Activation of soil and ground water outside the Beam Delivery System tunnel

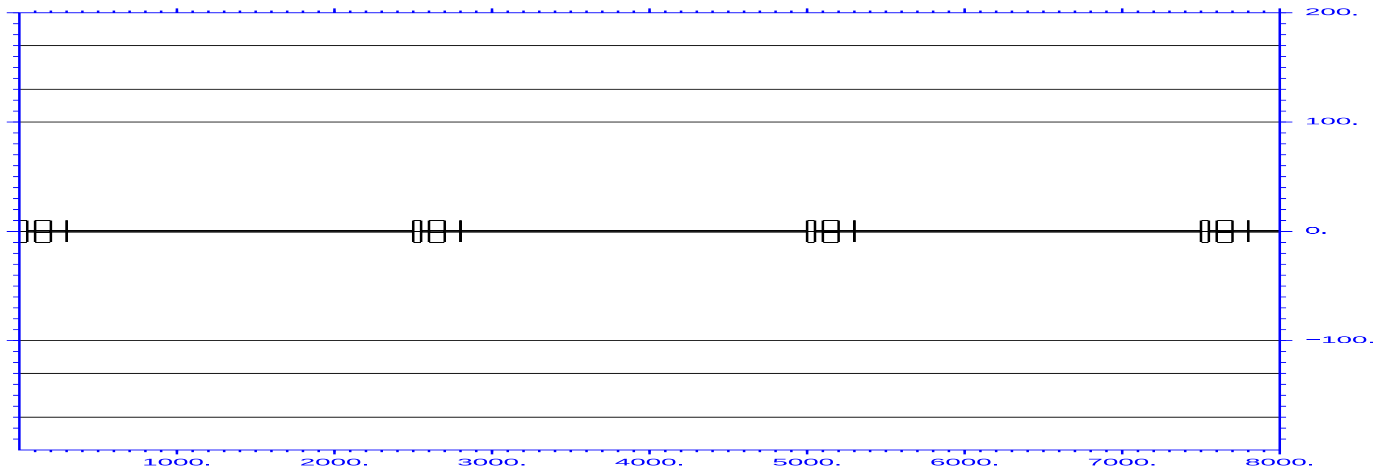
- Production of radioactive nuclei outside the BDS concrete shielding wall is mainly due to neutron interaction with silicon and oxygen nuclei.
- ^{3}H and ^{22}Na produced in soil are dissolved in the water.
- There are various regulations with regard to the activity of radioactive nuclei in water.
- There are no limits for the maximum permissible activity concentrations in soil.

Reactions in the soil and water

Element	Soil %	Water %	Reaction
O	55	89	$^{16}O(n,x)^{3}H$ $^{16}O(n,2\alpha\ 2\ n)^{7}\ Be$
Si	31		$^{28}Si(n,x)^{3}H$ $^{28}Si(n,x)^{7}Be$ $^{28}Si(n,\alpha\ P\ 2N)^{22}Na$
Al	4		$^{27}Al(n,\alpha\ 2n)^{22}Na$
Ca	1.2		$^{44}Ca(n,\gamma)^{45}Ca$

