



Induced Radioactivity at Accelerators

Lecture 2: Environmental Radioactivity at Accelerators

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Activation and environmental media-Air

It is convenient to express activation of air by sums over different spectral groups:

$$S = C \sum_i \left[\left\{ \sum_j N_j \bar{\sigma}_{ij\gamma} \phi_\gamma + \sum_j N_j \bar{\sigma}_{ijTH} \phi_{th} + \sum_j N_j \bar{\sigma}_{ijHE} \phi_{HE} \right\} \times \{1 - \exp(-\lambda_i t_{irrad})\} \exp(-\lambda_i t_c) \right] \quad (41)$$

- ϕ_γ is the average photon flux density
- ϕ_{TH} is the average thermal neutron flux density
- ϕ_{HE} is the average “high” energy particle flux density
- i represents the different radionuclides produced.

The role of irradiation t_{irrad} and cooling time t_c is the same as before.

One can use cross sections averaged over energy:

$$\bar{\sigma}_{ijk} = \frac{\int_{E_{min}}^{E_{max}} dE \sigma_{ijk}(E) \phi_k(E)}{\int_{E_{min}}^{E_{max}} dE \phi_k(E)} \quad (42)$$

Activation and environmental media-Air

$$S = C \sum_i \left[\left\{ \sum_j N_j \bar{\sigma}_{ij\gamma} \phi_\gamma + \sum_j N_j \bar{\sigma}_{ijTH} \phi_{th} + \sum_j N_j \bar{\sigma}_{ijHE} \phi_{HE} \right\} \times \{1 - \exp(-\lambda_i t_{irrad})\} \exp(-\lambda_i t_c) \right] \quad (41)$$

S is the total specific activity.

The constant C converts to units of specific activity.

If units of length are all cm (\Rightarrow cm², cm³, etc.)

one gets Bq cm⁻³ for $C=1$.

Sum over i is for over the different radionuclides produced

Sum over j is over the constituent nuclides in air having number densities N_j .

Activation and environmental media-Air

Table 5 Abundances of the most prominent stable nuclides in the atmosphere at sea level.

Nuclide	Percentage by volume in the atmosphere (atoms)	N_j at room temperature (atoms cm ⁻³)
¹⁴ N	78.16	4.199 x 10 ¹⁹
¹⁶ O	20.00	1.075 x 10 ¹⁹
⁴⁰ Ar	0.467	1.558 x 10 ¹⁷
¹⁵ N	0.290	2.149 x 10 ¹⁶
¹⁸ O	0.040	1.255 x 10 ¹⁷

Activation and environmental media-Air

Table 6 Radionuclides with half-life greater than 1 minute that can be produced in air at accelerators. [Adapted from Swanson and Thomas (1990).]

Radionuclide	Half-life	Emission	Parent Element	Production Mechanism	High Energy Cross Section (mb)
³ H	12.32 y	β^-	N	Spallation	30
			O	Spallation	30
⁷ Be	53.22 d	γ , elect. capt.	N	Spallation	10
			O	Spallation	5
			Ar	Spallation	0.6
¹¹ C	20.33 min	β^+	N	Spallation	10
			O	Spallation	0.7
			Ar	Spallation	0.7
¹⁴ C	5700 y	β^-	N	(n _{thermal} ,p)	1640
¹³ N	9.96 min	β^+	N	Spallation	10
			N	(γ ,n)	10
			O	Spallation	9
			Ar	Spallation	0.8
¹⁴ O	1.18 min	β^+ , γ	O	Spallation	1
			Ar	Spallation	0.06
¹⁵ O	2.04 min	β^+	O	Spallation	40
			O	(γ ,n)	10
			Ar	Spallation	

Activation and environmental media-Air

Table 6 Radionuclides with half-life greater than 1 minute that can be produced in air at accelerators. [Adapted from Swanson and Thomas (1990).]

Radionuclide	Half-life	Emission	Parent Element	Production Mechanism	High Energy Cross Section (mb)
¹⁸ F	1.83 h	β^+ ,	Ar	Spallation	6
²⁴ Ne	3.38 min	β^-,γ	Ar	Spallation	0.12
²² Na	2.603 y	β^+,γ	Ar	Spallation	10
²⁴ Na	14.95 h	β^-	Ar	Spallation	7
²⁷ Mg	9.46 min	β^-,γ	Ar	Spallation	2.5
²⁸ Mg	20.92 h	β^-,γ	Ar	Spallation	0.4
²⁸ Al	2.24 min	β^-,γ	Ar	Spallation	13
²⁹ Al	6.56 min	β^-,γ	Ar	Spallation	4
³¹ Si	2.62 h	β^-,γ	Ar	Spallation	6
³⁰ P	2.50 min	β^+,γ	Ar	Spallation	4.4
³² P	14.26 d	β^-	Ar	Spallation	25
³³ P	25.34 d	β^-	Ar	Spallation	9
³⁵ S	87.51 d	β^-	Ar	Spallation	23
^{34m} Cl	32.0 min	β^-,γ	Ar	Spallation	0.7
³⁸ Cl	37.24 min	β^-,γ	Ar	(γ ,pn)	4
³⁹ Cl	55.6 min	β^-,γ	Ar	(γ ,p)	7
⁴¹ Ar	1.83 h	β^-,γ	Ar	(n _{thermal} , γ)	660

Activation and environmental media-Air

In Table 6:

- (n_{th}, γ) and (n_{th}, p) cross sections are large ones for thermal neutron captures
- Others are generally saturation cross sections found at a few 10s of MeV
- Cross sections will be energy-dependent near thresholds.

Ventilation

Need to address effect of ventilation in enclosures

Use effective decay constant $\lambda' = \lambda + r$

$$r = \frac{D}{V} \quad (43)$$

- D is the ventilation rate (air volume per unit time)
- V is the enclosure volume
- r is the # of air changes per unit time.

Can write the following equation, like Eq. (6) $\frac{dn(t)}{dt} = -\lambda n(t) + N\sigma\phi$:

$$\frac{dn'}{dt} = -\lambda n'(t) - r n'(t) + N\sigma\phi = -\lambda' n'(t) + N\sigma\phi \quad (44)$$

Ventilation

$$\frac{dn'}{dt} = -\lambda n'(t) - rn'(t) + N\sigma\phi = -\lambda' n'(t) + N\sigma\phi \quad (44)$$

Starting with zero activation, after irradiation time t_i get:

$$n'(t_i) = \frac{N\sigma\phi}{\lambda + r} \left\{ 1 - \exp[-(\lambda + r)t_i] \right\} \quad (45)$$

Thus the specific activity with ventilation $a'(t_i)$ is

$$a'(t_i) = \lambda n'(t_i) = \frac{\lambda N\sigma\phi}{\lambda + r} \left\{ 1 - \exp[-(\lambda + r)t_i] \right\} \quad (46)$$

But, see Eq. (9), $a(t_i) = N\sigma\phi \{1 - \exp(-\lambda t_i)\}$, $N\sigma\phi$ is saturation concentration a_{sat} without mixing. With mixing the saturation concentration a'_{sat} is: $a'_{sat} = \frac{\lambda a_{sat}}{\lambda + r}$ (47)

Ventilation-qualitative considerations

- Low energy accelerators and beamlines are in continuous vacuum, otherwise too much energy loss!
- At high energy accelerators have air gaps
 - ✓ To accommodate “devices”
 - diagnostics
 - targetry
 - ✓ Only in linacs and extracted beamlines
 - ✓ Not in circular machines since numerous orbits through “windows” would amount to a thick slab of material
- High energy accelerators have high multiplicity of secondary particles.
 - ✓ Activate with beam spray, not just primary beam

Ventilation-qualitative considerations

Would have no release to environment if enclosures sealed

- Impractical, air changes needed for worker health
- Industrial hygiene says 1-2 air changes per hour
- Limits half-lives of dominant radionuclides to about 1 hr

Can minimize environmental releases by

- Decrease ventilation rate during operations if no one is in beam enclosures
- Increase ventilation rate before personnel access
 - Usually implies a “wait time”
 - Clears out short-lived airborne radionuclides
 - Side benefit: reduces radioactivity levels due to accelerator/beamline components.

Propagation of airborne radionuclides in the environment

Need to be concerned about both worker doses & public doses (when radionuclides are released)

Controls on worker doses at accelerators

- ✓ Limiting access to enclosures
- ✓ Timing of accesses (i.e., “wait times”)
- ✓ Ventilation controls
- ✓ Personal protective equipment rarely is used
- ✓ Compare with regulatory standards (here DOE-biased)

Controls on public exposures at accelerators

- ✓ Manipulate ventilation to prevent releases
- ✓ Measure against computer modeling programs (often mandated by regulations)
- ✓ Compare with regulatory standards (EPA-DOE-biased)

Gaussian plume model-Sutton's Equation

Will not describe computer models here!

Will only consider steady-state conditions

Release points are called stacks

Tall stacks at accelerators are relatively uncommon

Want concentration of a given radionuclide

$$\bar{c}(x, y, z) \quad (\text{Bq m}^{-3})$$

as function of coordinates (x, y, z) (all in meters)

Coordinates are measured from the base of the stack

x is along the centerline of the plume (along the wind direction)

y is transverse

z is vertical (above the ground)

Gaussian plume model-Sutton's Equation

Sutton's equation:

$$\bar{c}(x, y, z) = \frac{Q}{2\pi\sigma_y(x)\sigma_z(x)\bar{u}} \left\{ \exp\left[-\frac{\lambda}{\bar{u}}\sqrt{x^2 + y^2}\right] \right\} \\ \times \left\{ \exp\left(-\frac{y^2}{2\sigma_y^2(x)}\right) \right\} \left\{ \exp\left[-\frac{(z-h)^2}{2\sigma_z^2(x)}\right] + \exp\left[-\frac{(z+h)^2}{2\sigma_z^2(x)}\right] \right\} \quad (48)$$

Q is the emission rate of activity (activity s^{-1})

\bar{u} is the mean wind speed (m s^{-1})

$\sigma_y(x)$ and $\sigma_z(x)$ are “downwind” dispersion coefficients

First exponential term conservatively allows for decay in transit.

Gaussian plume model-Sutton's Equation

Sutton's equation:

$$\bar{c}(x, y, z) = \frac{Q}{2\pi\sigma_y(x)\sigma_z(x)\bar{u}} \left\{ \exp\left[-\frac{\lambda}{\bar{u}}\sqrt{x^2 + y^2}\right] \right\} \\ \times \left\{ \exp\left(-\frac{y^2}{2\sigma_y^2(x)}\right) \right\} \left\{ \exp\left[-\frac{(z-h)^2}{2\sigma_z^2(x)}\right] + \exp\left[-\frac{(z+h)^2}{2\sigma_z^2(x)}\right] \right\} \quad (48)$$

h is the effective chimney height found from

$$h = h_a + d \left(\frac{v}{\bar{u}}\right)^{1.4} \left(1 + \frac{\Delta T}{T}\right) \quad (49)$$

where d is the outlet diameter (meters)

v is the exit velocity of the released air (meters s⁻¹)

ΔT is the relative temperature difference between the released air and the absolute temperature T (e.g., °K) of the outdoor air.

Gaussian plume model-Sutton's Equation

Sutton's equation (ground level, $z = 0$, case):

$$\bar{c}(x, y, 0) = \frac{Q}{\pi\sigma_y(x)\sigma_z(x)\bar{u}} \left\{ \exp\left[-\frac{\lambda}{\bar{u}}\sqrt{x^2 + y^2}\right] \right\} \left\{ \exp\left[-\left(\frac{y^2}{2\sigma_y^2(x)} + \frac{h^2}{2\sigma_z^2(x)}\right)\right] \right\} \quad (50)$$

Now for the meteorological input!

