Chapter 7

THE SOURCE TERM

10/1/2016

7.1 INTRODUCTION

The source term designates the radioactive releases from reactor accidents. These include both groups of short lived and long lived isotopes, each group possessing different health hazard characteristics. The effective half-life of these isotopes in the human body depends on their biological half-lives as well as their radioactive half-lives. The source term is part of the Probabilistic Risk Assessment process.

7.2 LONG HALF LIFE ISOTOPES

Once injected in the body, the long lived isotopes can remain there over a lifetime. However, their activity is low compared with the short half lived isotopes. The activity is defined as:

$$\begin{aligned} A(t) &= \left| \frac{dN(t)}{dt} \right| \\ &= \left| -\lambda N(t) \right| \\ &= \lambda N(t) \\ &= \frac{\ln 2}{T_{\frac{1}{2}}} N(t) [\frac{transformations}{\sec}], [Bq]. \end{aligned} \quad (1)$$

and is larger the smaller the half life $T_{1/2}$ of the isotope.

The long half lives and consequently low activity isotopes pose a health hazard from the perspective of their longevity and long residence time once absorbed in the human body. Some of these isotopes resulting from the fission of fissile isotopes are shown in Fig. 1.

The most prominent among them are Sr^{90} with a half life of 28.74 years (Fig 2), and Cs^{137} with a half life of 30.04 years (Fig. 3). Once absorbed in the human body, Sr^{90}'s residence time is practically a lifetime. Strontium lies in the same period as calcium in the periodic table of the elements, and hence mimics calcium and is a bone seeker. Cesium lies in the same period as sodium and potassium, and hence it gets deposited in the muscle and organ tissues, and the whole body in the general..

Table 1. Long half-life fission products isotopes.

Isotope	Half life	Activity [kCi/MWth]		Boiling point [^{0}C]	Volatility	Health Physics
		After 1	After 5			

		year irradiation	years irradiation			
Kr^{85}	10.4 a	0.12	0.62	-153	gaseous	Slight health hazard
Sr^{89}	54 d	39	39	1366	moderately volatile	Internal hazard to bone and lung
Sr^{90}	28.74 a	1.2	6.0			
Ru^{106}	1.0 a	5	10	4080	Highly volatile oxides (RuO_3, RuO_4)	Internal hazard to kidney and gastro intestinal (GI) tract
Cs^{137}	30.04 a	1.1	5.3	670	Highly volatile	Internal hazard to whole body
Ce^{144}	282 d	30	50	3470	Highly volatile	Internal hazard to bone, liver and lung
Ba^{140}	12.6 d	53	53	1640	Highly volatile	Internal hazard to bone and lung

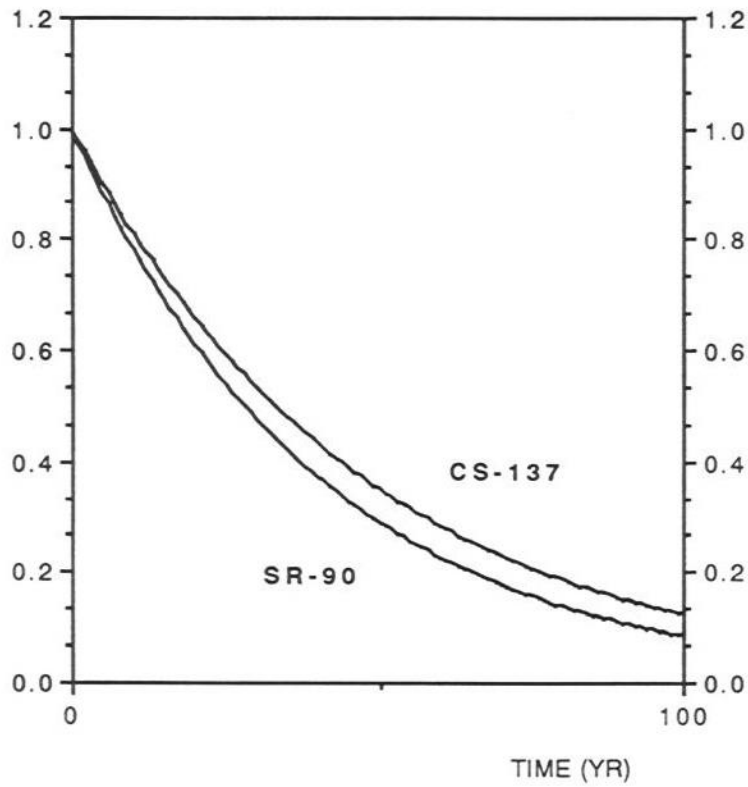

Figure 1. Decay curves of two long lived fission product isotopes, Cs^{137} and Sr^{90}.

