M.N.Morev, May 15, 2002

Here are presented results of intercomparison for activation data in terms of omega factors calculated by Barbier, Huntinen, and Morev. As I hope these note is to solve the notorious Aluminum Problem.

1) In Table B.5 of Barbier book there are presented **Gamma Danger Parameters,** which establish relation between high-energy proton flux and gamma-dose rate inside infinitely thick uniformly activated material.
Let's take, for example, Danger Parameters in Fe and Al for proton energy E_p=600 MeV, FLUX=10^6 proton.cm^{-2}.s^{-1}, irradiation time T=5000 d and cooling time t= 7 d. All the further estimations are made for these or close parameters.
Danger Parameters are 15.9 mrad/h (Al) and 32.9 mrad/h (Fe).

Barbier's **Danger Parameters** can be easily converted to omegas if one knows inelastic cross-section in Fe and Al. I took them from compilation by V.Sychev (book in Russian).
Inelastic cross-section are σ_{in}^{Al}= 440 mδ and σ_{in}^{Fe}= 739 mδ for proton energy 600 MeV.
Star density are estimated as following:
Stars[(stars.cm^{-3}.s^{-1})/(10^6 proton.cm^{-2}.s^{-1})]= n[10^{24}/cm^3] x 10^6[proton.cm^{-2}.s^{-1}] x σ_{in}[δ],
where n, 10^{24}/cm^3 is density of nuclei in the given material – n^{Al} = 0.0602, n^{Fe}= 0.084.

This gives us
Stars^{Al}= 2.6 10^4**,** (stars.cm^{-3}.s^{-1})/(10^6 proton.cm^{-2}.s^{-1})
Stars^{Fe}= 6.2 10^4**,** (stars.cm^{-3}.s^{-1})/(10^6 proton.cm^{-2}.s^{-1})

Since omega is dose rate at surface of semi-infinite source, we can estimate it as following

$$\omega = \frac{Danger}{2}\left[\frac{mrad/h}{10^6\ proton/(cm^2 s)}\right]\cdot 10^{-3}\left[\frac{rad}{mrad}\right]\cdot 10^{-2}\left[\frac{Gy}{rad}\right]\cdot 1\left[\frac{Sv}{Gy}\right]\frac{1}{Stars\left[\frac{star/(cm^3 s)}{10^6\ proton/(cm^2 s)}\right]}$$

This gives us
ω^{Al}(5000,7)=3.0 10^{-9}, [(Sv/h)/(Stars. cm^{-3}.s^{-1})]
ω^{Fe}(5000,7)=2.6 10^{-9}, [(Sv/h)/(Stars. cm^{-3}.s^{-1})]

2) In Table 10 (Al) and Table 16 (Fe) from CMS NOTE 2002/019 by Huntinen there are given omegas for different spectra. I assume that specter 2 is most relevant for intercomparison as its maximum is about 600 MeV.
So Huntinen report us the following figures
ω^{Al}(10y,7d)=1.1 10^{-8}, [(Sv/h)/(Stars. cm^{-3}.s^{-1})]
ω^{Fe}(10y,7d)=7.7 10^{-9}, [(Sv/h)/(Stars. cm^{-3}.s^{-1})]

3) My own code cannot produce omega immediately -- it produces specific **Activity** and specific **Gamma equivalent.** Specific gamma equivalent **K_v,** [(Sv.m^2)/(cm^3.s)] is dose rate from point-wise source at the distance 1 m.
For E_p=600 MeV and FLUX=10^6 I will have
K_v^{Al}(10y,7d)= 7.0 10^{-14}, [(Sv.m^2)/(cm^3.s)]
K_v^{Fe}(10y,7d)= 5.6 10^{-13}, [(Sv.m^2)/(cm^3.s)]
K_v^{Al}(5000d,7d)= 6.8 10^{-14}, [(Sv.m^2)/(cm^3.s)]
K_v^{Fe}(5000d,7d)= 5.6 10^{-13}, [(Sv.m^2)/(cm^3.s)]

The gamma equivalents can be easily converted to contact dose at surface of semi-infinite source $\dot{H}_{\frac{1}{2}\infty}$, Sv/h and then to omegas.