Gaussian plume model-Sutton's Equation

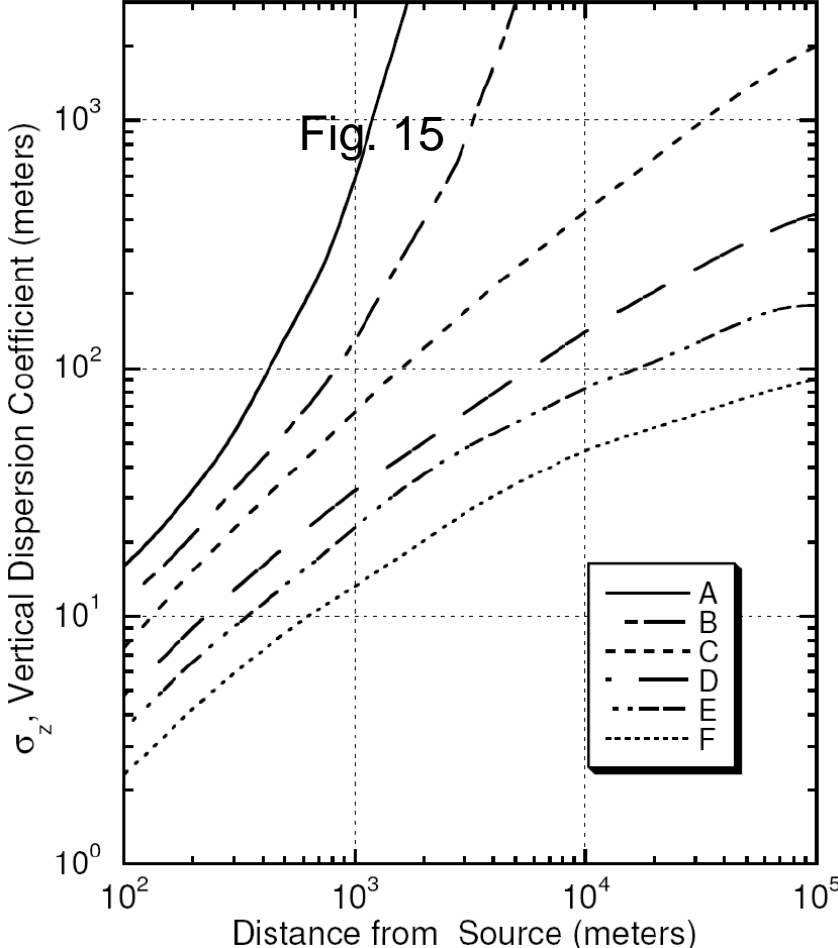
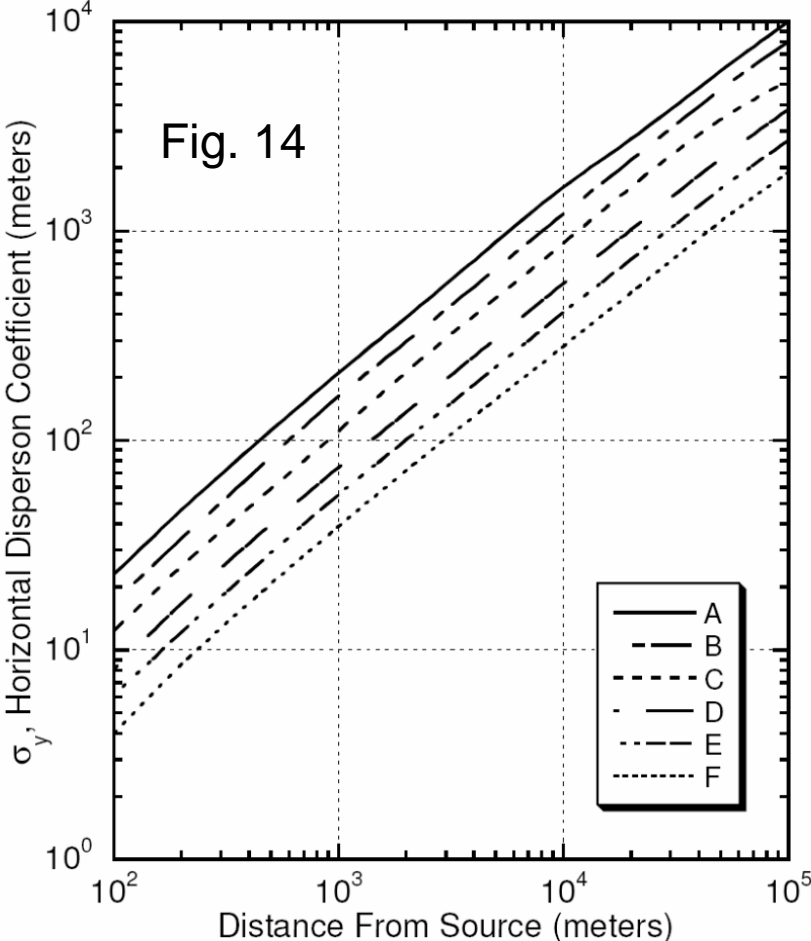
Table 7 Relation of turbulence types to weather conditions. [Adapted from Slade (1968).]

A-Extremely unstable conditions		D-neutral conditions ^a			
B-Moderately unstable conditions		E-Slightly stable conditions			
C-Slightly unstable conditions		F-Moderately stable conditions			
Surface Wind Speed (m/sec)	Daytime insolation			Nighttime conditions	
	Strong	Moderate	Slight	Thin overcast or $\geq 4/8$ cloudiness ^b	$\leq 3/8$ cloudiness
<2	A	A-B	B		
2	A-B	B	C	E	F
4	B	B-C	C	D	E
6	C	C-D	D	D	D
>6	C	D	D	D	D

^aApplicable to heavy overcast, day or night

^bThe degree of cloudiness is defined as that fraction of the sky above the local apparent horizon which is covered by clouds.

Gaussian plume model-Sutton's Equation



Airborne radioactivity-dose assessment & regulatory considerations

This section will be tied to current USDOE and USEPA Requirements. Sorry!

OCCUPATIONAL WORKERS

- Mostly not concerned with uptakes
- True uptakes of airborne radionuclides are rare at accelerators
- Dominated by immersion dose for radionuclides
 - Air samples are commonly used to evaluate
 - Can get crude estimates from survey instruments
 - Problem with immersion doses: Size of immersion cloud has an effect
- Standards expressed as Derived Air Concentrations (DACs)
- 50 mSv is received by a someone who spends his working year of 2000 h in a concentration of one DAC
- One DAC concentrations rarely encountered at accelerators, usually are preventable by applying ventilation and wait times
- Mixtures: Use the weighted sum

$$\sum_i \frac{C_i}{C_{\max,i}} \leq 1 \quad (51)$$

Airborne radioactivity-dose assessment & regulatory considerations

OCCUPATIONAL WORKERS

- US DOE facilities are in the process of changing its DCG values.
- Changes to 10 CFR 835 were issued in the Federal Register in June 2007
- Will need to be fully implemented by July 2010
- ICRP 60 and 68 methodology now being adopted.
- This change is **not** being made by other US agencies at the present time.
- Among other impacts this modifies tabulated DAC values.
- This talk is **based on the older values of DAC.**
- Note: use of DACs or their dose implication does not change, only the numerical values.

Airborne radioactivity-dose assessment & regulatory considerations

MEMBERS OF THE PUBLIC

- Also immersion dose, cannot use cloud size for outdoor exposure
- In USA, U. S. Environmental Protection Agency (USEPA) has specified requirements for USDOE facilities
 - Limit is 100 μSv to an individual in 1 year
 - EPA-approved monitoring required for doses $> 1.0 \mu\text{Sv}$ in one year.
- EPA requires specified methodologies, including computer codes, to estimate doses.
 - Limits are very small, cannot measure directly
 - Need to calculate release, apply plume model numerically
- DOE has issued Derived Concentration Guides (DCGs) for airborne radionuclides
 - A person would receive 1 mSv in a year, living in a 1 DCG cloud.
 - Weighted sum again applies for multiple radionuclides:
$$\sum_i \frac{C_i}{C_{\max,i}} \leq 1 \quad (51)$$

Airborne radioactivity-dose assessment & regulatory considerations

Table 8 Derived Air Concentrations (DACs) and Derived Concentration Guides (airborne exposure pathway) for radiation workers and the general population. These represent maximum concentrations $C_{max,i}$ for use in Eq. (51) for individual radionuclides, depending upon the circumstances of exposure^a. In general, where ambiguities exist, the most conservative value is listed.

	DAC- U. S. DOE Radiation Worker						DCG-General Population ^d	
	Inhaled Air Exposure ^b [50 mSv y ⁻¹ (40 h week ⁻¹)]		Immersion Exposure [50 mSv y ⁻¹ (40 h week ⁻¹)]				[1 mSv year ⁻¹ (168 h week ⁻¹)]	
	($\mu\text{Ci m}^{-3}$)	(Bq m^{-3})	Infinite Radius Cloud ^b		4 m Radius Cloud ^c		($\mu\text{Ci m}^{-3}$)	(Bq m^{-3})
³ H	20	8×10^5	unlisted	unlisted	unlisted	unlisted	0.1	3.7×10^3
⁷ Be	8	3×10^5	unlisted	unlisted	unlisted	unlisted	0.04	1.5×10^3
¹¹ C	200	6×10^6	4	1×10^5	59	2.2×10^6	0.02	7.4×10^2
¹³ N	unlisted	unlisted	4	1×10^5	41	1.5×10^6	0.02	7.4×10^2
¹⁵ O	unlisted	unlisted	4	1×10^5	27	1.0×10^6	0.02	7.4×10^2
²² Na	0.3	1×10^4	unlisted	unlisted	unlisted	unlisted	0.001	37
²⁴ Na	2	8×10^4	0.9	3×10^4	unlisted	unlisted	0.004	1.5×10^2
⁴¹ Ar	unlisted	unlisted	3	1×10^5	47	1.8×10^6	0.01	3.7×10^2

^b(U. S. Code of Federal Regulations 1998) Note: These entries do not reflect modifications that will be necessary under promulgated revisions to the regulations (U. S. Code of Federal Regulations 2007).

^c(Hoefert 1969) These values are not to be used for regulatory compliance purposes.

^d(U. S. Department of Energy 1990) The values listed are the most restrictive given in two different tables. This results given in Bq m^{-3} were calculated from the $\mu\text{Ci m}^{-3}$ entries.

Airborne radioactivity at electron accelerators

- As with components, bremsstrahlung photons dominate
- Cross sections for electron-induced nuclear reactions are about 2 orders of magnitude smaller than for photon-induced nuclear reactions
- Swanson, as done for components, has used shower theory to calculate saturation activities normalized to the beam power
 - Values are tabulated on the next frame
 - To use must multiply by the bremsstrahlung path length
 - Bremsstrahlung path length is set by room dimensions or by attenuation length of the bremsstrahlung radiation
 - Then divide by enclosure volume to get concentrations to compare with standards such as DCGs
- Will have threshold effects near reaction thresholds!
- Dominated by short-lived radionuclides
 - ^3H , ^{14}C , and ^7Be do not build to saturation due to long half-lives
 - $^{40}\text{Ar}(n,\gamma)^{41}\text{Ar}$ is a thermal neutron capture process, sometimes present. [$\sigma_{th} = 660 \text{ mb}$ at $E_n = 0.025 \text{ eV}$]

Table 9 Estimated saturation activities per unit bremsstrahlung path length and per unit beam power produced in air by an electron beam normalized to the beam power. "Cross section" ($\Sigma f\sigma$) refers to the integral radionuclide production cross section per MeV of beam energy inclusive of the natural isotopic abundance in air (see Table 5). [Adapted from Swanson (1979a).]

