NuMI Primary Beamline Groundwater Protection

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Groundwater Protection

- Hired several groundwater consultants to determine water levels and flow rates around the unlined regions of the NuMI tunnel.
  - All water within 10' of tunnel flows into the tunnel (within the aquifer region)
  - Most water flows in rapidly through the fractures
  - Determine an average inflow velocity based on groundwater consultant's inflow estimates

- Use the Fermilab Concentration Model, modified to allow for water flow
  - Fermilab Reports TM1851, TM2092, TM2009 (NuMI).
  - Updated to include our latest understanding of groundwater contamination by ^{22}Na and ^{3}H, the only radionuclides of concern (NuMI-B-495)
  - Flow dependent residency time of water in the region of the beamline (inflow or outflow) where applicable.
  - Irradiation time = residency time of the water in the activation region (not 8 years, lifetime of experiment)
    - Normal operation: time water is in the activation region
    - Accident condition: 5 pulses (1.9 sec pulse)

Groundwater Protection

Standard Groundwater Model	NuMI	Resulting Model
Static water	Water flows	Inflow (^{22}Na retarded)
Leaching based on glacial till, 90% leaching volume of water	Dolomite with fractures rock with porosity -> water volume	"Leaching" volume of water is the porosity "volume"
Radionuclide production based on NuMI measurements	Direct production of tritium in water	^{22}Na: FNAL measurement ^{3}H: based on Borak et.al.

$$C_i\left(\frac{pCi}{ml}\right) = \frac{N_p S_{avg} F_i}{0.037}\left[\frac{\lambda_i}{\left(\lambda_i + \frac{v_i}{r}\right)}\left(1 - e^{-\left(\lambda_i + \frac{v_i}{r}\right)t_{ir}}\right)\right]$$

Ci is the concentration of activity due to radionuclide *i* in groundwater flowing into the NuMI tunnel (in picoCuries per milliliter), and

$$F_i\left(\frac{atoms}{star}\right) = \frac{K_i L_i}{n}.$$

The factor (1/0.037) is the conversion factor used to convert disintegrations per second (dps) to picoCuries, and the term in brackets is the buildup/removal factor, accounting for radionuclide buildup, decay and removal due to inflow.

Groundwater Protection

Parameters Defined:

N_p is the number of incident protons per second at the source (protons/sec).

S_{avg} is the average star density per incident proton in a region of unprotected rock close to the source of production (stars/cm^3/proton).

K_iL_i is the atoms per star for isotope *i* that is in the water (atoms/star).

n is the porosity of the rock formation; that is the ratio of the volume of void in the rock (generally filled with water) to the volume of rock (unitless).

t_{ir} is the irradiation time (average residency time in activation volume for flowing water).

λ_i is the inverse mean lifetime of radionuclide *i*, measured in units consistent with those of time t_{ir}.

r is the radial distance from the tunnel wall that defines the volume over which the star density is averaged to determine S_{avg} (99.9% volume, r is about 1-2 meters).

v_i is the flow velocity for radionuclide *i* in water.

Groundwater Protection

- Calculations must be below the regulatory limit including uncertainties (FNAL memo, DOE Environmental Assessment response letter)
  - Use uncertainties in all parameters to determine overall uncertainty
    - **Determine effect on results and add in quadrature**
- Calculations are conservative:
  - Comparing concentrations in inflow water, which will be pumped to the surface, to groundwater limits
  - In "dry" regions, grout less to allow more inflow
  - Model includes worst case conditions, most likely will not encounter (haven't yet!)
    - **Update flow model to incorporate inflow measurements and geotechnical data obtained during construction**
  - Does not include decay during migration to a well
    - **Water along the unlined beamline tunnel can not get to any well other than the NuMI beamline "well"**
  - Does not include dilution & dispersion in transit to a well
- Use Beam Loss Budget System to estimate beam loss (beam loss monitors)

Bottom Line:

- Ensure compliance with monitoring well(s)

Groundwater Protection: Primary Beam

- Three different regions in the extraction/primary beam:
  - Lined tunnel in glacial till
  - Lined tunnel in mixed glacial till/rock (dolomite interface)
  - Unlined tunnel in dolomite
- Each case must be treated differently for groundwater contamination concerns.

- Lined tunnel in glacial till (MI extraction region and first ~125' section of carrier tunnel):
  - Standard Fermilab Concentration model
    - Activation occurs in soil and water (assume for lifetime of facility)
    - Migrates (slowly, ~0.55 cm/year vertical seepage velocity) to the class one groundwater
    - Migration taken into account with R_{till} (1e-5), decay/dispersion factor in transit to aquifer
    - Use an average distance of 10 feet to the aquifer (ranges from 0 to 20 feet)
  - Slow migration to aquifer means not such a problem region.

