requirement for extremity dose of column II, Table 32.28, 10 CFR 32.27.

These low dose rates reemphasize the fact that very few X-rays emerge from inside the shield. In practice, the IMS is a subsystem inside a 1/16" thick steel cabinet. This arrangement ensures that a worker will never be closer than 20 cm from the IMS. The exposure to radiation will become essentially nil.

3.3.2 Accident Situation

The construction of the IMS enclosure is rugged and tamperproof. Moreover, the manufacture of the IMS is performed in Canada. The probability is low that a member of the public in the US will come in contact with the bare Ni^{63} source. If this were to happen and the source was in contact with the skin the following equivalent dose rates would occur:

- if the source is held with the active face towards the skin, a local (extremity) dose rate of 0.84 rem/hour (5%) will result. This was obtained again through Monte Carlo calculations of the dose deposited in ICRU tissue at a depth of 70 μm;
- if the source is held with the inactive side towards the skin, a dose rate of 0.0074 rem/hour (26%) will result.

An unsuspecting individual might carry the source active face towards or away from the skin with equal probability. In this case the useful dose rate is about 0.4 rem/hour. The individual would have to carry the source, against his skin for 18.75 hours in order to exceed the dose limit of 7.5 rem. The probability of this event is **low**. The extremity dose limit of column II, table 32.28 of 10CFR32.27 is fulfilled now for this unusual accident situation. The individual would also require to have the source against his skin for 500 hours of the year (62 working days) in order to exceed the extremity dose limit of column III of table 32.28 of 10CFR32.27. Such accidental exposure requires a string of events: opening of the IMS shield, removal of the source disk and pressing of the source against the skin for an extended length of time. The probability of all these events occurring is **negligible**.

3.4 Dose to the Whole Body and other Organs

3.4.1 Normal use of IMS

The resulting dose equivalent to the skin during normal use of the IMS (subsection 3.3.1) is of less than 0.14 rem/year (constant contact with the source enclosure). This guarantees that the whole body limit of 0.5 rem/year (column II, Table 32.28, 10CFR 32.27) cannot be exceeded, and this for two reasons. First, most regions of the whole body will be distant from the source, thus decreasing further the x-ray flux and the dose. Second, whole body dose is defined at 1 cm depth. The low energy x-rays of concern here yields lower equivalent doses at a 1 cm depth compared to 70 μm (Table C1, ref. [7]). We conclude that, in normal use, the IMS subsystem complies with columns II and III of table 32.28 of 10CFR32.27 for both the *whole body* and other *organs categories*.

3.4.2 Accident Situation

As in section 3.3.2, the highest dose rates may result in the unlikely event that a member of the public in the US comes in proximity to the active side of the Ni^{63} source disk. In

such a circumstance, CYLTRANP simulations provide us with the photon spectrum emitted in a 2π solid angle away from the active side of the source. It is assumed that the contribution of β particles to the whole body dose is negligible since 1 meter of air provides an absorbing layer 50 times thicker than the range of the most energetic 67 keV electrons. The photon spectrum on the active side of the source is given in Table 1.

Table 1: Calculated bremstrahlung spectrum on the active side of the Ni^{63} source

Energy interval (keV)	#photons/(keV*steradian)/β	1 σ (%)
1 - 6.7	8.24x10-6	0
6.7 - 13.5	4.1x10-6	1
13.5 - 20.2	1.49x10-6	1
20.2 - 27.0	6.18x10-7	1
27.0 - 33.8	2.47x10-7	1
33.8 - 40.5	9.15x10-8	1
40.5 - 47.3	3.02x10-8	4
47.3 - 54.0	8.39x10-9	6
54.0 - 60.8	1.88x10-9	8
60.8 - 67.5	1.1x10-10	35

This spectrum is folded with flux to dose equivalent conversion coefficients [6] and a dose rate of $9x10^{-5}$ rem/hour at 1 meter is obtained at a depth of 1 cm in ICRU tissue. A person would have to stay at 1 meter from the source for over 5000 hours in order to exceed the most stringent limit of column II, table 32.28 of 10CFR32.27. The risk of this happening is negligible. A person would have to be located at 1 meter from the source for more than a year in order to exceed the most stringent **annual** limit of column III, table 32.28, 10CFR32.27. This is simply not possible.