$$\dot{H}_{\frac{1}{2}\infty} = \frac{4\pi K_v\left[\frac{Sv.m^2}{cm^3 s}\right]\cdot 10^4\left[\frac{cm^2}{m^2}\right]\cdot 3600\left[\frac{s}{h}\right]}{2\mu_{en}[1/cm]},$$

where μ_{en} [1/cm] is photon energy absorption coefficient, which can be found for example in Hubble's tables (http://physics.nist.gov/PhysicsData/XrayMassCoef/elemTab/z13.html and ~/z26.html). Here I assume energy 1 MeV for photons emitted from activated material, as the coefficient changes slowly in the energy region of interest and average energy of activation products ranges from 0.8 to 1.5 MeV.
So μ_{en}^{Al} =0.0724 and μ_{en}^{Al} =0.204 for photon energy 1 MeV.

Finally, omegas are as follow:

$$\omega = \frac{\dot{H}_{\frac{1}{2}\infty}\left[Sv/h\right]}{Stars\left[Star/(cm^3 s)\right]}$$

These give us
ω^{Al}(5000d,7d)=8.1 10^{-9}, [(Sv/h)/(Stars. $cm^{-3}.s^{-1}$)]
ω^{Fe}(5000d,7d)=1.0 10^{-8}, [(Sv/h)/(Stars. $cm^{-3}.s^{-1}$)]

4) Let's summarize our figures

Material	Barbier, ω(5000d,7d), [(Sv/h)/(Stars. $cm^{-3}.s^{-1}$)]	Huntinen, ω(10y,7d), [(Sv/h)/(Stars. $cm^{-3}.s^{-1}$)]	Morev, ω(10y,7d), [(Sv/h)/(Stars. $cm^{-3}.s^{-1}$)]
Al	3.0 10^{-9}	1.1 10^{-8}	8.3 10^{-9}
Fe	2.6 10^{-9}	7.7 10^{-9}	1.0 10^{-8}

As one can see from the table above, Morev's and Huntinen's figures are within 30% and Barbier's figures are within 3-4 from the two first. This is quite surprising, but here we are. By the way, Barbier never clamed to be precise more than within factor of 3.
Another thing to mention is that despite a rather good agreement in absolute values between Morev and Huntinen, there is disagreement in Al/Fe ratio. The reason is that I use a most conservative estimation for ^{52}Mn production. In my library I have only ^{52m}Mn+^{52}Mn cross-section and use it as ^{52}Mn cross-section. This results in overestimation of Fe activation because the nuclides decay most independently. The uncertainty is unavoidable as there is no data on isomer production branching. When I assume the branching to be 0.5 for both ^{52m}Mn and ^{52}Mn then ω^{Fe}(5000d,7d)= 0.7 10^{-8} [(Sv/h)/(Stars. $cm^{-3}.s^{-1}$)].

5) So, if Morev and Huntinen are close about omegas, where the **Aluminum Problem** came from?
I see two reasons why aluminum beam-pipe gives an order of magnitude less doses than iron beam-pipe.

First point is that beam-pipe is a thin object and can be considered as superposition of point-wise sources rather than semi-infinite source, consequently it will follow after **Gamma equivalent** and not after omegas. It roughly will give us a factor of 8.

Second point is -- what irradiation condition we assume – is it operation at constant luminosity for 10 y or step-wise time dependent function. In the table below I present **Gamma equivalents** for different irradiation conditions and cooling time t=7 days at the end of irradiation. While activation is almost constant in iron, activation in aluminum exhibits an exponential dependence against luminosity averaged over calendar year. This results from the fact that activation in aluminum at t=7d is dominated by ^{22}Na only, which half decay is much longer than a single irradiation cycle. This gives us additional decrease by 3 (120 d irradiation cycle) or 2 (180 d irradiation cycle).

Material	Then cycles with 120 days irradiation and 245 days cooling	Then cycles with 180 days irradiation and 185 days cooling	Constant irradiation over 10 years
Al	2.4 10^{-14}	3.4 10^{-14}	7.0 10^{-14}
Fe	4.8 10^{-13}	3.6 10^{-13}	5.6 10^{-13}