Calculation of saturation activity

- Used FLUKA to calculate the saturation activity of different radio-nuclide in soil.
- Cylinder slab geometry for the tunnel,magnets and other beam components.
- Electromagnetic and hadronic cascades initiated from the interaction of 500 GeV beam on a spoiler.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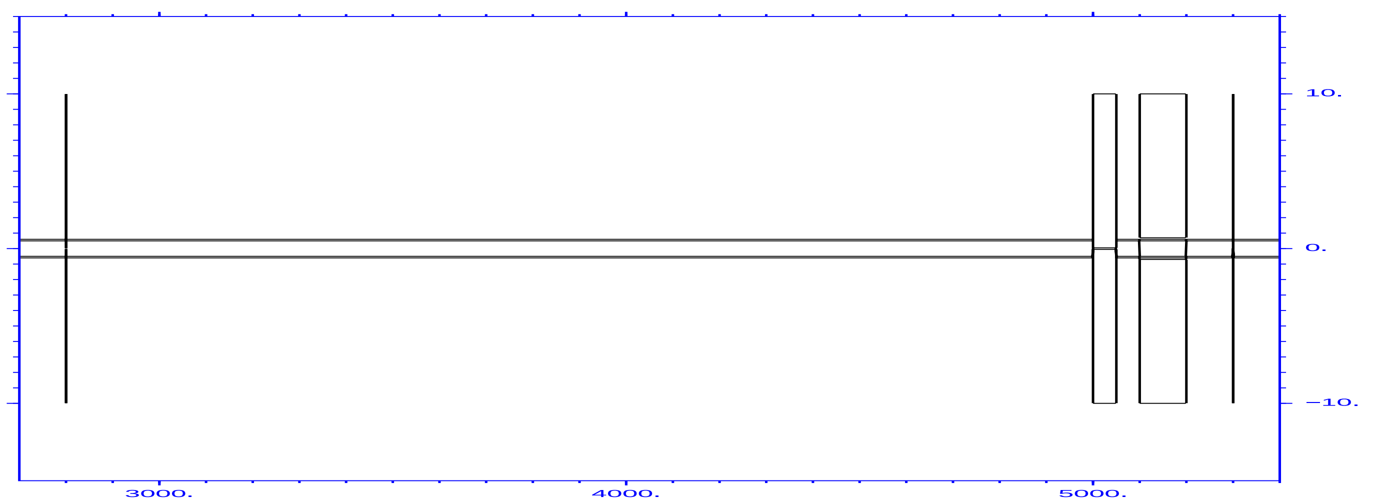
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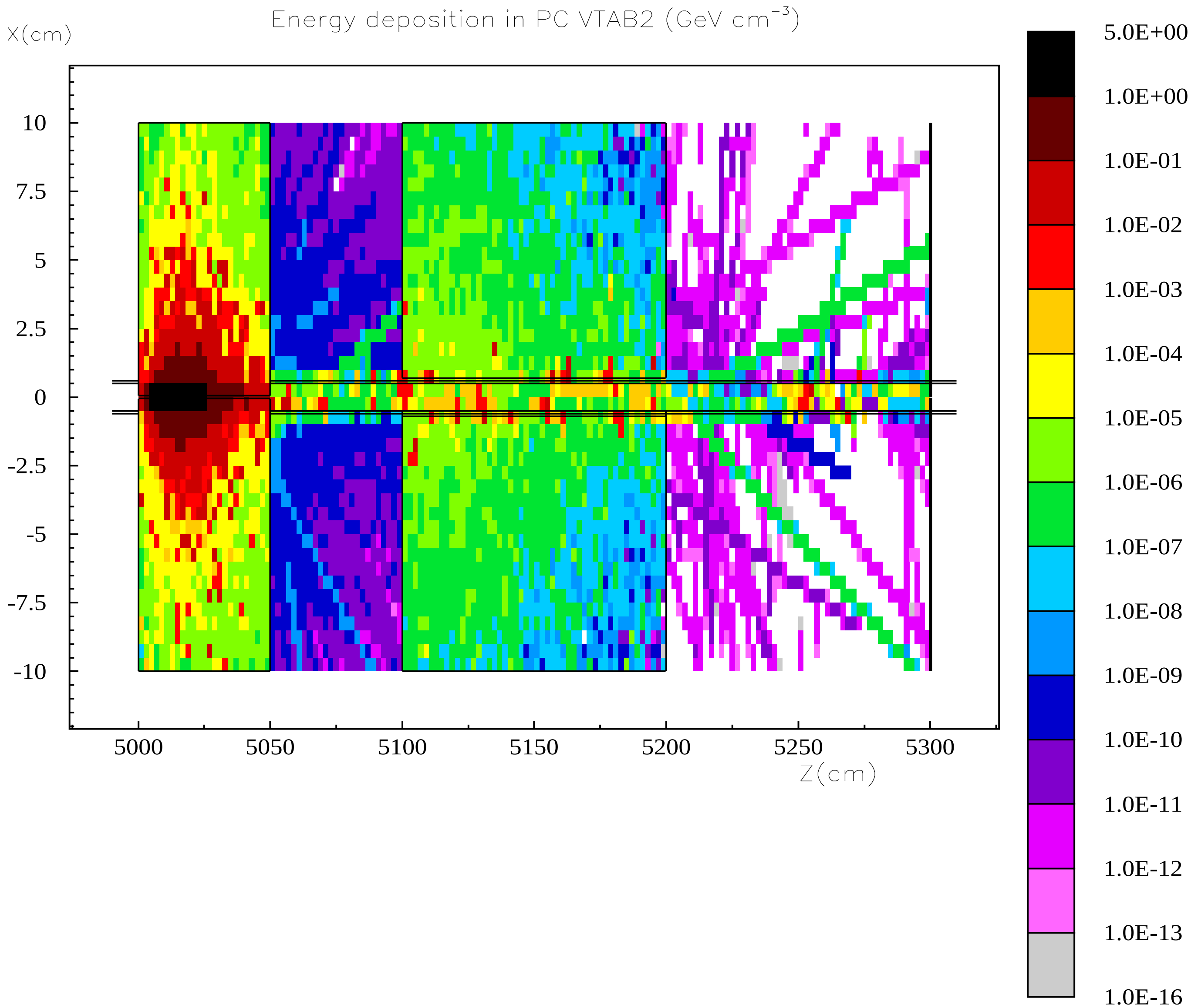
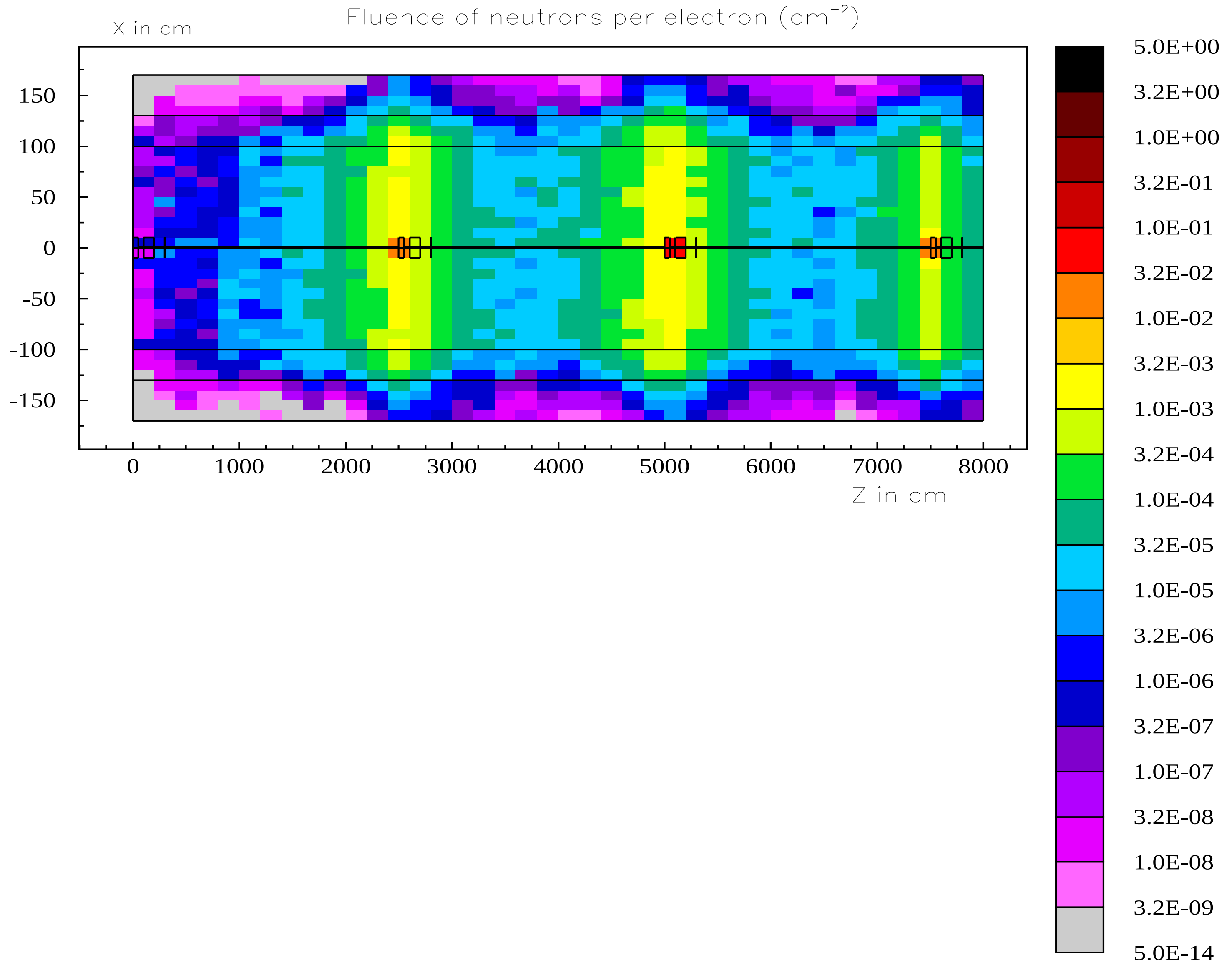