Produced Radionuclide		Parent Stable Nuclide			Cross Section, $\Sigma f\sigma$	Saturation Activity per Unit Length and Beam Power ^a	
Nuclide	Half-life	Nuclide	Reaction Type	Threshold (MeV)	($\mu\text{b MeV}^{-1}$)	($\text{MBq m}^{-1} \text{ kW}^{-1}$)	($\mu\text{Ci m}^{-1} \text{ kW}^{-1}$)
³ H	12.32 y	¹⁴ N	($\gamma, ^3\text{H}$)	22.7	3	5.2	140
		¹⁶ O	($\gamma, ^3\text{H}$)	25.0	3		
⁷ Be	53.22	¹⁴ N	(γ, sp) ^b	37.8	0.6	1.11	30
		¹⁶ O	(γ, sp) ^b	31.9	0.6		
¹¹ C	20.33 min	¹² C	(γ, n)	18.7	0.011	11	300
		¹⁴ N	(γ, sp) ^b	22.7	6		
		¹⁶ O	(γ, sp) ^b	25.9	6		
¹³ N	9.96 min	¹⁴ N	(γ, n)	10.6	310	520	1.4×10^4
¹⁵ O	2.04 min	¹⁶ O	(γ, n)	15.7	32	55.5	1.5×10^3
¹⁶ N	7.13 s	¹⁸ O	(γ, np)	21.8	0.01	0.018	0.5
³⁸ Cl	37.24 min	⁴⁰ Ar	(γ, np)	20.6	0.13	0.22	6
³⁹ Cl	55.6 min	⁴⁰ Ar	(γ, p)	12.5	0.86	1.5	40
⁴¹ Ar	1.83 h	⁴⁰ Ar	(n, γ) ^c	-	-	variable	variable

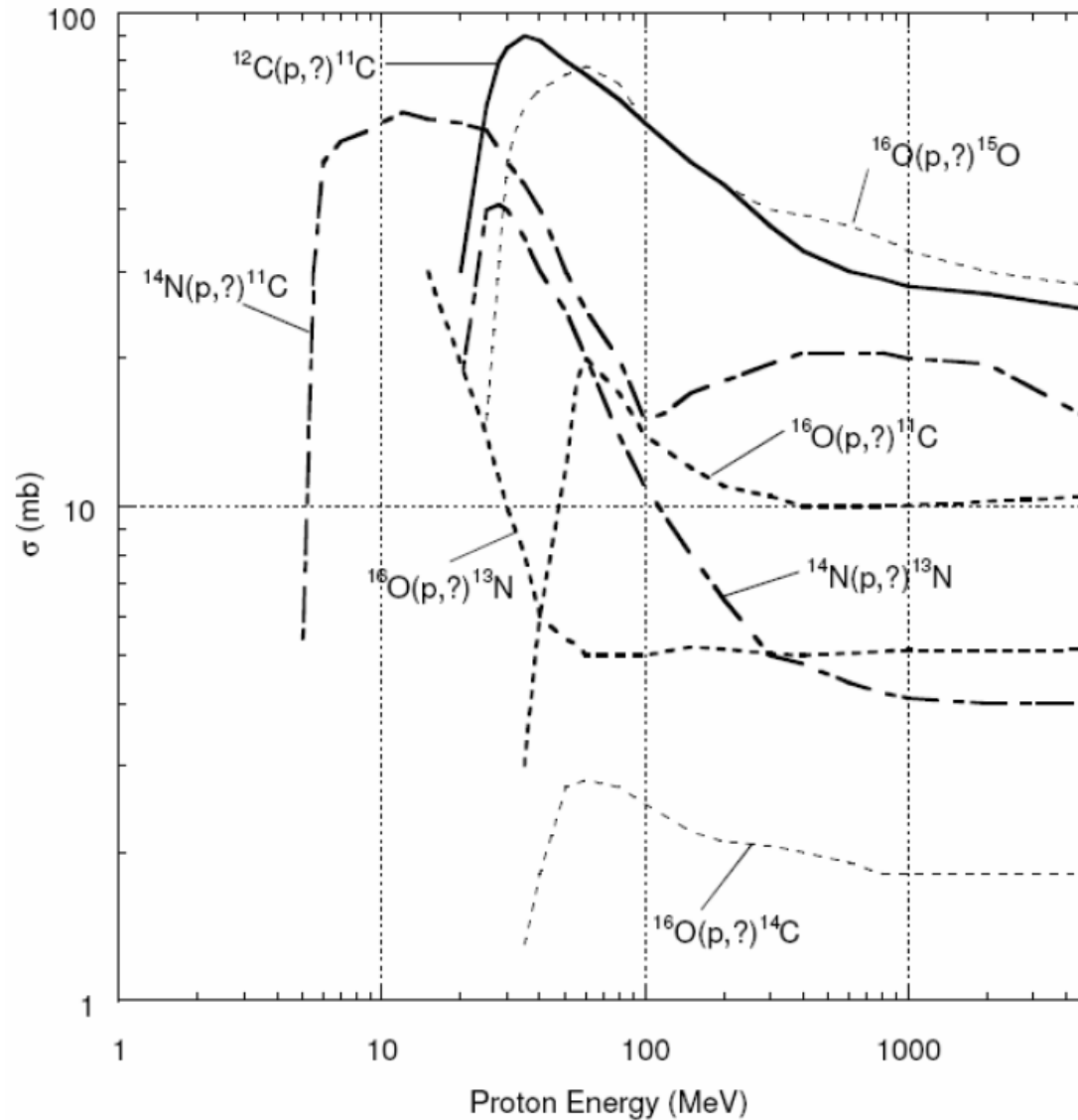
^aNormalized per bremsstrahlung pathlength in air (m) and electron beam power (kW) incident on a high-Z target, summed over individual contributing reactions.

^bSpallation reaction

^cThermal neutron capture reaction that where high neutron fluences are moderated by water or concrete shielding.

Airborne radioactivity at proton accelerators

See Fig. 4
again:



Airborne radioactivity at proton accelerators

- Generally dominated by the positron emitters ^{11}C , ^{13}N , and ^{15}O
- Also get ^{41}Ar , again by thermal neutron capture
- Some facilities have seen others, notably ^{39}Cl and ^{38}Cl
 - Lots of photons around, especially with thermal neutrons
 - $^{40}(\gamma,p)^{39}\text{Cl}$ and $^{40}(\gamma,pn)^{38}\text{Cl}$ reactions proceed
- The positron emitters have no γ -ray signature, only have 0.511 MeV photons due to positron annihilation
 - Can trap a sample and use a multi-channel scaler with appropriate window
 - Fit decay curve to the lifetimes
 - Determine relative contributions to total activity measured

Airborne radioactivity at proton accelerators

- Geometry can affect composition
 - Iron shield surrounded immediately with concrete => little or no ^{41}Ar , ^{39}Cl , ^{38}Cl
 - Iron shield in open room with concrete walls => more ^{41}Ar , ^{39}Cl , ^{38}Cl
 - Conclusion:
 - ✓ Large flux of low energy neutrons emerging from the iron can thermalize in the larger room
 - ✓ Capture γ -rays present, can produce the chlorine isotopes.

Table 10 Measured examples of radionuclide compositions of typical airborne releases at proton accelerators.

Situation	Radionuclides (Activity Per Cent)					
	^{11}C	^{13}N	^{15}O	^{38}Cl	^{39}Cl	^{41}Ar
CERN 28 GeV protons ^a	31.0	47.0	8.0			14.0
Fermilab 800 GeV protons ^b						
no gap between iron and concrete walls	46.0	19.0	35.0			
gap between iron and concrete walls	42.0	14.0	0.0	0.0	10.0	34.0
Fermilab 120 GeV protons ^c	58.5	37.9		1.0	1.1	1.5
Fermilab 120 GeV protons ^d	64.6	30.5				5.0

Water and geological media activation

- Water is a valuable resource
- Public is concerned about water quality
- Radioactivity can be produced in soil or rock or the water it contains.
- Can be a concern for worker protection as well as for members of the public
- Can start calculations from first principles using the **activation equation**

$$a(t_c) = N\sigma\phi \{1 - \exp(-\lambda t_i)\} \{\exp(-\lambda t_c)\} \text{ (Bq cm}^{-3}\text{)}(10)$$

Water activation at electron accelerators

- Situation is somewhat less complicated for electrons than for protons and ions
- Swanson, once again, used shower theory for water activation
- Such activation will principally occur in water used to cool magnets
- Can become a radioactive waste issue
- Swanson gives results as saturation activities normalized to the beam power
 - Includes
 - ✓ Specific gamma ray constants Γ useful for calculating absorbed dose rates near components, tanks, etc
 - ✓ Production cross sections per MeV of beam energy
- Assumes all beam power is absorbed in the water
 - For ^3H , this maximizes the activation for cooling loops, coils, etc due to voids

Water activation at electron accelerators

Table 11 Estimated saturation activities in water per unit beam power produced in ^{16}O by an electron beam normalized to the beam power. [Adapted from Swanson (1979a).]

Produced Radionuclide	Reaction Parameters			Specific Gammy Ray Constant, Γ		Saturation Activity per Unit Beam Power		
	Half-life	Reaction	Threshold (MeV)	Cross Section, σ ($\mu\text{b MeV}^{-1}$)	(mGy h^{-1}) \times (GBq m^{-2}) $^{-1}$	(rad h^{-1}) \times (Ci m^{-2}) $^{-1}$	(GBq kW^{-1})	(Ci kW^{-1})
$^3\text{H}^{\text{a}}$	12.32 y	($\gamma, ^3\text{H}$)	25.0	1.5	-	-	7.4	0.2
^7Be	53.22 d	($\gamma, 5\text{n}4\text{p}$)	31.9	0.3	0.008	0.03	1.5	0.04
^{10}C	19.26 s	($\gamma, 4\text{n}2\text{p}$)	38.1	1	0.29	1.06	3.7	0.1
^{11}C	20.33 min	($\gamma, 3\text{n}2\text{p}$)	25.9	3	0.17	0.62	14.8	0.4
^{13}N	9.96 min	($\gamma, 2\text{n}\text{p}$)	25.0	0.9	0.17	0.62	3.7	0.1
^{14}O	1.18 min	($\gamma, 2\text{n}$)	28.9	1	0.45	1.7	3.7	0.1
^{15}O	2.04 min	(γ, n)	15.7	75	0.17	0.62	330	9

^aDoes not present an external radiation hazard.

Water activation at electron accelerators

- Radionuclides are produced by **spallation of the oxygen**
- Due to low atomic number target (hydrogen, oxygen) only see
 - Natural oxygen is 99.76 % ^{16}O
 - Short lived positron emitters, ^{11}C , ^{13}N , and ^{15}O
 - ^3H and ^7Be
- True even for most of the ^3H
 - To produce ^3H from water would require successive capture reactions; $^1\text{H}(n,\gamma)^2\text{H}$ followed by $^2\text{H}(n,\gamma)^3\text{H}$
 - Each has a small thermal capture cross section, fractions of a mb.
- ^3H atoms readily combine to make HTO molecules, especially in an environment with lots of ionization present.
- As water vapor, this “water” readily can become **airborne radioactivity**.

Water activation at electron accelerators

IMPORTANT NOTICE!

At electron accelerators the characteristic scaling length of shielding is a material property, the radiation length.

At proton accelerators, the characteristic scaling length of shielding is also a material property, the interaction length.

For materials with atomic numbers > 3 , the radiation length is much smaller than the interaction length (We don't make shields with hydrogen, helium, or lithium!)

Bulk shielding for electron accelerators is, in general, much smaller than that needed at proton, or even ion accelerators.

This makes soil activation a much smaller problem at electron machines.

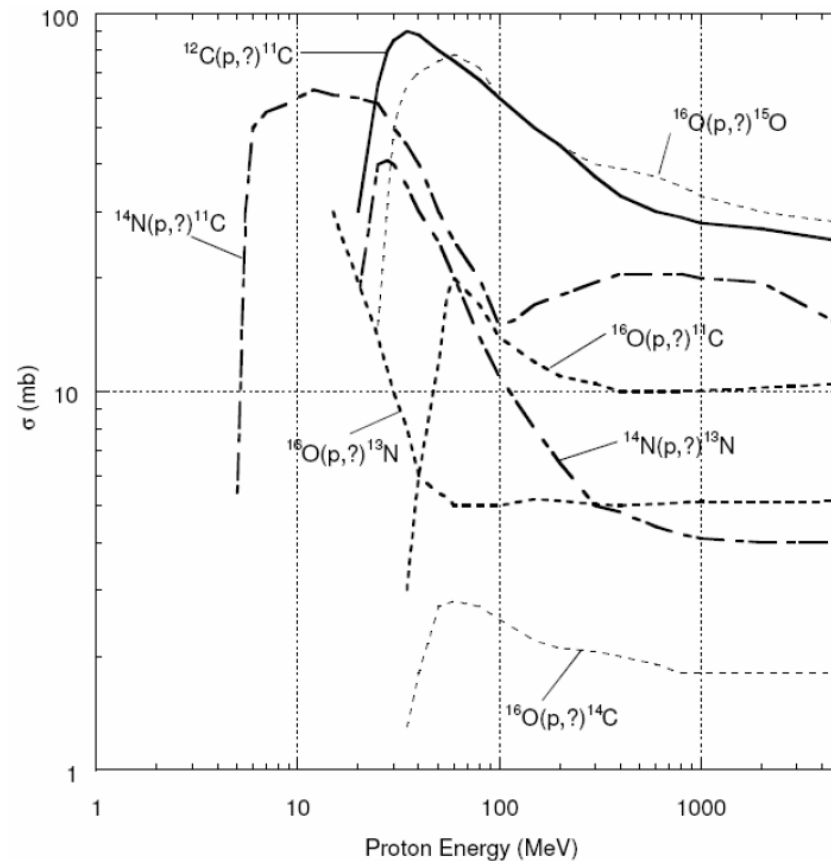
Water and geological media activation at proton accelerators-water activation