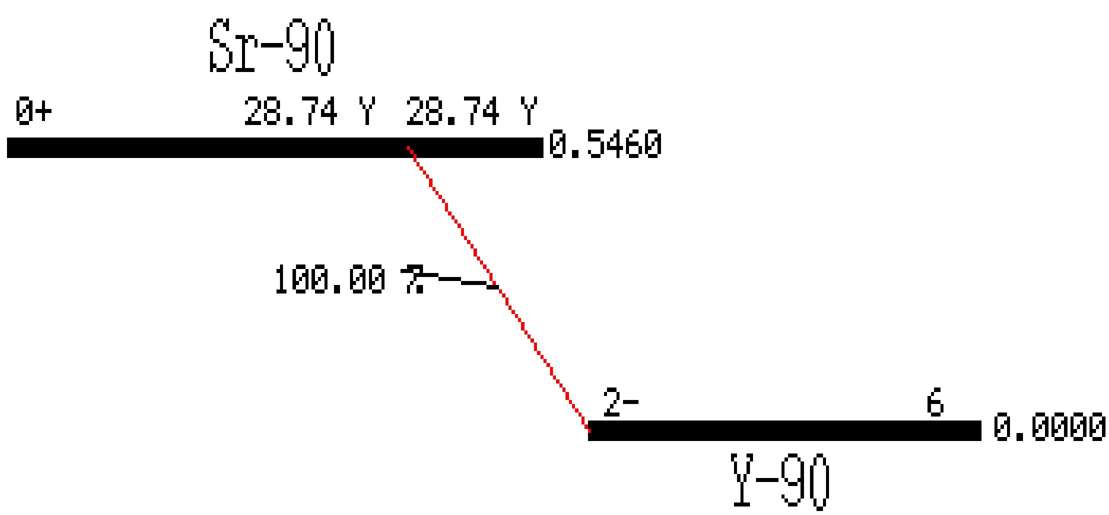

Figure 2. $Strontium^{90}$ decay graph.

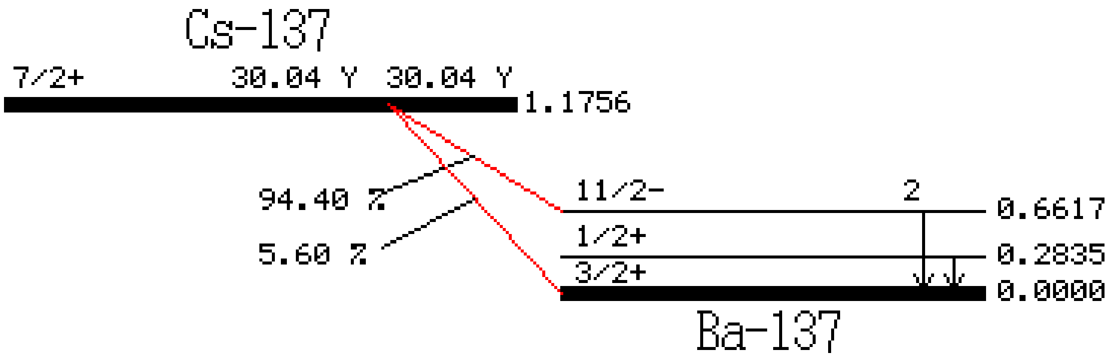

Figure 3. Cesium^{137} decay graph.

It must be noted that regarding human exposure, the biological half life of Cs^{137} is 110 days, whereas the biological half-life of bone-seeker Sr^{90} is 18 years, making it the more serious consideration. On the other hand, Sr^{90} (boiling point = 1,336 ^{o}C) is considered as moderately volatile and is released if higher temperatures are attained in a postulated accident, so that a smaller amount than the highly volatile Cs^{137} (boiling point = 670 ^{o}C) is released. In atmospheric nuclear testing both isotopes are fully released.

7.3 SHORT HALF LIFE ISOTOPES

By virtue of their short half lives, these isotopes possess a high activity, and consequently release a substantial amount of energy in a short period of time in the affected living tissue. In this case the radiation dose rate can be a modification of Eqn. 1 as:

$$\begin{aligned}\dot{D}(t) &= Q\gamma \frac{\bar{E}}{m} A(t) = Q\gamma \frac{\bar{E}}{m} \left| \frac{dN(t)}{dt} \right| \\ &= Q\gamma \frac{\bar{E}}{m} \left| -\lambda N(t) \right| \\ &= Q\gamma \frac{\bar{E}}{m} \lambda N(t) \\ &= \frac{\ln 2}{T_{1/2}} Q\gamma \frac{\bar{E}}{m} N(t) [\frac{ergs}{gm.\mathrm{sec}}],[\frac{rem}{\mathrm{sec}}],[\frac{Sievert}{\mathrm{sec}}] \qquad (2)\end{aligned}$$

$\bar{E}$ is the energy release per disintegration,

m mass of tissue affected,

γ is the fraction of energy deposited in the considered tissue,

Q is the radiation's quality factor.