Energy deposition in PC VTAB2 (GeV cm^{-3})
X(cm)
10
7.5
5
2.5
0
-2.5
-5
-7.5
-10
5000
5050
5100
5150
5200
5250
5300
Z(cm)
5.0E+00
1.0E+00
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
1.0E-07
1.0E-08
1.0E-09
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-16

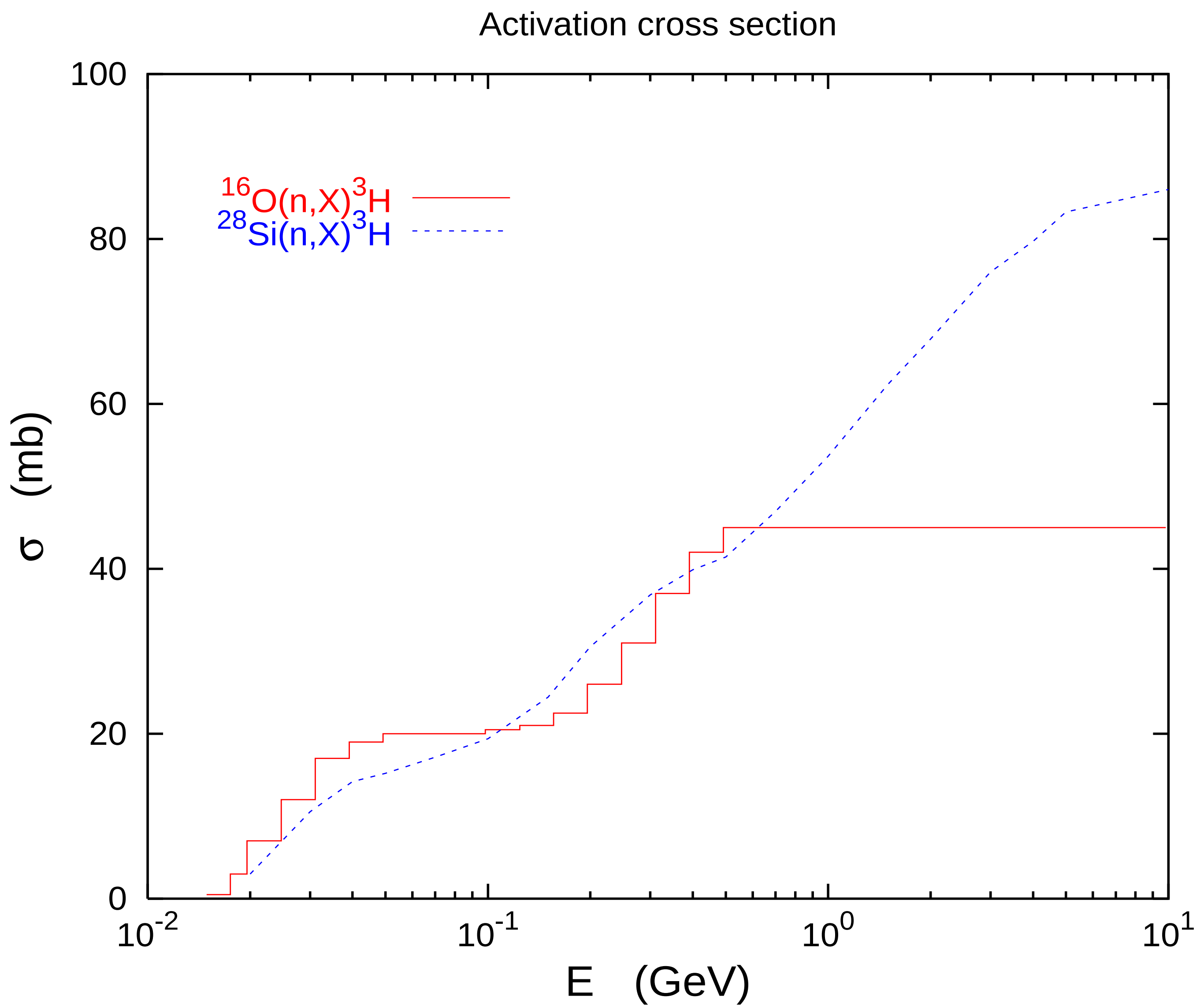
Source terms for 0.1% loss (10 kW)

Location	$E \pm \delta E$ (GeV)	Power (kW)
HZAB1	142.0 ±1.3	2.8
VTAB2	219.4 ±0.7	4.3
HZAB2	64.2 ±0.5	0.13
VTAB3	24.8 ±3.4	0.05
HZAB3	10.4 ±4.0	0.02

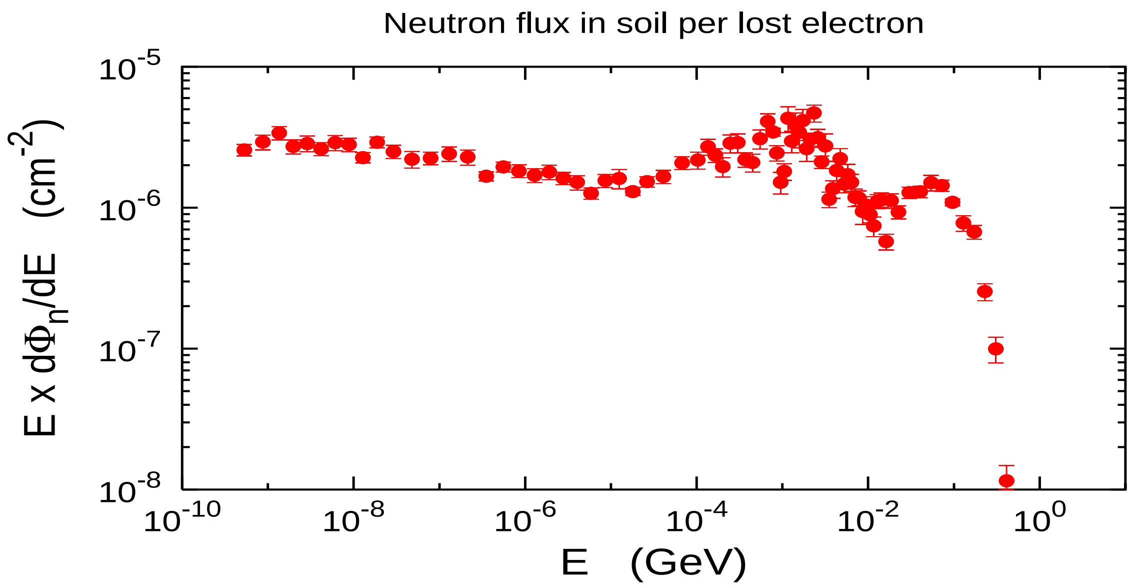
Calculation of saturation activity-continued