At proton accelerators can produce radioactivity directly in water

One can calculate activation directly if cross sections are known

See Fig 4 examples

once more



Water and geological media activation at proton accelerators-water activation

Production of ^3H is of special importance

Again, most of the ^3H comes from spallation of oxygen since two successive thermal captures (our friends $^1\text{H}(n,\gamma)^2\text{H}$ followed by $^2\text{H}(n,\gamma)^3\text{H}$)

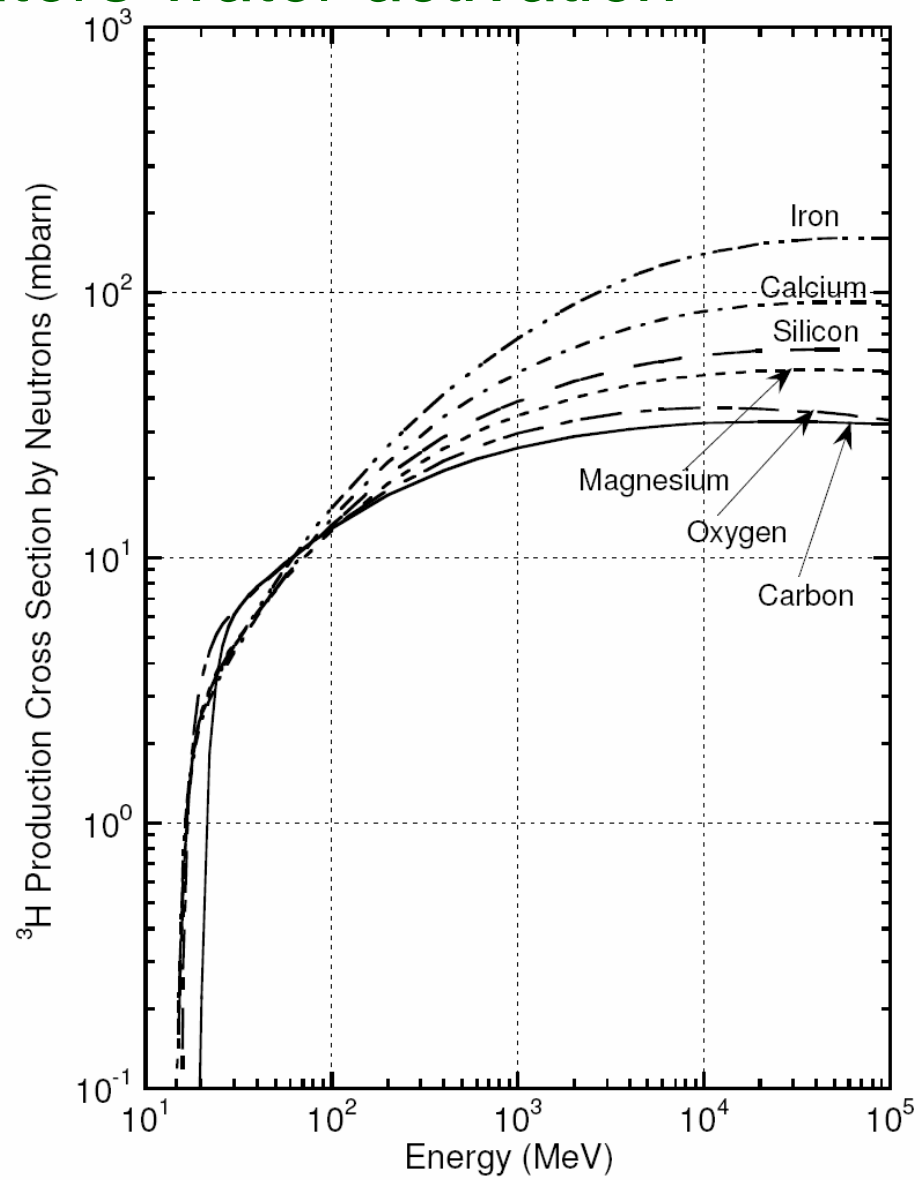
Global fit to data exists covering materials found in soil as well as for oxygen.

Developed by Konobeyev and Korovin for **neutrons**

Proton interactions would be similar.

Proton accelerators-water activation

Fig. 16



Proton accelerators-geologic media activation

Some work never grows old! (Borak et al. 1972) (Same methods still used.)

1. Measured radioactivity produced in soil by high energy hadrons
 - Used ZGS (12 GeV, ANL-dismantled), AGS (28 GeV, BNL)
 - Limited to radionuclides with $t_{1/2} > 15$ days.
 - Identified by radiochemical analysis:
 - ^3H , ^7Be , ^{22}Na , ^{45}Ca , ^{46}Sc , ^{48}V , ^{51}Cr , ^{54}Mn , ^{55}Fe , ^{59}Fe , & ^{60}Co
2. Did leaching experiments
 - Measured macroscopic cross sections
 - Determined ion velocities relative to that of water
 - Found that only the following leach: ^3H , ^{22}Na , ^{45}Ca , & ^{54}Mn
 - Assumed all ^3H as HTO was leachable

Proton accelerators-geologic media activation

3. Get **specific activities** at saturation A_i (Bq g⁻¹) related to microscopic cross sections by

$$A_i = \phi \sum_j n_j \sigma_{ij} \quad (52)$$

ϕ is the flux density (cm⁻²s⁻¹)

n_j is the number density of j^{th} target nuclide (atoms g⁻¹)

σ_{ij} is the cross section for producing radionuclide i from target nuclide j (cm²)

The summations in Eq. (52) are the total macroscopic cross sections

Results from Borak et al. are tabulated for various Fermilab soils.

Proton accelerators-geologic media activation

Table 13 Macroscopic cross section for soil normalized to unit flux of hadrons with kinetic energies greater than 30 MeV. [Adapted from Borak et al. (1972).]

Nuclide	Glacial Till Σ (cm ² g ⁻¹)	Gray Sandy Clay Σ (cm ² g ⁻¹)	Red Sandy Clay Σ (cm ² g ⁻¹)	Gray Clay Σ (cm ² g ⁻¹)
⁷ Be	2.9 x 10 ⁻⁴	3.7 x 10 ⁻⁴	3.2 x 10 ⁻⁴	2.7 x 10 ⁻⁴
⁵¹ Cr	1.7 x 10 ⁻⁵	3.7 x 10 ⁻⁵	2.8 x 10 ⁻⁵	3.1 x 10 ⁻⁵
²² Na	2.1 x 10 ⁻⁴	2.3 x 10 ⁻⁴	2.0 x 10 ⁻⁴	1.6 x 10 ⁻⁴
⁵⁴ Mn	5.9 x 10 ⁻⁵	4.1 x 10 ⁻⁵	3.5 x 10 ⁻⁵	3.7 x 10 ⁻⁵
⁴⁶ Sc	3.0 x 10 ⁻⁵	1.3 x 10 ⁻⁵	9.6 x 10 ⁻⁶	1.1 x 10 ⁻⁵
⁴⁸ V	4.1 x 10 ⁻⁶	1.1 x 10 ⁻⁵	6.7 x 10 ⁻⁶	7.4 x 10 ⁻⁶
⁵⁵ Fe	9.3 x 10 ⁻⁵	1.2 x 10 ⁻⁴	7.0 x 10 ⁻⁵	2.1 x 10 ⁻⁴
⁵⁹ Fe	3.2 x 10 ⁻⁶	1.7 x 10 ⁻⁶	1.3 x 10 ⁻⁶	1.6 x 10 ⁻⁶
⁶⁰ Co	3.3 x 10 ⁻⁵	1.4 x 10 ⁻⁵	1.1 x 10 ⁻⁵	1.3 x 10 ⁻⁵
⁴⁵ Ca	1.6 x 10 ⁻⁴	2.0 x 10 ⁻⁵	3.0 x 10 ⁻⁵	1.6 x 10 ⁻⁵
³ H	8.2 x 10 ⁻⁴	1.1 x 10 ⁻³	3.3 x 10 ⁻⁴	5.2 x 10 ⁻⁴
³ H ^a	5.9 x 10 ⁻³	5.9 x 10 ⁻³	4.1 x 10 ⁻³	4.4 x 10 ⁻³

^aCross sections per gram of water in soil.

Proton accelerators-geologic media activation

Leachability results – chemistry, not physics!

³H: macroscopic cross section = $5.1 \times 10^{-3} \text{ cm}^2\text{g}^{-1}$ of water

Migrates at the same velocity as water

²²Na: 10-20 % leachable

Migrates at about 40 % of the velocity of water

⁴⁵Ca: At most 5 % leachable

Very small migration velocity

⁵⁴Mn: At most 2% leachable

Negligible migration velocity

Conclusion: ³H as HTO and ²²Na are almost always the only radionuclides produced in geological media that will move in groundwater.

Proton accelerators-geologic media activation

Monte Carlo results are useful in estimating groundwater activation.

Can calculate total stars in some volume

Then get total number of atoms P_i of the i^{th} nuclide produced in that same volume from

$$P_i = \frac{\Sigma_i}{\Sigma_{in}} \quad (53)$$

Σ_i is the macroscopic cross section for producing the i^{th} radionuclide (cm^2g^{-1})

Σ_{in} is the total macroscopic inelastic cross section (cm^2g^{-1}). A good value is $\Sigma_{in} = 1.1 \times 10^{-2}$.

Modern codes can do activation calculations directly.

Proton accelerators-geologic media activation

Example values for ^3H and ^{22}Na in Fermilab glacial till:

$$P_3 = \frac{8.2 \times 10^{-4}}{1.1 \times 10^{-2}} = 0.075 \quad (54a) \quad P_{22} = \frac{2.1 \times 10^{-4}}{1.1 \times 10^{-2}} = 0.020 \quad (54b)$$

After calculating the # of atoms, one can multiply by the decay constant to get total activity in the same volume

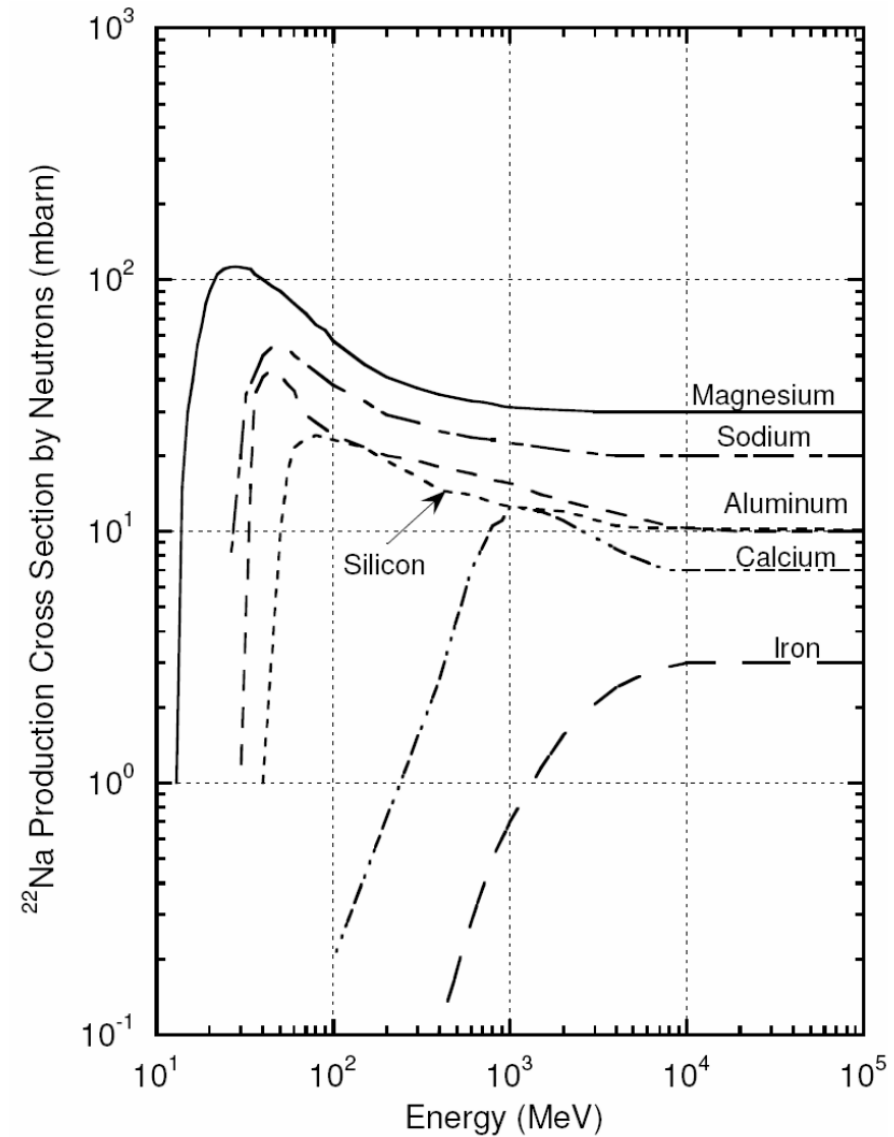
$$A_{tot}(t) = -\frac{dN_{tot}(t)}{dt} = \frac{1}{\tau} N_{tot}(t) = \lambda N_{tot}(t) \quad (3)$$

For specific soil or rock compositions, use individual cross sections and composition percentages.

