## Introduction:

One significant hazards associated with nuclear reactors is the potential release of the "gap inventory" of fission product rare gases from the fuel. This can happen from manufacturing defects, if fuel is overheated and the cladding melts, from mechanical damage to the fuel during fuelling operations or post-irradiation handling, and from deliberate breach of the cladding for post irradiation examination, isotope production or fuel re-processing.

Significant fission product rare gases include: Kr-85 (11y), Kr-88 (2.8h), Xe-133 (5.3 d), Xe-135 (9.2 h), Xe-138 (14 m).

Because the rare gases are non-reactive, they are readily released from the high temperature and pressure environment in the cladding, through the reactor cooling system and into the environment. They may be held up the reactor containment system or released to the environment where they will lead to exposure to workers or the public.

There are other situations that may result to rare gas exposures, such as use of rare gases in research or in isotope production. An example of the latter case can be found in MNR where large quantities of Xe-125 are handled in the I-125 production process.

Ar-41 is also produced and released routinely as an activation product from irradiation of dissolved air.

Rare gases are generally not metabolized by the body and so present an external hazard only. The level of hazard from an accidental release of rare gases can be significant. The exposure situations described below actually apply to any airborne radioactivity, but they are not usually a significant contributor to effective dose (compared to intakes) and are thus ignored.

## Photon Exposure from Rare Gases

From Evans ("The Atomic Nucleus"), the rate of energy absorption (MeV/g.s) from direct gamma rays ($R_{prim}$) and scattered gamma rays ($R_{sec}$) at the centre of a sphere of radius X is given by:

$$R_{prim} + R_{se} = \frac{n \cdot E_{\gamma}}{\mu_0}(\mu_a \cdot (1 - e^{-\mu_0 X}) + \sigma_s[1 - e^{-\mu_0 X}(1 + \mu_0 X)]$$

$\mu_a$ = mass absorption coefficient
$\sigma_s$ = Compton scattering coefficient
$\mu_o$ = total attenuation coefficient
$\mu_a = \mu_o - \sigma_s$
n = photons/s.g of energy $E_\gamma$ MeV

For large X, $\mu_o X >> 1$

$R = \{nE_\gamma/\mu_o\}\{\mu_a + \sigma_s\} = nE_\gamma$ MeV/g.s

**That is, the rate of energy absorption per gram is equal to the rate of energy emission per gram.**

In air, for 1 MeV, $\mu_o = 8.25\text{x}10^{-5}$ cm$^{-1}$

For $\mu_o X \gg 1$ $X \gg 1/\mu_o$ = 1.2x104 cm = 120 m

Thus for distances much greater than this (say, greater than about 0.5 km), the geometry can be considered an infinite sphere. However, for beta particles, radii of greater than about a few meters can be considered infinite; that is, one invariably has infinite geometry for beta particles.

Also, in the environment, there is a factor of two to consider since the geometry becomes an infinite hemisphere, not an infinite sphere. However, in an area of finite geometry, say a room where the floor doesn't limit the exposure, and $\mu_o X \ll 1$.

$$R_{prim} + R_{se} = \frac{n \cdot E_\gamma}{\mu_0}(\mu_a \cdot (1 - e^{-\mu_0 X}) + \sigma_s [1 - e^{-\mu_0 X}(1 + 0)] = \frac{n \cdot E_\gamma}{\mu_0}(\mu_a \cdot (1 - e^{-\mu_0 X}) + \sigma_s (1 - e^{-\mu_0 X}))$$

$$R_{prim} + R_{se} = \frac{n \cdot E_\gamma}{\mu_0} \mu_0 \cdot (1 - e^{-\mu_0 X}) = R_\infty (1 - e^{-\mu_0 X})$$

Thus for a rare gas, the DAC will depend upon the geometry of the room. It is common to take the volume of the room and then determine the radius of a hemisphere that would have the same volume and use this for “X” in the preceding equation. The ICRP used to give the DAC for a selection of room volumes. Dose coefficients are now provided for infinite cloud exposure (see handout) and it is left to the user to correct for geometry if appropriate or required. One correction is nearly always appropriate – at ground level a person is only exposed from the cloud above. This is the semi-infinite sphere geometry and the dose rate (neglecting reflection from the ground) is half of that from an infinite sphere.

## Example

MNR releases 41Ar which has a gamma-ray of 1.29 MeV (100%). What dose rate would be received by an individual exposed at ground level to a very very large cloud of 1 Bq/m$^3$?

## Beta Exposure from Rare Gases

The situation of beta exposure from airborne activity is well described by Cember. Again, we start from the premise that the rate of energy emission is equal to the rate of energy absorption. Then, the absorbed dose rate in air for a concentration of a radionuclide C with mean beta energy E

$$\dot{D}_{\inf}\left(\frac{mGy}{h}\right) = \frac{C\left(\frac{Bq}{m^3}\right)\cdot 1\left(\frac{s^{-1}}{Bq}\right)\cdot \overline{E}\left(MeV\right)\cdot 1.6E-13\,\frac{J}{MeV}\cdot 3600\,\frac{s}{h}}{1.293\,\frac{kg}{m^3}\cdot 1\,\frac{J}{kg\cdot Gy}\cdot\frac{1Gy}{1E3mGy}} = 4.45E-7\cdot C\cdot \overline{E}\left(\frac{mGy}{h}\right)$$

Correcting for the irradiation from one side only and the fact that tissue absorbs about 10% more energy per kilogram than does air, and correcting for attenuation of the beta particles to the depth of the basal layer (7 mg cm$^{-2}$)

$$\dot{D}_b = 0.5\times 1.1\times \dot{D}_{\inf}\times e^{-\mu_{\beta,t}\times 0.007}\,\frac{mGy}{h}$$

$$\dot{D}_b = 2.45E-7\cdot C\cdot \overline{E}\times e^{-\mu_{\beta,t}\times 0.007}\,\frac{mGy}{h}$$

Cember is using the approximation of exponential attenuation of beta rays in a medium at depths less than the range in the above equations. The attenuation coefficient in tissue, $\mu_{\beta,t}$ for a radionuclide emitting beta particles with a maximum energy of $E_{max}$ (MeV)can be approximated by:

$$\mu_{\beta,t} = 18.6(E_{\max} - 0.036)^{-1.37}\,cm^2 g^{-1}$$

## Example

Calculate the equivalent dose rate to the skin of a person immersed in a large cloud of Kr-85.

## References:

1. Harvey, Physics 776 Course Notes.
2. Cember, Introduction to Health Physics, Third Ed., 1996, McGraw Hill, New York.
3. ICRP-68, Dose Coefficients for Intakes of Radionuclides by Workers, Annals of the ICRP Vol. 24 No. 4, 1994
4. Schlein, Health Physics and Radiological Health Handbook, Scinta, 1992