- Folding the neutron fluence spectra calculated by FLUKA with experimental cross sections.
- Scoring directly residual nuclei produced in inelastic interactions with FLUKA.
- Using FLUKA to estimate the number of inelastic reactions by hadrons of > 50 MeV (star) in soil.
  - Use proportionality factors to convert the star density to activity concentration.
  - Widely used at hadron machines, should work outside thick shields in electron machines as well.

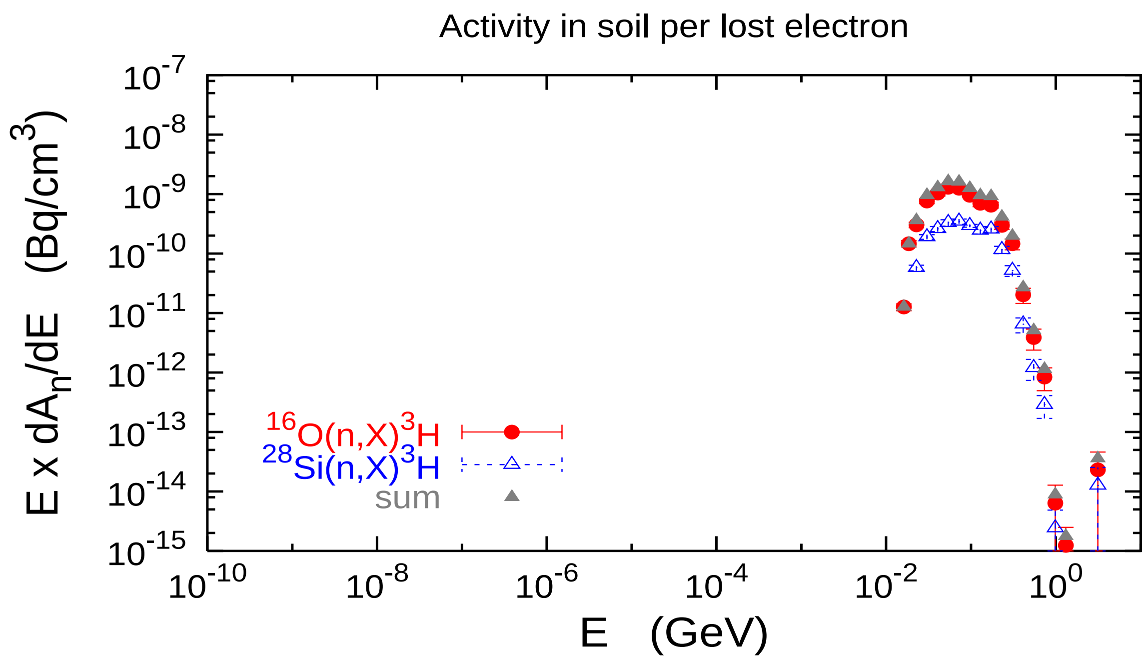

Fluence of neutrons per electron (cm⁻²)
X in cm
150
100
50
0
-50
-100
-150
0
1000
2000
3000
4000
5000
6000
7000
8000
Z in cm
5.0E+00
3.2E+00
1.0E+00
3.2E-01
1.0E-01
3.2E-02
1.0E-02
3.2E-03
1.0E-03
3.2E-04
1.0E-04
3.2E-05
1.0E-05
3.2E-06
1.0E-06
3.2E-07
1.0E-07
3.2E-08
1.0E-08
3.2E-09
5.0E-14