Need cross sections for ^{22}Na production!

Proton accelerators-geologic media activation

Fig. 17
(companion to Fig. 16)



Water activation – regulatory standards

- Most countries and USA states have drinking water regulations
- These vary considerably
- Not always based on consistent methodologies
- *Sometimes* differ between drinking water supplies and surface water discharges
- If different, higher concentrations *may* be allowed in surface waters
- Depends on the *authority having jurisdiction*
 - USA *states* vary considerably
 - Some local governments have their own limits to protect drinking water resources.
 - Usually tied in some way to *Federal* requirements
- **CANNOT GENERALIZE THIS HERE**

Water activation – regulatory standards

³H as HTO – Drinking water

USEPA

Community Drinking Water systems:

20 pCi cm⁻³ (7.4 x 10⁵ Bq m⁻³) – stated to correspond to 40 μSv in a year to a member of the public who uses such water as his household drinking water source.

Most states adopt this explicit limit for drinking water supplies.

USDOE

Derived Concentration Guides (DCGs)

80 pCi cm⁻³ (3 x 10⁶ Bq m⁻³) – also stated to correspond to 40 μSv in a year to a member of the public who uses such water as his household drinking water source.

Note: USEPA uses an obsolete ICRP methodology but retains the more stringent explicit limit for ³H concentration as being more protective.

Water activation – regulatory standards

²²Na – Drinking water

USEPA

Community Drinking Water systems:

No explicit limit, concentrations must correspond to 40 μSv in a year to a member of the public who uses such water as his household drinking water source.

USDOE

Derived Concentration Guides (DCGs)

0.4 pCi cm^{-3} (1.5×10^4 Bq m^{-3}) – also corresponds to 40 μSv in a year to a member of the public who uses such water as his household drinking water source.

Water activation – regulatory standards

³H as HTO – Surface Water

USEPA

No stated limits, but some states do have limits, some even impose the drinking water standards on all surface water.

USDOE

Derived Concentration Guides (DCGs)

2000 pCi cm⁻³ (3 x 10⁶ Bq m⁻³) – corresponds to 1 mSv in a year to a member of the public who should use such water as his household drinking water source.

(Note: similar USNRC limit of 1000 pCi cm⁻³ for discharges from licensees corresponds to 0.5 mSv in a year and uses the same methodology as present DOE requirements.)

Water activation – regulatory standards

²²Na – Surface Water

USEPA

No stated limits, but some states do have limits, some even impose the drinking water standards on all surface water.

USDOE

Derived Concentration Guides (DCGs)

10 pCi cm⁻³ (3.7 x 10⁴ Bq m⁻³) – corresponds to 1 mSv in a year to a member of the public who should use such water as his household drinking water source.

Water activation – regulatory standards

As with air, with multiple radionuclides present, use weighted sum:

$$\sum_i \frac{C_i}{C_{\max,i}} \leq 1 \quad (51)$$

Propagation of radionuclides in geological media

Methodologies

- Could be specified by the authority having jurisdiction
- May be influenced by institutional conservatism

Most conservative approach:

- Assume accelerator operates “forever”
- Radioactivity never moves
- This is unrealistic; does not represent a viable source of drinking water
- However, will start with this approach.

Propagation of radionuclides in geological media

Static concentration C_i of i^{th} radionuclide is given by

$$C_i = \frac{N_p P_i L_i S_{ave}}{31.62 \rho w_i} \{1 - \exp(-t_{irrad} / \tau_i)\} \exp(-t_c / \tau_i) \text{ (Bq m}^{-3}\text{)} \quad (55)$$

N_p = # of protons delivered y^{-1}

P_i = # of atoms star^{-1} for i^{th} radionuclide [recall Eq. (53): $P_i = \frac{\Sigma_i}{\Sigma_{in}}$]

L_i = fraction of i^{th} radionuclide that is leachable

S_{ave} = average star density (stars cm^{-3}) in the volume of interest

ρ = density of the medium (g cm^{-3})

w_i = mass (grams) of water per unit mass (grams) of medium required to achieve L_i .

The “times”, t_{irrad} , t_c , and τ are as before.

Propagation of radionuclides in geological media

Static concentration C_i of i^{th} radionuclide is given by

$$C_i = \frac{N_p P_i L_i S_{ave}}{31.62 \rho w_i} \{1 - \exp(-t_{irrad} / \tau_i)\} \exp(-t_c / \tau_i) \text{ (Bq m}^{-3}\text{)} \quad (55)$$

The constant 31.62 $\Rightarrow C_i$ in Bq m⁻³

Replace with 1.17×10^6 for C_i in pCi cm⁻³

The ratio L_i/w_i should be determined from measurement for the media in question.

The porosity p is defined by $p = \rho w_i$ (56).

- Porosity can be understood as the pore volume of the material in a unit volume of soil
- In consolidated materials (i.e., rock) it does not include sealed pores that don't permit water movement.
- Values vary, but the range $0.2 < p < 0.35$ is useful.

Need to take water movement into account!

Propagation of radionuclides in geological media

Fermilab's antiquated single residence model (SRM)

- Gollon (1978) based this Borak, et al.'s (1972) work
- Only used in glacial till soil
- Assumed vertical migration of water to be 2.2 m y^{-1}
 - Extremely conservative; in our soils, likely large by $> \times 10$
 - But, allows for cracks, fissures, sand lenses
- Vertically, HTO assigned this velocity
- Vertically, ^{22}Na assigned 1.0 m yr^{-1} (based on Borak et al.)
 - Only the leachable fraction of ^{22}Na was included
- Horizontal velocities were regarded as instantaneous.

Propagation of radionuclides in geological media

Fermilab's antiquated single residence model (SRM)

Steps:

1. Calculate annual production of total activity in a given volume due to operations
2. Allow decay in transit of this total activity during vertical transit
3. Calculate concentration in water consumed by an individual who uses $0.15 \text{ m}^3 \text{ d}^{-1}$
 - ✓ conservative value, achieved in drought emergencies
 - ✓ Amounts to dilution of annual production in $55 \text{ m}^3 \text{ y}^{-1}$
4. Check against limits using Eq. (51) $\sum_i \frac{C_i}{C_{\max,i}} \leq 1$
5. If Eq. (51) not satisfied, redesign shielding.

Propagation of radionuclides in geological media

Fermilab's antiquated single residence model (SRM)

Deficiencies:

- Assumes water movement uniform from year-to-year
- Ignores spacial nonuniformities in production and transport
- Ignores the fact that radionuclides have an initial concentration that is not infinite
 - There are no mechanisms for increasing concentrations other than activation.
- Does not allow for **increase** in concentration due to activation in transit.

Need better model!

Propagation of radionuclides in geological media

The Fermilab Concentration Model

Steps:

1. Start with as an initial concentration.
$$C_i = \frac{N_p P_i L_i S_{ave}}{31.62 \rho w_i} \{1 - \exp(-t_{irrad} / \tau_i)\} \exp(-t_c / \tau_i) \text{ (Bq m}^{-3}\text{)} \quad (55)$$
2. Use up-to-date modeling methods to calculate dilution occurring in migration to groundwater resource aquifer
✓ Available from work done for other water contaminants.
3. Check with Eq. (51) $\sum_i \frac{C_i}{C_{max,i}} \leq 1$ to be sure design is adequate.
4. If Eq. (51) not met, redesign the shielding.

Propagation of radionuclides in geological media

A bit of hydrogeology is needed (see references).

Often, a definite potential gradient exists in a medium

This condition is called advective.

This gradient is called the hydraulic gradient or hydraulic head; dh/dx .

v , the seepage velocity is given by Darcy's Law.

$$v = \frac{K}{p} \frac{dh}{dx} \quad (57)$$

where $p = \rho w_i$ is the effective porosity

K is the hydraulic conductivity, a function of material, moisture content, etc.

This is for one dimension, vector methods are needed for multiple dimensions.

Propagation of radionuclides in geological media

Table 14 Examples of typical values of hydraulic conductivity. [Adapted from Batu (1998).]

Group	Porous Materials	Range of K values (cm s^{-1})
Igneous Rocks	Weathered granite	$(3.3-52) \times 10^{-4}$
	Weathered gabbro	$(0.5-3.8) \times 10^{-4}$
	Basalt	$(0.2-4250) \times 10^{-6}$
Sedimentary Materials	Sandstone (fine)	$(0.5-2250) \times 10^{-6}$
	Siltstone	$(0.1-142) \times 10^{-8}$
	Sand (fine)	$(0.2-189) \times 10^{-4}$
	Sand (medium)	$(0.9-567) \times 10^{-4}$
	Sand (coarse)	$(0.9-6610) \times 10^{-4}$
	Limestone and dolomite	$(0.4-2000) \times 10^{-7}$
	Karst limestone	$(1-20000) \times 10^{-4}$
	Gravel	$(0.3-31.2) \times 10^{-1}$
	Silt	$(0.09-7090) \times 10^{-7}$
	Clay	$0.1-47) \times 10^{-8}$
Metamorphic Rocks	Schist	$(0.002-1130) \times 10^{-6}$

Propagation of radionuclides in geological media

Can apply Darcy's Law to determine the rate of migration

- Concentration will decrease by decay in transit
- Concentration will increase due to any ongoing activation while in transit.
 - Irradiation periods often comparable to radionuclide half-lives
- Complex media demand computer modeling

Will give 2 examples of simple analytical cases

Propagation in media – Example # 1

Recall Eq. (6): $\frac{dn(t)}{dt} = -\lambda n(t) + N\sigma\phi$

Can write continuity equation

- Function of position x and time t
- For concentration of i^{th} radionuclide $C_i(x,t)$
- Assumes velocity of water movement v varies slowly or is constant in time in some volume of space (the activation volume).

$$\frac{\partial C_i}{\partial t} + v \frac{\partial C_i}{\partial x} + \lambda_i C_i(x,t) = \frac{L_i}{w_i'} Q_i(x,t) \quad (58)$$

where

λ_i is the decay constant of the i^{th} radionuclide

w_i' is the water content of the media per unit volume

$Q_i(x,t)$ represent the production of the i^{th} radionuclide, includes time-dependence of beam delivery. $Q_i(x,t) = N_p S_{ave} / (31.62 \rho)$ in Eq. (55).

Propagation in media – Example # 1

$$\frac{\partial C_i}{\partial t} + v \frac{\partial C_i}{\partial x} + \lambda_i C_i(x, t) = \frac{L_i}{w_i'} Q_i(x, t) \quad (58)$$

Right hand side is production and leaching

Left hand side:

Right-most term is loss by decay

Middle term is loss by transport

Very often, simple exponential functions adequately describe production:

$$Q_i(x, t) = Q_{oi}(t) \exp(-\xi x) \quad (59)$$

Mokhov (1997) has solved Eq. (58) for conditions $C_i(x, 0) = 0$ and

$$x \geq 0, t \geq 0: C_i(x, t) = \frac{L_i}{w_i} \int_0^t dt' Q_i(x - vt', t') \exp(-\lambda t') \quad (60)$$

Propagation in media – Example # 1

$$C_i(x, t) = \frac{L_i}{w_i} \int_0^t dt' Q_i(x - vt', t') \exp(-\lambda t') \quad (60)$$

Substituting $Q_i(x, t) = Q_{oi}(t) \exp(-\xi x)$ (59)

get
$$C_i(x, t) = Q_{oi}(t) \frac{L_i}{w_i} \frac{1}{\eta_i} \exp(-\xi x) [\exp(\eta_i \tau) - 1] \quad (61)$$

with $\eta_i = \xi v - \lambda_i$

$$\tau = t \quad \text{for } t < x/v$$

$$\tau = x/v \quad \text{for } t \geq x/v$$

The maximum in the concentration is not at $x=0$, it is at:

$$x_{i, \max} = - \frac{v}{\lambda_i} \frac{\ln\left(\frac{\xi v}{\lambda_i}\right)}{1 - \frac{\xi v}{\lambda_i}} \quad (62)$$

Propagation in media – Example # 1

Caution!