Hence, in case of external exposure in an accident situation, none of the limits imposed by 10CFR32.27 will be exceeded.

3.4 Dose Following Ingestion (uptake)

The activity consists of 3.3 mCi of Ni^{63} electroplated on a Nickel substrate. High temperature (1200°C) stress tests and wipe testing of Ni^{63} based smoke detectors reveal that only 0.01%, or .33 μCi of activity would be released in the event of a fire [11]. Such a release in the US would be due to an accidental fire or disposal of the instrument at an incinerator. However, the units are expected to be shipped back to the manufacturer for disposal.

The organ dose due to the uptake by a single individual of 10% of the total activity released by the source in the event of a fire is given in Table 2 (based on organ dose commitments to exposed persons, table 4.1 of ref. [11]):

Table 2: Individual dose due to the uptake of an incinerated Ni^{63} source.

Organ	Dose (rem)	10CFR 32.27 limits (column I, table 32.38)
Total body	$1.3x10^{-4}$	$5x10^{-3}$
Liver	$2.8x10^{-4}$	$1.5x10^{-2}$
Bone	$4x10^{-3}$	$1.5x10^{-2}$
Lungs	$3.9x10^{-4}$	$1.5x10^{-2}$

The events which may lead an individual to absorb 10% of the released activity are unlikely. The resulting organ doses following the uptake would still be within the limits of column I, table 32.28 of 10CFR32.27.

4. Storage and Disposal

The IMS is not targeting a wide consumer market. Expected sales are of 50 to 100 units a year, with 3.3 mCi of Ni^{63}/unit. Such an activity is more often found in undergraduate teaching laboratory. Full instruments containing the IMS will not be stockpiled in storage. The total activity in any place at one time might be a few times the unit activity of 3.3 mCi.

Manufacture and disposal of the IMS and its Ni^{63} are to proceed outside the boundaries of the US. However, we must consider the possibility that some units might enter, by neglect or intent, the US waste disposal system. Let us assume that the disposal of 10 units per annum occurs in the United States, with 90% going to landfill sites and 10% (or one unit) to incinerators [11]. Because of the small quantity, the problem is *discrete* and it may be safely assumed that a landfill site would contain only one 3.3 mCi Ni^{63} source and that only 10 such new sites would exist. Of importance is that the total activity disposed of per year is only 33 mCi. In the event of the accidental incineration of a unit in the US, it has been shown in section 3.4 that organ doses resulting from the uptake will not exceed the limits set by the US regulations. We next consider the problem of disposal at landfill sites.

It is useful to compare the problem at hand to the analysis presented in reference [11]. It presented an extensive study of the environmental assessment of the Am^{241} used in the fabrication of smoke detectors. In particular, it contained a detailed analysis of the disposal of smoke detector units and the pathways by which their radioactivity might be transported in the environment and expose the general public. However, this analysis was

"macroscopic". It considered the disposal of 30 Ci of Am^{241} activity per annum in 10 million smoke detectors disposed of each year, an activity which is close to 1000 times greater than in the case of the disposal of IMS units. In [11] it was assumed that 90% of this activity was distributed evenly through the 18500 landfill sites which were known to exist at the time. Every landfill site in the United State would then contain, on average, 545 smoke detectors and a total activity of 1.5 mCi, i.e. an activity comparable to that of one IMS unit (3.3 mCi) in every landfill site in the country. The report then demonstrated that the leaking of this activity in the aquifer or the incineration of remaining 10% of the units of it would lead to insignificant dose levels to the public compared to background. Table 3 lists the activity uptake and whole body dose to an individual due to the disposal or incineration of the smoke detectors. Doses to specific organ were also given in [11] and they are of the same order as the whole body doses. The projected dose levels comply to the most stringent criteria of table 32.28 of 10CFR32.27.