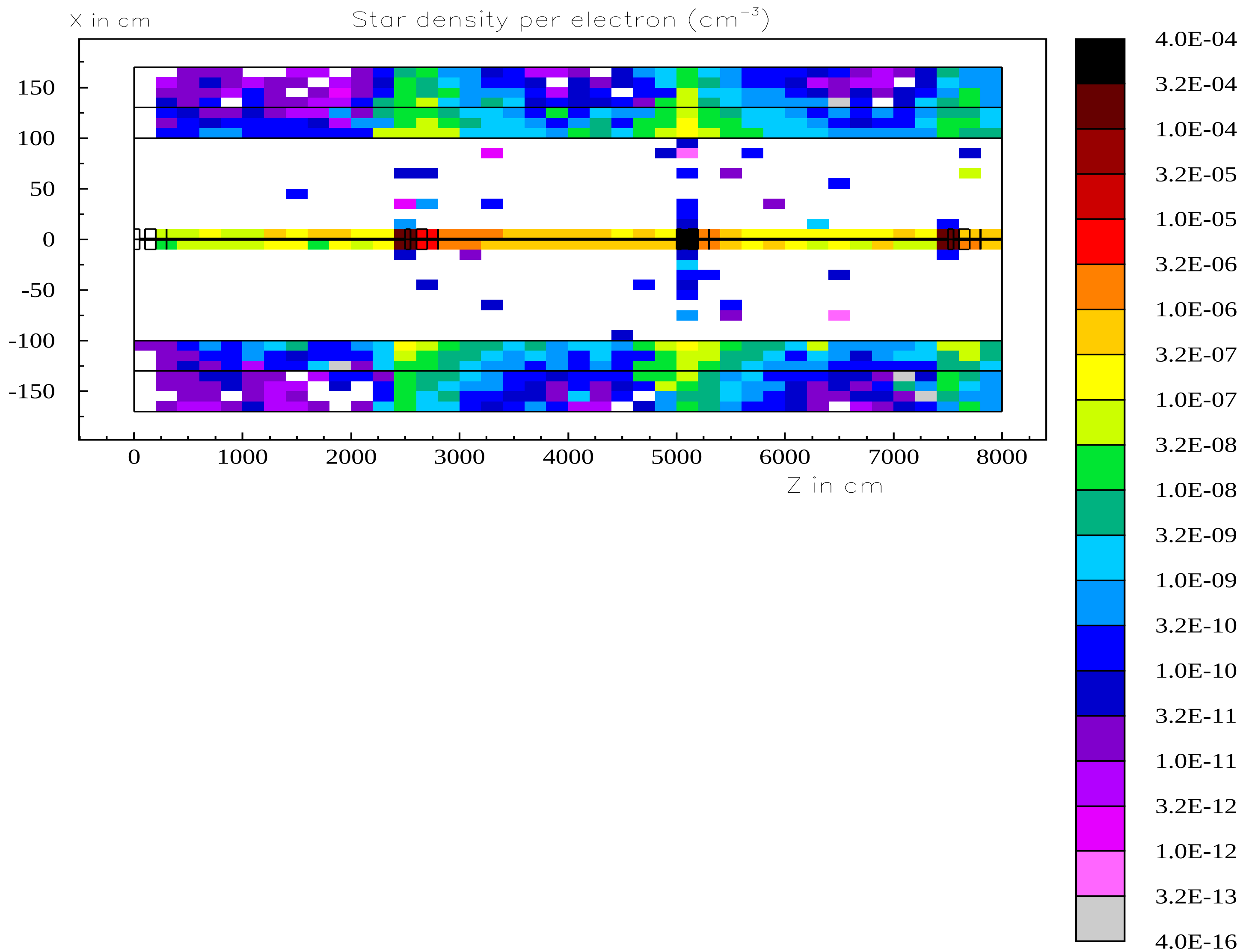
Activation cross section
100
80
60
40
20
0
σ (mb)
^{16}O(n,X)^{3}H
^{28}Si(n,X)^{3}H
10^{-2}
10^{-1}
10^{0}
10^{1}
E (GeV)



Neutron flux in soil per lost electron
E x dΦn/dE (cm-2)
10-5
10-6
10-7
10-8
10-10
10-8
10-6
10-4
10-2
100
E (GeV)



Activity in soil per lost electron
E x dAn/dE (Bq/cm3)
10-7
10-8
10-9
10-10
10-11
10-12
10-13
10-14
10-15
16O(n,X)3H
28Si(n,X)3H
sum
10-10
10-8
10-6
10-4
10-2
100
E (GeV)


X in cm
Star density per electron (cm⁻³)
150
100
50
0
-50
-100
-150
0
1000
2000
3000
4000
5000
6000
7000
8000
Z in cm
4.0E-04
3.2E-04
1.0E-04
3.2E-05
1.0E-05
3.2E-06
1.0E-06
3.2E-07
1.0E-07
3.2E-08
1.0E-08
3.2E-09
1.0E-09
3.2E-10
1.0E-10
3.2E-11
1.0E-11
3.2E-12
1.0E-12
3.2E-13
4.0E-16

Radionuclide concentration in soil (nuclei/cc/e)

