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Assessment of Ingestion and Inhalation of Tritiated Water Produced by NuMI Operations

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Assessment of Ingestion and Inhalation of Tritiated Water
Produced by NuMI Operations

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Purpose

The purpose of this note is to assess dosimetric and health consequences of ingesting or inhaling tritiated water, HTO, from waterborne and airborne sources. Standard references will be utilized for this purpose. Where possible, multiple guidance documents produced by DOE, regulatory agencies, and international advisory organizations will be employed[1].

Ingestion of HTO as Drinking Water

The International Commission on Radiation Protection (ICRP) has issued annual limits for intakes (ALIs) of radionuclides by workers. Ingesting one ALI of a single radionuclide corresponds to the delivery of a dose equivalent of 50 mSv (5000 mrem). The ALI for oral ingestion (drinking) of tritium in the form of HTO is 3×10^9 Bq (8.1×10^{10} pCi) (ICRP 79). Values of this quantity for elemental diatomic hydrogen in the form of HT or TT are not given in this reference because they are approximately 4 orders of magnitude larger due to the scant uptake of elemental diatomic hydrogen into body tissues. In practice, exposure to tritiated water (HTO) represents the limiting exposure and the elemental hydrogen forms will not be considered further.

Assume a person uses water containing a concentration of 20 pCi cm^{-3} of HTO as his/her drinking water supply for an entire year. The ICRP has established specifications for "Reference Man". These are average parameters related to humans (ICRP 74) and give the typical level of water intake[2] of an adult male to be 2000 cm^3 day^{-1}. Females and children take in less water per day. This would mean that such a person using this water for normal household purposes would ingest during one year:

$$\frac{20 \text{ pCi}}{\text{cm}^3} \times \frac{2000 \text{ cm}^3}{\text{day}} \times \frac{365 \text{ days}}{\text{year}} = 1.46 \times 10^7 \text{ pCi}.$$

From the definition of one ALI in (ICRP 79), this would correspond to a dose equivalent of

$$1.46 \times 10^7 \text{pCi} \times \frac{5000 \text{ mrem}}{8.1 \times 10^{10} \text{ pCi}} = 0.9 \text{ mrem}.$$

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[1] When comparing such results it should be noted that these various sources commonly issue their results with limited precision. When comparisons are made, "round-offs" constrain their accuracy.

[2] Including only "free" water, not water bound in other chemical substances.

Based upon (ICRP 79), DOE has established Derived Concentration Guides (DCG_{water}) which relate concentrations in water to dose equivalent delivered to the recipient based upon the same ICRP recommendations (DOE 5400.5). If only one radionuclide is present, a person using water containing one DCG_{water} for their personal water supply for a one year period will receive a dose equivalent of 0.1 mSv or 100 mrem. For HTO in water, the DCG_{water} is 2000 pCi cm^{-3}. The user of water containing a concentration of 20 pCi cm^{-3} would thus receive a dose equivalent of

$$20 \text{ pCi cm}^{-3} \times \frac{100 \text{ mrem}}{2000 \text{ pCi cm}^{-3}} = 1 \text{ mrem}.$$

The two results agree within "round off", an outcome reflective of the derivation of the DOE DCG_{water} values from those given by (ICRP 79).[3]

The U. S. Environmental Protection Agency (EPA) has developed multiplicative risk coefficients that directly connect exposures to radionuclides with cancer risks (EPA 99). The values tabulated in (EPA 99) are based on recommendations of the ICRP. The "mortality coefficient" connects intake with the probability of fatal cancer per unit of activity inhaled or ingested. The "morbidity coefficient" connects intake with the probability of cancer diagnosis per unit of activity inhaled or ingested, inclusive of but not limited to those that eventually prove to be fatal. These values are for average members of the public. For purposes of this note, the morbidity coefficients will be used, in recognition of the traumatic nature of any diagnosis of such disease.

For water ingested rather than inhaled, the morbidity coefficient is 1.37×10^{-12} Bq^{-1}. 1.46×10^{7} pCi corresponds to 5.4×10^{5} Bq so the person who uses water having a concentration of 20 pCi cm^{-3} as his household water source for a period of one year has a probability of 7.4×10^{-7} of developing cancer from this source. Should this consumption of water continue for a lifetime, taken to be 75 years in (EPA 99), the lifetime cancer probability from this source would be 5.6×10^{-5}.

One can imagine that a person drinks water having a concentration of 20 pCi cm^{-3} as his/her sole source of fluids for only one day. (EPA 99) gives a value of 1110 cm^{3} as a typical quantity of tap water ingested daily. The resulted ingestion of HTO during this one day consumption would thus be 20 pCi cm^{-3} x 1110 cm^{3} = 22,200 pCi = 821 Bq. The probability of developing cancer from this single event using this methodology is estimated to be 1.1×10^{-9}.