Table 3: Individual uptake of Am241 due to its disposal [11]

Mode of ingestion	Maximum individual intake (μCi)	Total body dose in 50 years (rem)
Contaminated groundwater	1.6×10^{-4}	8.7×10^{-6}
Contaminated food crops	1.0×10^{-8}	5.7×10^{-10}
Contaminated air inhalation ingestion	 1.1×10^{-12} 3.4×10^{-11}	 1.0×10^{-8} 1.8×10^{-12}
Incineration inhalation ingestion	4.7×10^{-9}	1.1×10^{-7}

In we now consider the specific effects of Ni^{63} activity compared to Am^{241} activity on the dose delivery, Ni^{63} has a 6000:1 advantage over Am^{241}, as shown on Table 4 (from data of table 4.1 [11]). Finally, the Ni^{63} half life (92 years) is shorter than that of Am^{241} (428 years) which leads to its more rapid elimination from the environment.

Table 4: Dose delivery as a function of nuclide species and activity

Nuclide	Whole body dose per pCi of intake (inhalation) [rem/pCi]
Ni^{63}	3.8×10^{-9}
Am^{241}	2.4×10^{-5}
ratio (Ni^{63}/Am^{241})	~1/6300

We thus conclude that the accidental disposal of all the IMS units in the United States does not pose a health risk to the population for two reasons. First, it is clear that the inventory of Ni^{63} activity in disposal operations of the IMS will be insignificant compared to that of Am^{241}. Second, for equal amounts of activity uptake, Ni^{63} would deliver only $1/6300^{th}$ of the whole dose of Am^{241} and an even lesser fraction when critical organs are considered (table 4.1 [11]).

5.0 Conclusion

Using simple analysis it has been demonstrated that the presence of a Ni^{63} source in the IMS complies with all aspects of 10CFR32.27. In fact, in all cases, the predicted annual doses are orders of magnitude inferior to the annual limits.

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Name: Al McEachern
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FAX: (613) 230-3805

Address: CPAD Technologies Inc.
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In my fax dated 13 Dec 96, I indicated that the "pages to follow" was 2, this was an error, I only faxed one page.

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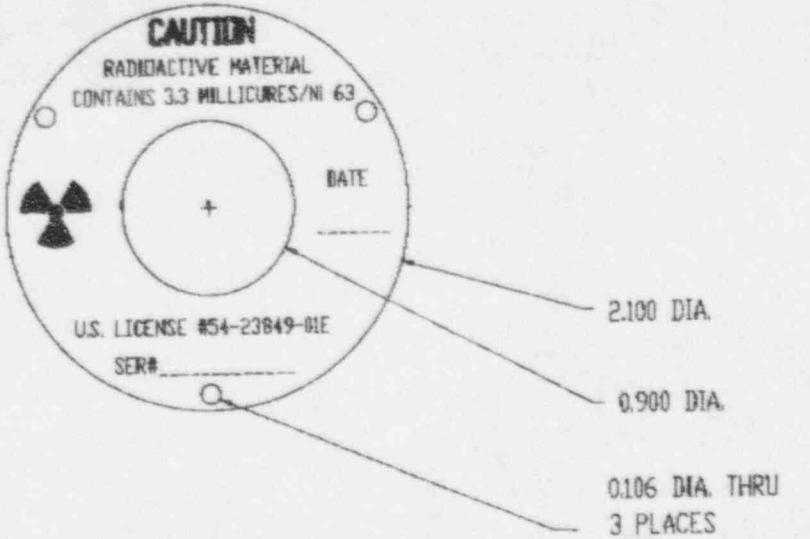

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