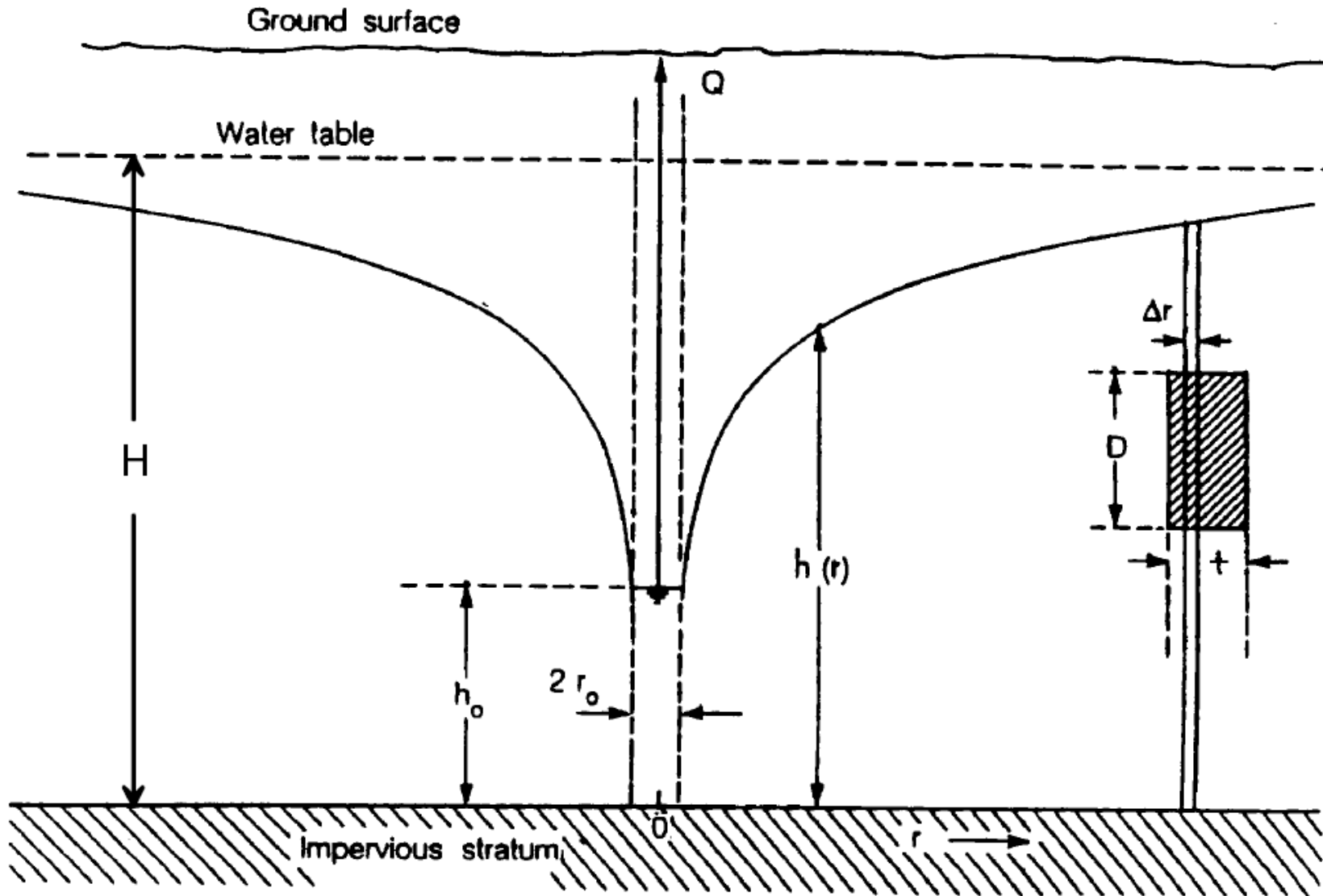
One must be careful to keep algebraic signs of x and v straight

If seepage velocity is extremely slow, the situation is said to be diffusive rather than advective

Implies use of the diffusion with second partial derivatives is needed.

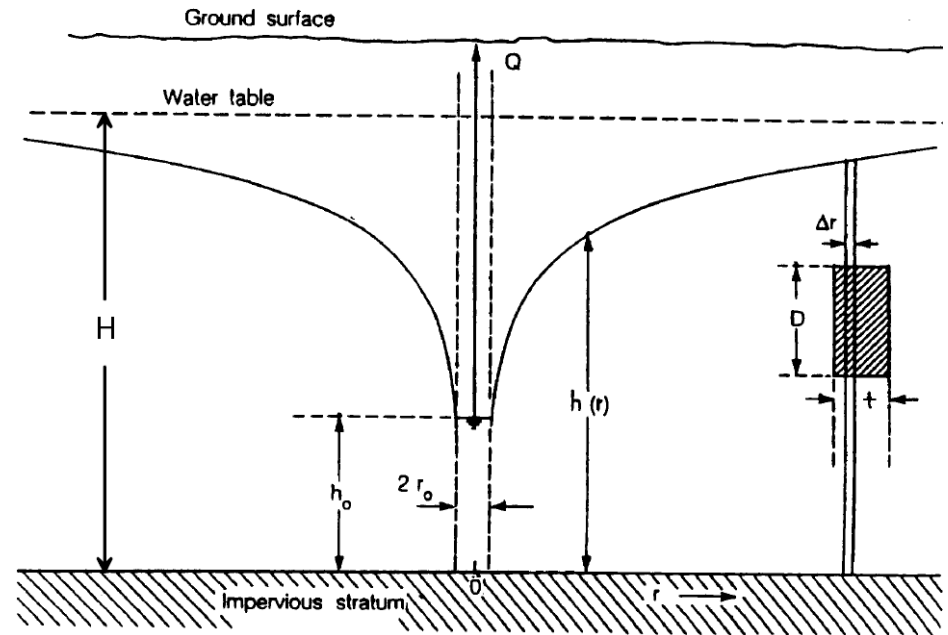
Probably better handled with computer modeling.

Propagation in media – Example # 2



Propagation in media

– Example # 2



Goal: Estimate activity in a shallow uncased well a distance r from a beam loss also in the same aquifer.

Assumptions:

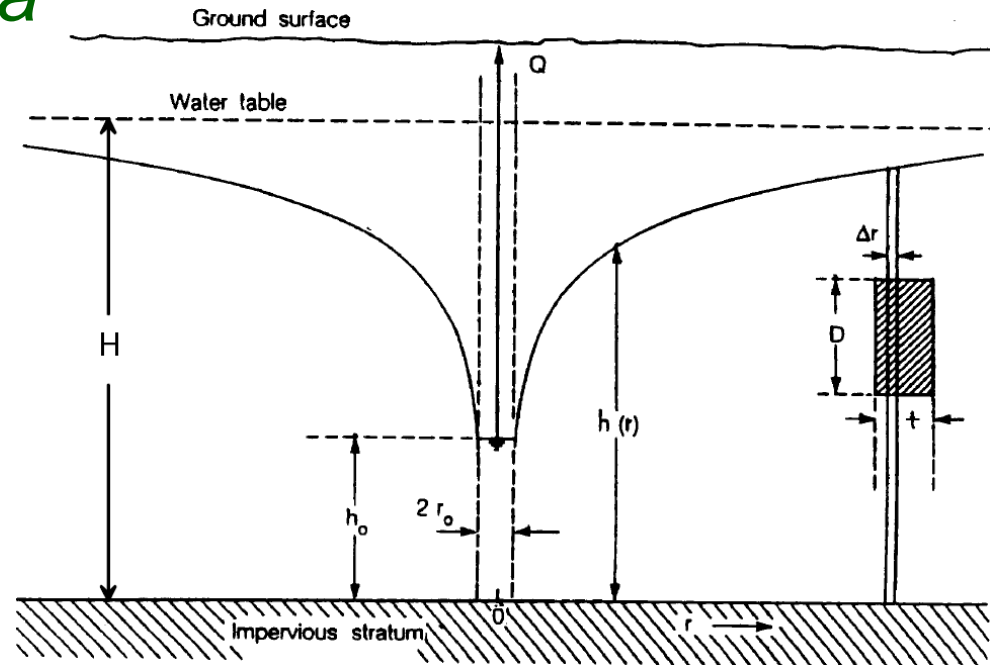
Beam loss is within cone of influence of the well.

$h(r)$ is depth of water in well (function of r)

The well supplies a daily volume Q of water per day.

Propagation in media

– Example # 2



Another version of Darcy's Law is applicable: $S_r = k \frac{dh(r)}{dr}$ (63)

S_r is inward flux at r

k is related to the hydraulic conductivity (see text for units)

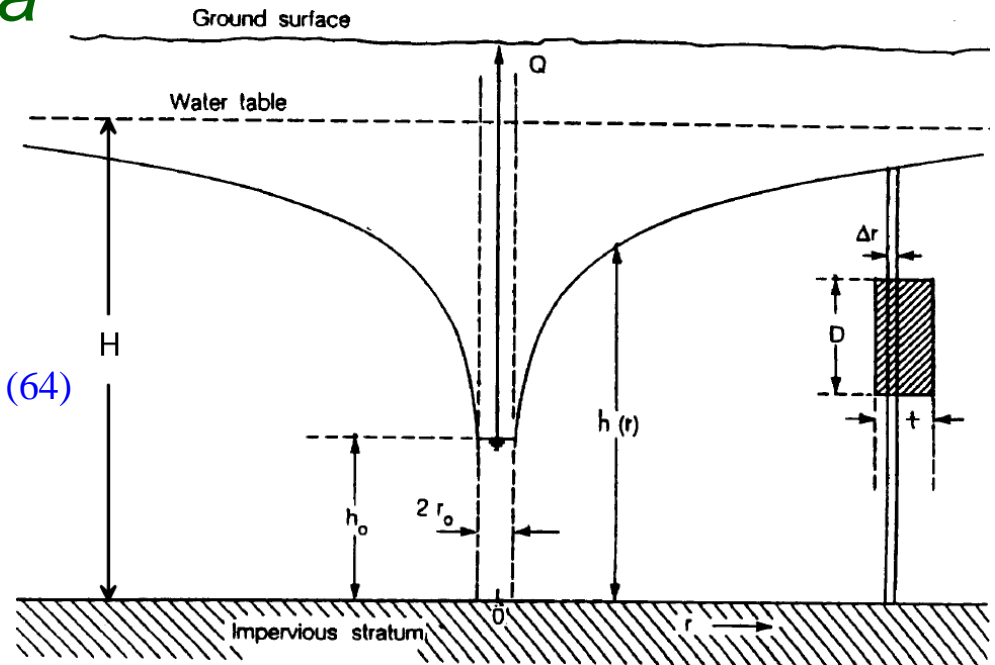
Conservation and incompressibility of water yields:

$$Q = 2\pi r h(r) S_r = 2\pi r k h \frac{dh}{dr} = \pi k \frac{d(h^2)}{d(\ln r)} \quad (64)$$

Propagation in media

– Example # 2

$$Q = 2\pi r h(r) S_r = 2\pi r k h \frac{dh}{dr} = \pi k \frac{d(h^2)}{d(\ln r)} \quad (64)$$



$2\pi r h dh/dr$ is rate of change of the volume of the cylindrical shell of height h (the hydraulic head) with respect to r

Can solve Eq. (64):

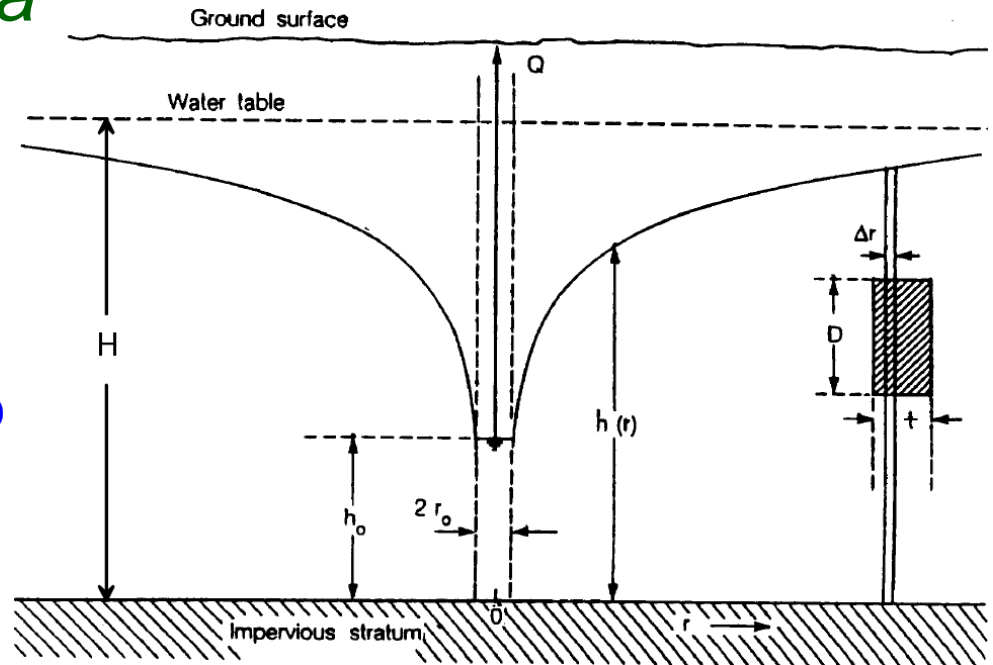
$$Q \ln \left(\frac{r}{r_o} \right) = \pi k \left\{ h^2(r) - h_o^2 \right\} \quad (65)$$

where r_o is the radius of the well, h_o is the height of water above the impervious stratum in the well.