The decay of Te^{132} produces I^{132}. An amount of 38 kilocuries of I^{132} is produced per megawatt thermal of reactor power. The Te^{132} released from a reactor accident will also produce I^{132} outside the reactor according to the reaction:

$$_{52}Te^{132} \rightarrow {}_{53}I^{132} + {}_{-1}e^{0} + \nu^{*} + \gamma \qquad (3)$$

The main hazard from the short lived isotopes results from I^{132} with a half life of 2.3 hours, which seeks the thyroid gland, and can cause the occurrence of thyroid nodules. For this reason, the source term can be expressed in terms of I^{132} equivalent.

Table 2. Short half life fission products isotopes.

Isotope	Half life	Activity [kCi/MWth]		Boiling point [^{0}C]	Volatility	Health Physics
		Shutdown	1 day after shutdown			
Br^{83} Br^{84} Br^{85} Br^{87}	2.3 h 32 m 3 m 56 s	3 6 8 15	0 0 0 0	59	Highly volatile	External whole body radiation, moderate health hazard
Kr^{83m} Kr^{85m} Kr^{87} Kr^{88} Kr^{89} Kr^{90}	114 m 4.4 h 78 m 2.8 h 3 m 33 s	3 8 15 23 31 38	0 0.2 0 0.1 0 0	-153	Gaseous	External radiation, slight health hazard
I^{131} I^{132} I^{133} I^{134} I^{135} I^{136}	8 d 2.3 h 21 h 52 m 6.7 h 86 s	25 38 54 63 55 53	23 0 25 0 4.4 0	185	Highly volatile	External radiation, internal radiation of thyroid gland, high radio toxicity
Xe^{131m} Xe^{1331m} Xe^{133} Xe^{135m} Xe^{135} Xe^{137} Xe^{138} Xe^{139}	12 d 2.3 d 5.3 d 15.6 m 9.2 h 3.9 m 17 m 41 s	0.3 1 54 16 25 48 53 61	0.3 0.7 47 0 4 0 0 0	-108	Gaseous	External radiation, slight health hazard
Te^{127m} Te^{127} Te^{129m} Te^{129} Te^{131m}	105 d 9.4 h 34 d 72 m 30 h	0.5 2.9 2.3 9.5 3.9	0.5 0.5 2.3 0 2.2	-	Product of uranium oxidation	External Radiation, moderate health hazard.

Te^{131} Te^{132} Te^{133m} Te^{133} Te^{134} Te^{135}	25 m 77 h 63 m 2 m 44 m 2 m	26 38 54 54 63 55	0 31 0 0 0 0			Health hazard from I^{132} daughter.

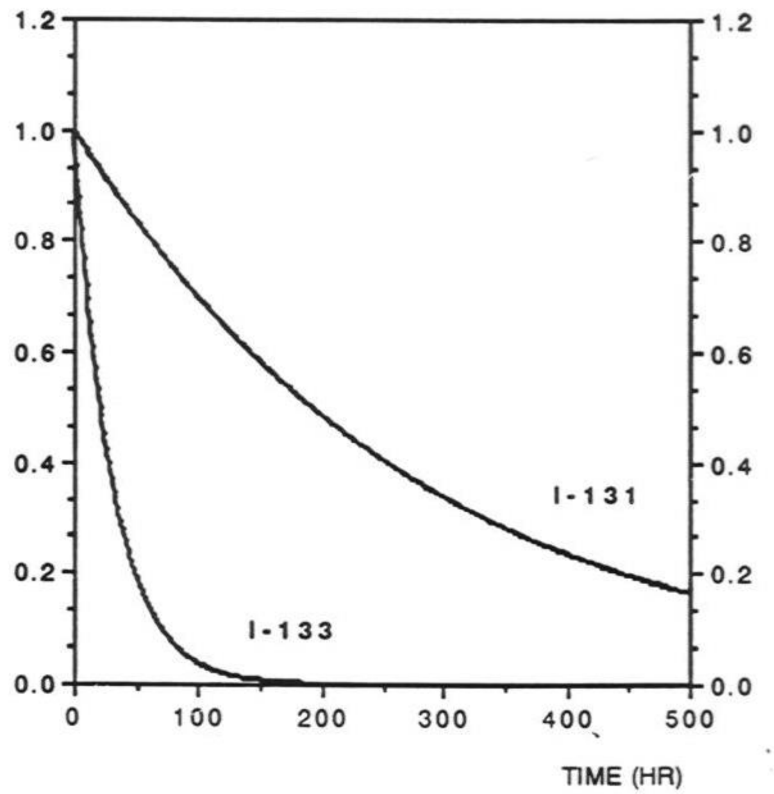

Figure 4. Decay curves of two short lived fission product isotopes, I^{131} and I^{133}.