	Fluence x cross section	Direct Isotope production	Star density
3H	2.8×10^{-9}	1.0×10^{-9}(31%)	1.4×10^{-9}(16%)
22Na		5.1×10^{-10}(72%)	3.8×10^{-10}
7Be		1.2×10^{-10}(36%)	5.4×10^{-10}

Saturation activity calculations in water

- Calculated saturation activity of different radioactive nuclei in soil
- Assumed 0.26 for fraction of water in soil
- Used (1 for ^{3}H 0.15 for ^{22}Na) extraction fraction from soil into water
- Density of water = 1 gm/cc
- Density of soil = 2.1 gm/cc

Saturation Activity of radionuclide in water immediately outside the shielding wall

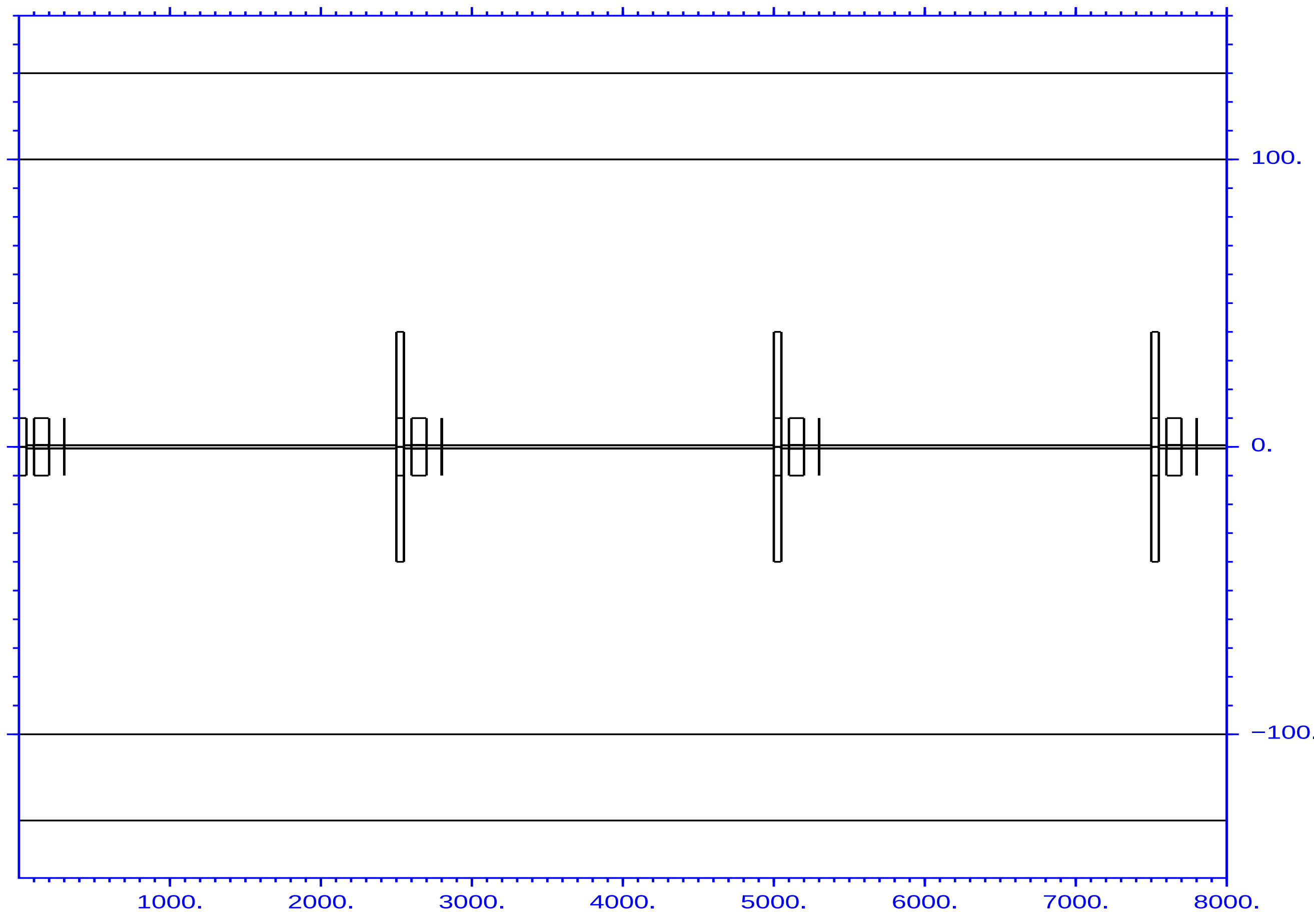
- ^{3}H = 9,450 pCi/cc
- ^{22}Na = 258 pCi/cc

- The calculated ^{3}Hsaturation activity concentration for the SLC dump is 46,000 pCi/cc.