Propagation in media

– Example # 2

$$Q \ln \left(\frac{r}{r_o} \right) = \pi k \{ h^2(r) - h_o^2 \} \quad (65)$$



H is the depth of the impervious stratum below the water table far away.

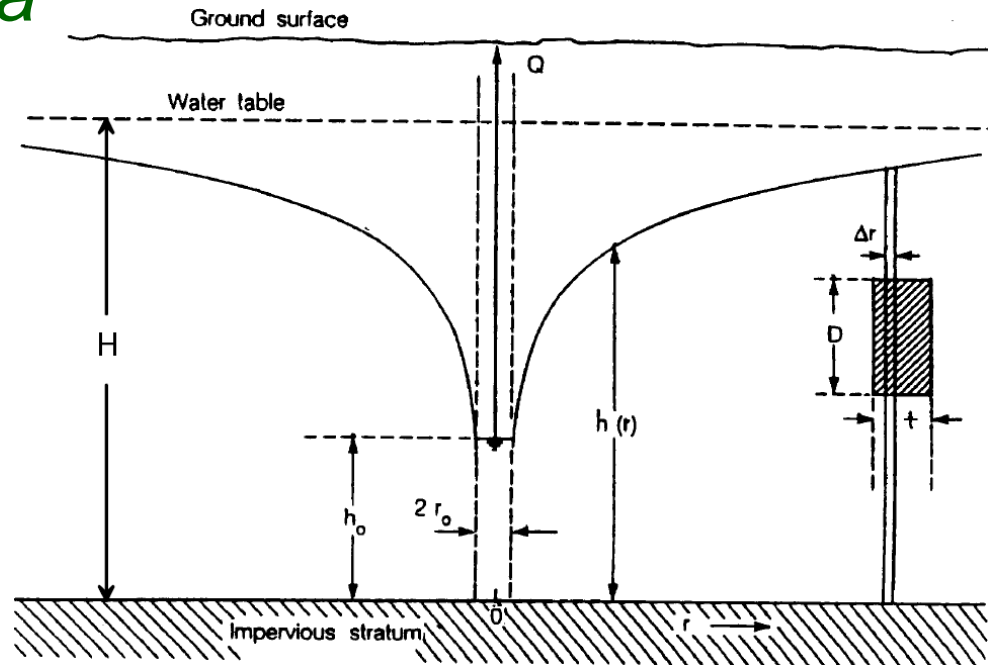
The radius of influence of the well R is:

$$\ln \frac{R}{r_o} = \frac{\pi k \{ H^2 - h_o^2 \}}{Q} \quad (66)$$

Propagation in media

– Example # 2

$$\ln \frac{R}{r_o} = \frac{\pi k \{H^2 - h_o^2\}}{Q} \quad (66)$$



Don't need detailed solution.

See well distance r away from a shaded box representing an activation zone at an accelerator.

- ✓ The whole zone is below the water table (conservative assumption)
- ✓ The whole zone is within the cone of influence of the well

Cylindrical shell of volume $\Delta V = 2\pi r h(r) \Delta r$ yields $Q \text{ d}^{-1}$ of water.

Propagation in media – Example # 2

Cylindrical shell of volume

$\Delta V = 2\pi r h(r) \Delta r$ yields Q d⁻¹ of water.

If $\Delta r < t$ a fraction F of the
activation zone is included

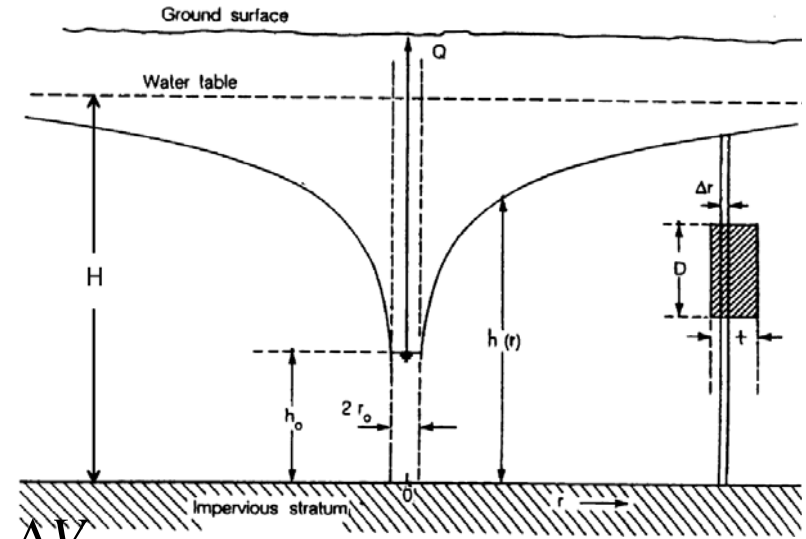
in the shell:

$$F = \frac{\Delta r}{t} = \frac{2\pi r h \Delta r}{2\pi r h t} = \frac{\Delta V}{2\pi r h t} \quad (67)$$

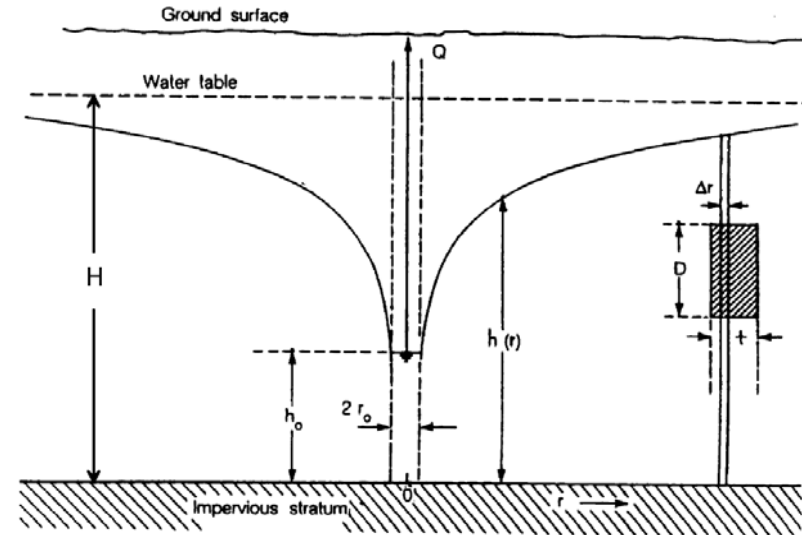
If the activation zone has a total activity A , assuming uniform
activation, the specific activity a in the water drawn is:

$$a = F \frac{A}{Q} = F \frac{A}{p \Delta V} = \left[\frac{\Delta V}{2\pi r h t} \right] \frac{1}{p} \left[\frac{1}{\Delta V} \right] A = \frac{1}{2\pi r t D} \frac{f}{p} A \quad (68)$$

where $f = D/h$, the fraction of height of the shell occupied by the
activation zone. p is, again, the effective porosity.



Propagation in media – Example # 2



$$a = F \frac{A}{Q} = F \frac{A}{p \Delta V} = \left[\frac{\Delta V}{2\pi r h t} \right] \frac{1}{p} \left[\frac{1}{\Delta V} \right] A = \frac{1}{2\pi r t D} \frac{f}{p} A \quad (68)$$

Eq. (68) is:

Useful for simple cases

Requires relatively uniform media to be valid

Not good for sand lenses, cracks in rock strata etc.

$f < 1$ and a minimal value of p can be used for estimates

Activation Detectors

Radioactivation has been used as important part of radiation measurements at accelerators

- Sharp thresholds give useful information about hadron spectra
- Leveling-off of cross sections at high energies is very helpful
- Activation gives us a radiation detector that is free of duty factor limitations
 - Duty factor is the fraction of time a beam is actually present, some accelerators have very small duty factors.
 - Small values of duty factor can render some “live” instruments useless.

Activation Detectors

Table 15 Important characteristics of various nuclear reactions used in activation detectors.

Detector	Reaction	Energy Range (MeV)	Half-Life	Typical Detector Size	Cross Section-Peak (mb)	Cross Section-High Energy(mb)	Particle Detected
sulfur	$^{32}\text{S}(n,p)^{32}\text{P}$	> 3	14.26 d	4 g disk	500 ^a	10 ^a	β^-
aluminum	$^{27}\text{Al}(n,\alpha)^{24}\text{Na}$	> 6	14.95 h	16 - 6600 g	11 ^b	9 ^b	γ
aluminum	$^{27}\text{Al}(n,x)^{22}\text{Na}$	> 25	2.603 y	17 g	30 ^b	10 ^b	γ
plastic scintillator	$^{12}\text{C} \rightarrow ^{11}\text{C}$	> 20	20.33 min	13-2700 g	90 ^b	30 ^b	β^+, γ
plastic scintillator	$^{12}\text{C} \rightarrow ^7\text{Be}$	> 30	53.22 d	17 g	18 ^b	10 ^b	γ
mercury	$^{198}\text{Hg} \rightarrow ^{149}\text{Tb}$	> 600	4.12 h	up to 500 g	2 ^b	1 ^b	α, γ
gold	$^{197}\text{Au} \rightarrow ^{149}\text{Tb}$	> 600	4.12 h	0.5 g	1.6 ^b	0.7 ^b	α, γ
copper	$\text{Cu} \rightarrow ^{24}\text{Na}$	> 600	14.95 h	580 g	4 ^c	3.9 ^c	γ
copper	$\text{Cu} \rightarrow ^{52}\text{Mn}$	> 70	5.59 d	580 g	5 ^c	4.6 ^c	γ
copper	$\text{Cu} \rightarrow ^{54}\text{Mn}$	> 80	312.1 d	580 g	11 ^c	11 ^c	γ