The iodine^{131} isotope is used for the treatment of thyroid nodules and Grave's syndrome, since iodine tends to accumulate in the thyroid gland. This also makes it a health hazard in the short range in postulated reactor accidents. Its decay curve is shown in Fig. 5.

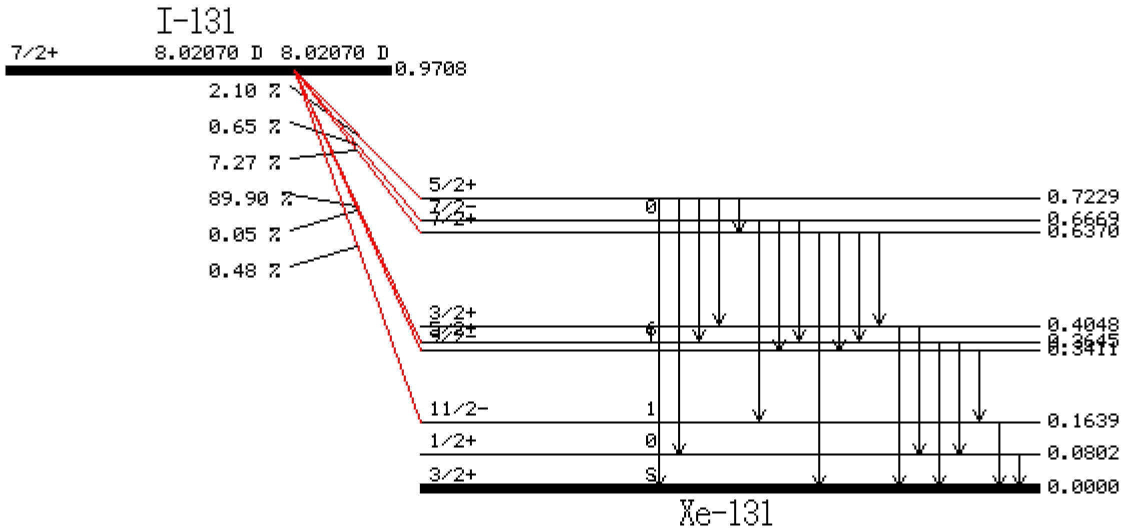

Figure 5. Decay curve of I^{131}, used in the diagnosis and treatment of thyroid gland disorders, but also of reactor safety concern.

RADIONUCLIDES EFFECTIVE HALF LIVES

Some radionuclides are hazardous because of their long effective half-lives. The effective half-life of a radionuclide in terms of its radioactive half-life and its biological half-life in the human body is given by:

$$\frac{1}{T_{eff}} = \frac{1}{T_r} + \frac{1}{T_b} \tag{4}$$

where:
T_{eff} = effective half-life,
T_r = radioactive half-life,
T_b = biological half-life.

which yields:

$$T_{eff} = \frac{T_r . T_b}{T_r + T_b} \tag{5}$$

Table 3. Effective, radioactive and biological half-lives of typical isotopes.

	T_r	T_b	T_{eff}	Critical organ	Source
Tritium, $_1T^3$	12.33 a	12 d	11.97 d	Whole body	Induced activity, fission

					product. As tritiated water in body.
Manganese^{54}	312.5 d	25 d	23 d	liver	Induced activity
Iron^{55}	2.7 a	600 d	388 d	spleen	Induced activity
Iron^{59}	44.6 d	600 d	41.9 d	spleen	Induced activity
Cobalt^{60}	5.27 a	99.5 d	9.5 d	Whole body	Induced activity
Strontium^{90}	29 a	50 a	18 a	bone	Fission product
Iodine ^{131}	8.041 d	138 d	7.6 d	Thyroid	Fission product
Cesium^{137}	30.17 a	70 d	70 d	Whole body	Fission product
Plutonium^{239}	24,110 a	200 a	198 a	bone	Actinide
	24,110 a	500 d	500 d	lung	Actinide