Groundwater Protection: Primary Beam

- Lined carrier tunnel in mixed glacial till/rock (next ~140' section of carrier tunnel):
  - The flow of water in this region can vary from 4 ft/year to 50 feet/year
    - Depending on the mix of soil and rock.
  - The exact location, extent and soil/rock makeup of this section of the carrier tunnel will not be known until the digging starts.
  - Standard Fermilab Concentration model with a conservative residency time based on a flow away from the tunnel at 20'/year.
    - Velocities estimated by P. Kesich.
    - Velocity direction is horizontal and away from the tunnel (P. Kesich)
    - Conservatively assume the water flows out of the activation region at 20'/year and then is immediately in the class one groundwater.
  - Problem region due to medium migration time (fortunately large aperture):
    - Allows long enough residency time to allow contamination
    - Due to the variable nature of the region, we can not assume any decay/dilution time in transit to the aquifer.

Groundwater Protection: Primary Beam

- Unlined tunnel (last 135’ section of carrier tunnel and pretarget hall):
  - Water flows in at a rate of 800 feet/year (~2 feet/day)
  - Use the “Standard” NuMI Inflow model
  - Lower section of carrier tunnel: beam loss rates not as much of a concern here due to high inflow rates and large aperture
  - Pretarget: beam loss rates are a concern due to smaller device apertures

    (low level DC losses)

Results:

- Based on average star densities over the 99.9% activation volume

  (volume out radially to where star density falls to 0.1% of maximum)

Groundwater Protection: Primary Beam

Preliminary MARS14 Primary beamline results, operational beam losses:

Region	Star Density Limit star/cc/proton	Beam Loss Limit	Location
Lined Carrier Pipe GT Accident	6.4E-04	1.3E+04	HT107
Lined Carrier Pipe (Interface) Accident	2.1E-12	1.8E-04	HT107
Unlined Carrier Pipe Accident	5.7E-10	>1.8E-4	HT107
Pre Target Accident (US)	4.8E-10	6.0E-03	V110-1, HT108
Pre Target Accident (Mid)	6.4E-10	>6E-3	Baffle-1
Pre Target Accident (Shaft)	6.4E-10	>6E-3	Baffle-3
Pre Target Accident (DS)	6.4E-10	>6E-3	Baffle-5

For shaded yellow, note: Limit of 1E-6 for a direct primary beam hit in carrier tunnel, this is prevented except for fault modes such as a vacuum pipe collapse or magnet coil failure.

Groundwater Protection: Primary Beam

- Open apertures and “Autotune” will help keep beam nominal and “clean”

- Enable beam extraction to NuMI only when conditions are nominal (Beam Extraction Permit)
  - Magnet currents within nominal limits this pulse
  - Limit on beam loss last pulse and integrated beam loss (beam loss monitors, Beam Loss Budget System)
  - Interlocked radiation detectors
  - “Clean” Main Injector beam

- Detailed simulations (MARS14) of the primary beamline and possible accident and DC (continuous) loss conditions have been studied.
  - Magnet power supply regulation levels needed to keep losses minimal are obtainable.
  - Strong indication that beam loss monitors (BLM) signals closely track groundwater activation levels.
  - Plan to test as much of the Extraction Beam Permit System and Beam Loss Budget System as possible in the P150 line starting this year.

Groundwater Protection: Primary Beam

Preliminary MARS14 Primary beamline results, normal operation:

- Determine worst loss locations for normal operation
- Leads to power supply regulation (and Main Injector beam) requirements
- With presently envisioned power supply regulation:
  - **All normal (DC) losses in the primary beam region are at least an order of magnitude below what is necessary to meet the groundwater regulations.**
- Main Injector emittance tails and position stability:
  - **No beam loss if less than 3 mm horizontal orbit shift (vertical requirements are very loose)**
  - **Modeled range of emittance and tails:**
    - No beam loss if $\leq 40\pi$ emittance with tails
    - Expect ~ 20π emittance with tails to 40π
- Beam loss monitors look to be very good for tracking groundwater activation.
  - **Use Beam Loss Budget System to keep track of losses.**

Groundwater Protection: Primary Beam

Preliminary MARS14 Primary beamline results, accident losses:

Region	Water residency time (years)	Water residency time (days)	Lost pulses allowed in residency time	Comment
Lined Carrier Pipe GT Accident	8.00000	2920.00	4.E+11	V105, 0.6%
Lined Carrier Pipe (Interface) Accident	1.50919	550.85	125	V104-2, 30%
Unlined Carrier Pipe Accident	0.00487	1.78	204	V104-2, 13%
Pre Target Accident (US)	0.01082	3.95	178	V105, 0.2%
Pre Target Accident (Mid)	0.01821	6.65	656	V105, 0.2%
Pre Target Accident (Shaft)	0.04618	16.86	5799	V105, 0.2%
Pre Target Accident (DS)	0.04028	14.70	16693	V105, 0.2%