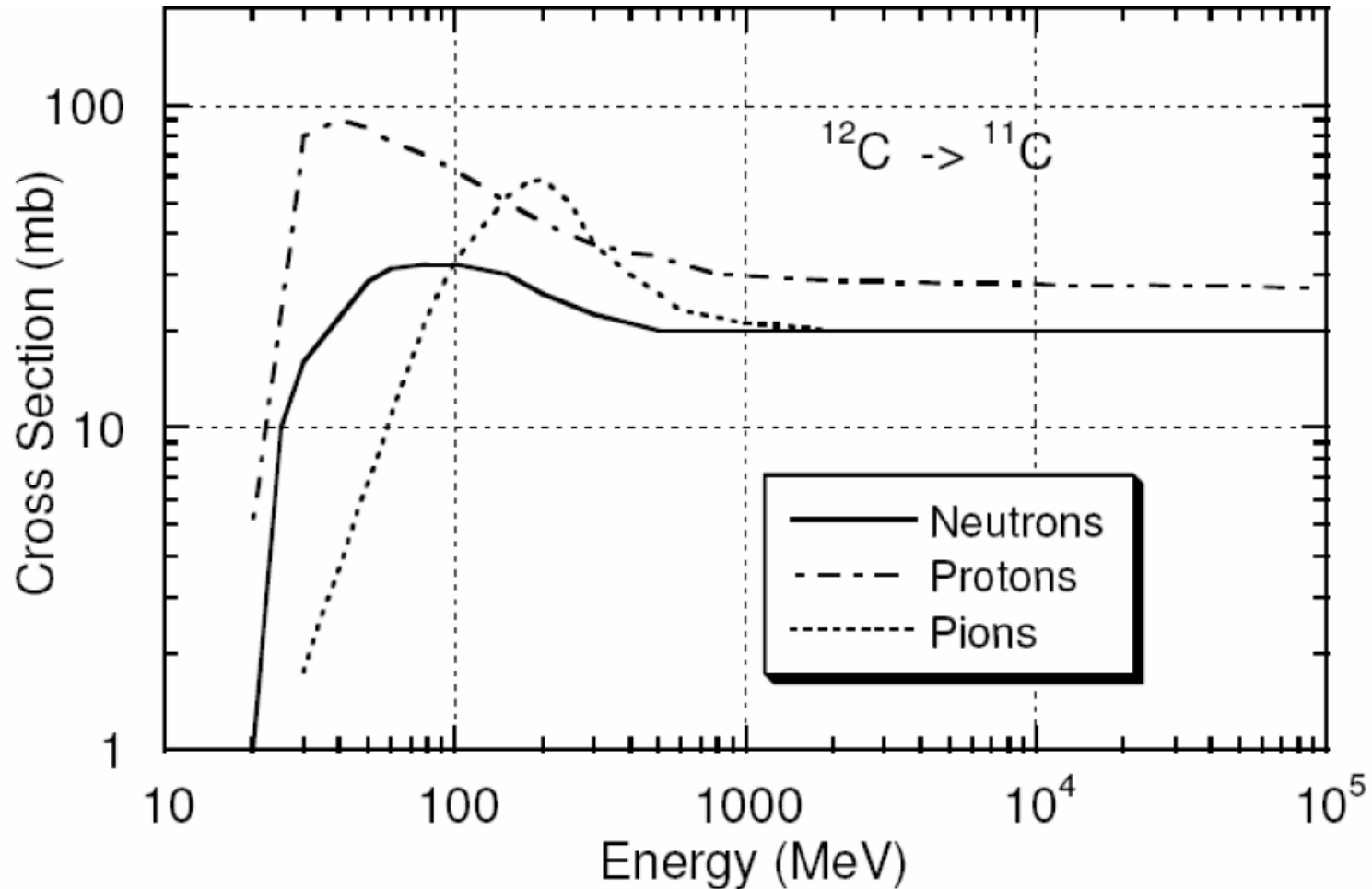
^aSwanson and Thomas (1990)

^bBarbier (1969)

^cBaker et al. (1984) and Baker et al. (1991).

Activation Detectors

Reactions that produce ^{11}C are of special utility (Fig. 19).



Activation Detectors

The reactions that produce ^{11}C are of special utility.

Stevenson found that 28 fSv m^2 ($2.8 \times 10^{-4} \mu\text{Sv cm}^2$) can be used to convert measured fluence of neutrons with $E_n > 20 \text{ MeV}$ to the dose equivalent due to them

Typical accelerator shield spectrum found outside earth or concrete is assumed.

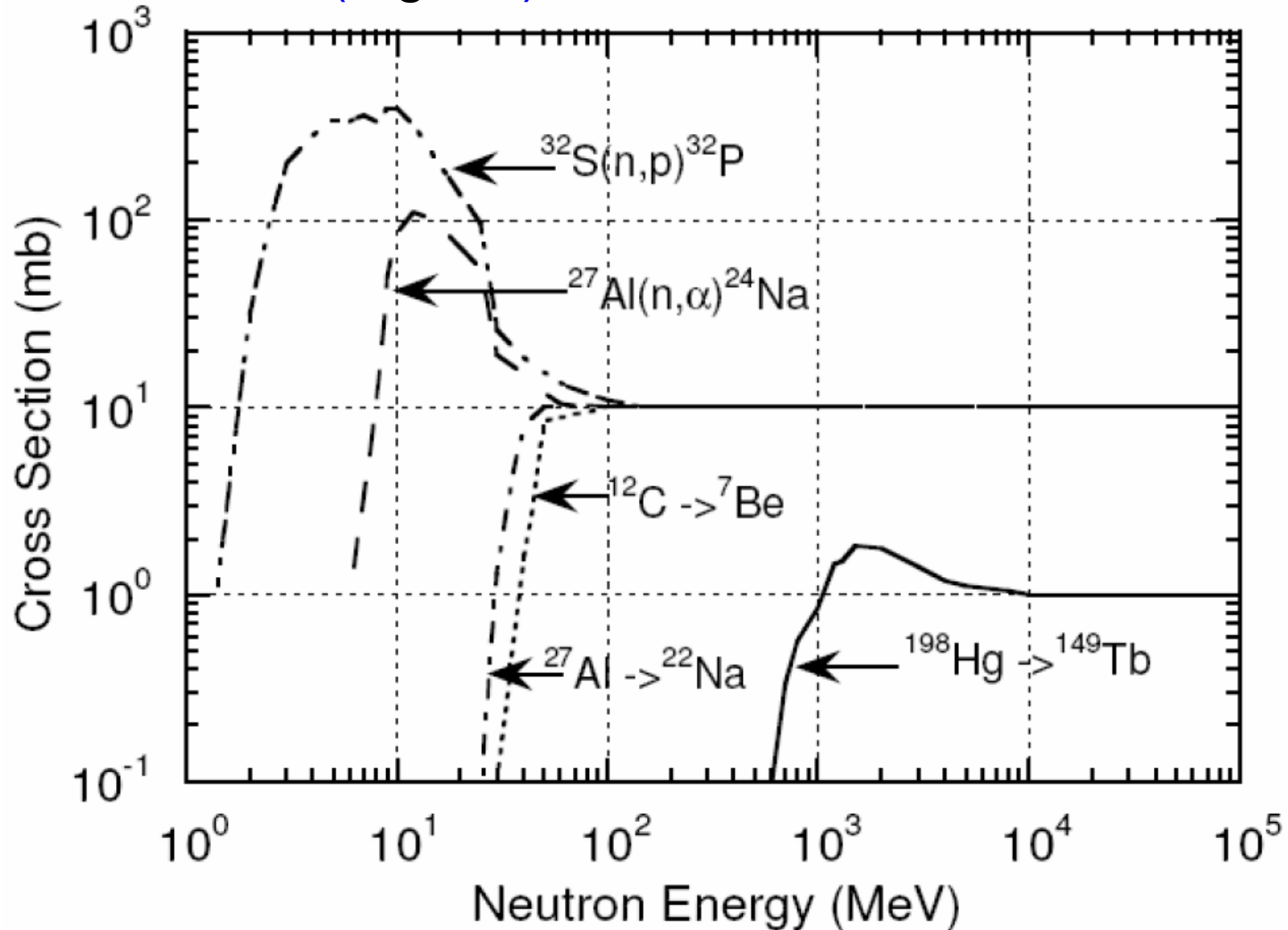
Can use to estimate high energy component of spectrum

^{11}C activation is useful if plastic scintillators are used to detect neutrons using the carbon in the scintillator.

Text refers reader to work by Moritz (1989) in using this to supplement Bonner sphere measurements in the higher energy neutron region.

Activation Detectors

More reactions (Fig. 20):



Activation Detectors

Table 15 Important characteristics of various nuclear reactions used in activation detectors.

Detector	Reaction	Energy Range (MeV)	Half-Life	Typical Detector Size	Cross Section-Peak (mb)	Cross Section-High Energy(mb)	Particle Detected
mercury	$^{198}\text{Hg} \rightarrow ^{149}\text{Tb}$	> 600	4.12 h	up to 500 g	2 ^b	1 ^b	α, γ
gold	$^{197}\text{Au} \rightarrow ^{149}\text{Tb}$	> 600	4.12 h	0.5 g	1.6 ^b	0.7 ^b	α, γ
copper	$\text{Cu} \rightarrow ^{24}\text{Na}$	> 600	14.95 h	580 g	4 ^c	3.9 ^c	γ
copper	$\text{Cu} \rightarrow ^{52}\text{Mn}$	> 70	5.59 d	580 g	5 ^c	4.6 ^c	γ
copper	$\text{Cu} \rightarrow ^{54}\text{Mn}$	> 80	312.1 d	580 g	11 ^c	11 ^c	γ

^aSwanson and Thomas (1990)

^bBarbier (1969)

^cBaker et al. (1984) and Baker et al. (1991).

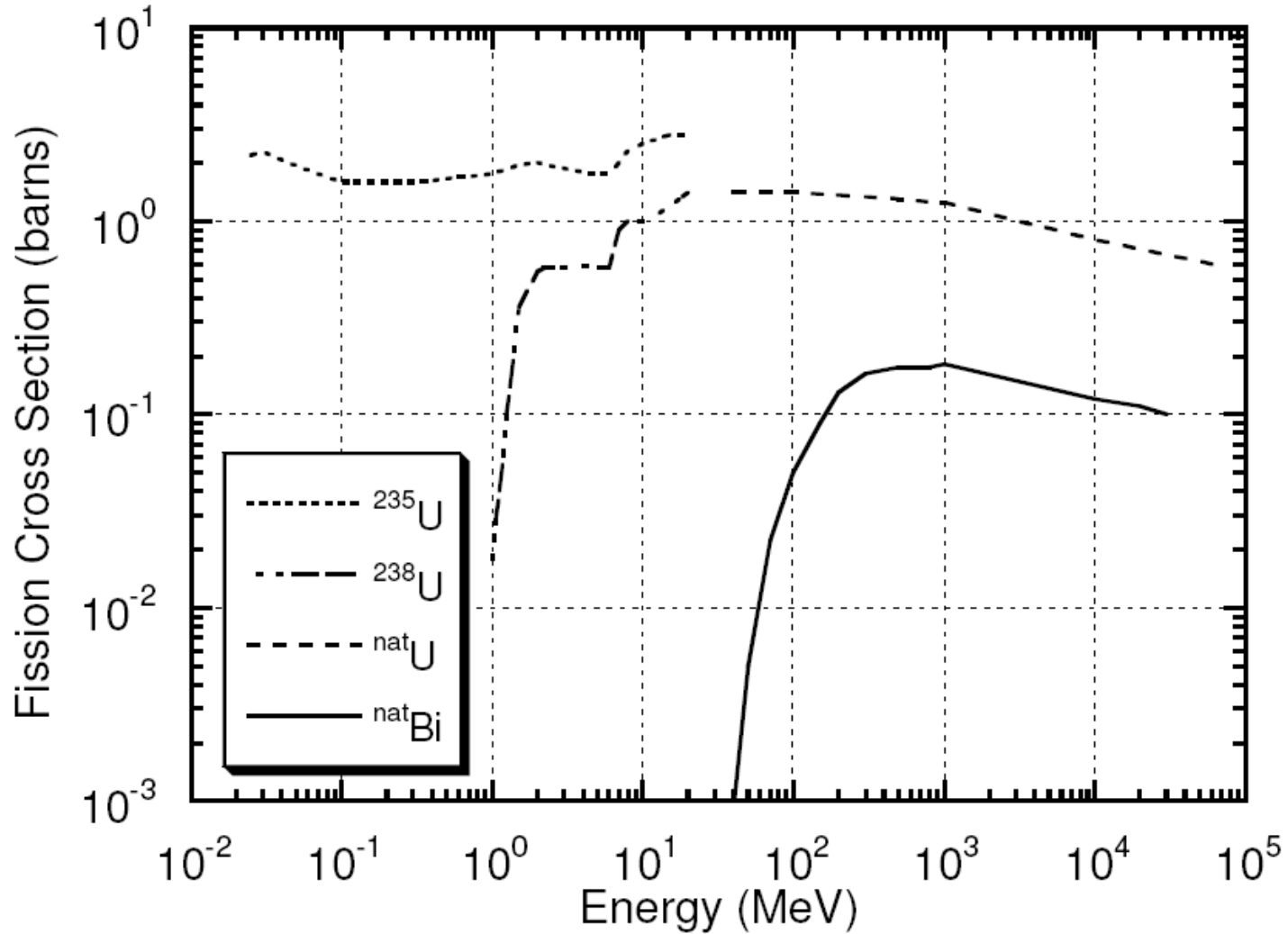
Need high energy detector

^{149}Tb is good, but short-lived (Inconvenient for sample retrieval)

Reactions on Cu work well, have been tested from 30 to 800 GeV.

Activation Detectors

See Fig. 20



Activation Detectors

Fission Reactions

- Very large Q-values (200 MeV)
- Usable thresholds
- Bismuth is especially useful due to high energy threshold.
- McCaslin (1968) used to supplement Bonner sphere data.

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