- The limits for activity concentration of ^{3}H is the drinking water limit of 20 pCi/cc.

Shielding

- With site specific factors such as dilution due to the size of the well, distance of well to the shielding wall, the activity concentration in a drinking well could be lower by several order of magnitudes.
- Example: assume a dilution factor of 25 .
- Need reduction by a factor of 20, or 4.3 HVLs.
- HVL for high energy neutrons is 14” in concrete and 4.8” in lead. Need 60” of extra concrete, or 21” of lead.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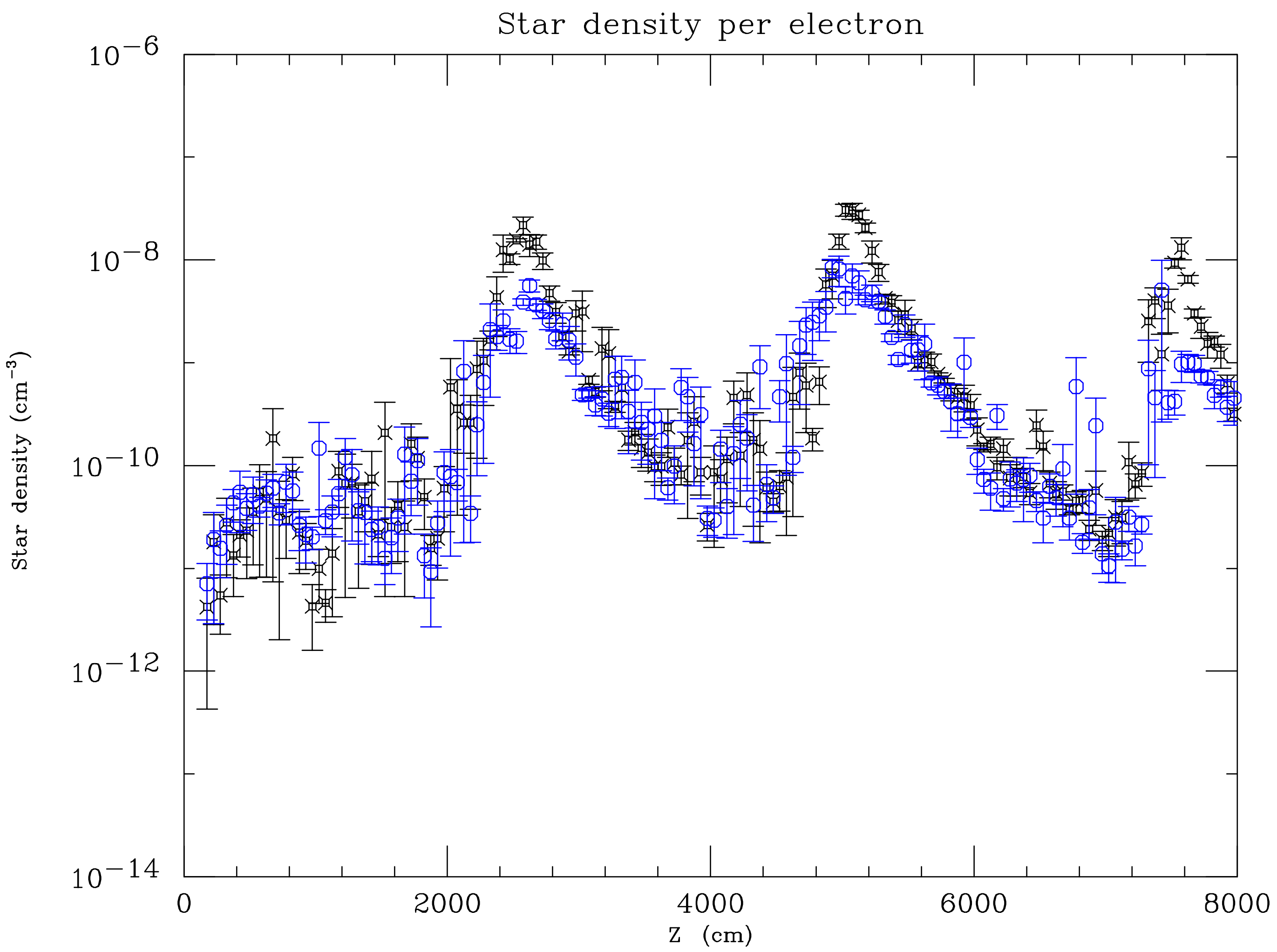

Star density per electron
Star density (cm^{-3})
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
0
2000
4000
6000
8000
Z (cm)

Conclusions

- Different methods using FLUKA to calculate the radio-nuclide activity concentration in soil are consistent.

- Preliminary results of calculations for the activity concentration for ^{3}H in soil for the BDS collimation section is lower than the level calculated for the soil around the SLC dump.