APPENDIX

Procedure decay.f90

This procedure "decay.f90" computes the ratio $N(t)N_0$ for a radioactive isotope, and stores the output in file "output1" for input to a plotting routine. The plotted decay curve using Excel is shown in Fig. A1.

```
!       Decay Curve generation for any radioactive isotope
!       N(t)=No*exp(-lambda*t)
!       lambda=decay constant= - ln 2 / T
!       T=half-life
!       Program saves output to file:output1
!       This output file can be exported to a plotting routine
!       M. Ragheb, Univ. of Illinois at Urbana-Champaign
!
        program decay
        real x, lambda
!       This half life is for the tritium 1T3 nucleus
        real :: T = 12.33
        integer :: steps=50
        real ratio(51), time(51)
!       Calculate decay constant
        x = log(2.0)
        lambda = x/T
```

```
        write(*,*) x, lambda
!       Open output file
        open(10,file='output1')
!       Calculate ratio N(t)/No
        steps = steps + 1
        do i =  1, steps
                time(i) = i - 1
                ratio(i) = exp (- lambda*time(i))
!       Write results on output file
                write(10,*) time(i), ratio(i)
!       Display results on screen
                write(*,*) time(i), ratio(i)
!               pause
        end do
        end
```

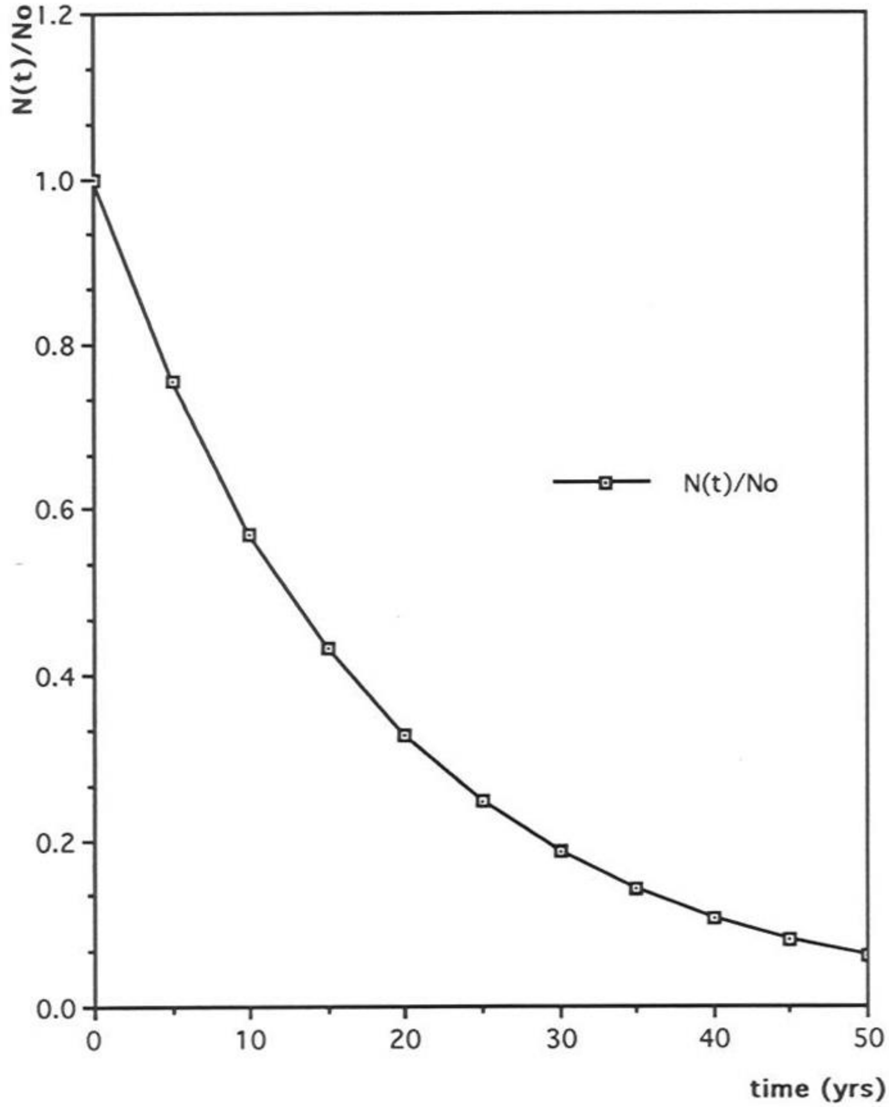

Figure A1. Decay curve showing the ration N(t)/N0 for the tritium isotope with a half life of 13.33 years.