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[3] The USEPA drinking water standard of 20 pCi cm^{-3} set forth in 40 CFR 141 is connected with an annual dose equivalent of 4 mrem, not the 1 mrem obtained here. This apparent inconsistency is due to the fact that in 40 CFR 141, USEPA has chosen to retain NBS (National Bureau of Standards, U. S. Department of Commerce) Handbook 69, as amended August 1963, as the basis of its drinking water standard for radionuclides rather than the more up-to-date, and internationally accepted, model promulgated in (ICRP 79). It is indeed somewhat perplexing that (ICRP 79) was accepted by USEPA in the underlying basis of (EPA 99), but not in nearly concurrent amendments to 40 CFR 141.

Ingestion of HTO in Air Evaporated from the CUB Cooling Towers

Prior to late March 2006, a near-maximal value of the concentration of HTO in the water discharged from the NuMI tunnel into the ICW system was about 20 pCi cm^{-3}. As of this writing, subsequent to the major shutdown of the spring of 2006, the concentration of HTO into this water has been a factor of 3-4 lower due to the addition of considerable dehumidification capacity. The dosimetric and cancer risk consequences of ingesting such water are stated above. One might be concerned about the consequences of breathing air containing such vapor, for example in the visible "cloud" commonly emergent from the Central Utility Building (CUB) cooling towers. In these cooling towers, the water from NuMI is not presently evaporated with complete efficiency. However, for simplicity in this discussion, it will be assumed that the water from NuMI is evaporated with 100 % efficiency and is the only water that is evaporated there with no further dilution. Consultation with FESS confirmed that the maximum temperature of water that is ever evaporated in this process is about 90 °F (32 °C). Consultation of tables of absolute humidity as a function of temperature for barometric pressures characteristic of low altitudes such as the Fermilab site finds that at 30° C (86° F) the saturated water vapor density in the air is 32.7 g m^{-3} (ACGIH 88). At lower temperatures, the saturated vapor density is even less since over the range of temperatures likely to be encountered, this quantity is a monotonically increasing function of temperature. Thus, a value of about 30 g m^{-3} can be taken to be the maximum amount of water present in the air[4]. At lower temperatures, there will be even less water content in the "cloud" that could be inhaled. Thus, it is rather easy to calculate the maximum concentration of tritium in air under these conditions:

$$20\frac{\text{pCi}}{\text{g}_{\text{water}}}\times 30\frac{\text{g}_{\text{water}}}{\text{m}^3_{\text{air}}}=600\frac{\text{pCi}}{\text{m}^3_{\text{air}}}.$$

10 CFR 835 gives values of Derived Air Concentrations (DACs) for radionuclides. Breathing air containing one DAC of a single radionuclide under occupational conditions (i.e., for 2000 hours per year), is correlated with receiving a dose of 5000 mrem per year, the present limit on whole body occupational dose equivalent. The DAC values are derived from the ALIs of (ICRP 79) and are equivalent to them within "round-off" in the associated unit conversions. The value of the DAC for tritium is 2×10^{-5} μCi cm^{-3} = 20 μCi m^{-3} = 2×10^{7} pCi m^{-3}. Thus, the concentration referenced above is 3×10^{-5} DAC. If a person spent their entire working year in this "cloud", this leads to a dose equivalent of 0.15 mrem.

As a cross-check, (DOE 5400.5) also gives DCG values for HTO in air also based on (ICRP 79). From this reference one $DCG_{air} = 1 \times 10^{-7}$ μCi cm^{-3} = 0.1 μCi m^{-3} = 1×10^{5} pCi m^{-3}. Air containing one DCG_{air} of a single radionuclide, if breathed by a person for

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[4] At this and lower temperatures, the evaporation process is less efficient but some of this water may be released in the "cloud" as the droplets or ice crystals that make the cloud visible. A check on this value being "sensible" derived by alternate means is as follows. According to S. Krstulovich, the CUB cooling towers at full capacity mix 1.18×10^{6} ft^3 min^{-1} (3.34×10^{4} m^3 min^{-1}) of air with the water from NuMI (175 gal min^{-1} = 6.62×10^{5} cm^3 min^{-1}). The result is 20 g_{water} m^{-3} of air.

every hour of a given year (8766 hours, non-occupational conditions) is correlated with a dose equivalent in a year of 100 mrem. Thus, the air from the CUB represents 0.006 DCG_{air}. Hence, a person breathing this air would receive a dose equivalent of 0.6 mrem. These results are consistent, reflective of their common origin, when one takes into account the difference in the time durations of the postulated exposure.

For shorter periods of exposure, one can simply scale the above values by the actual time duration of the exposure. For example, if someone is exposed to this air for a time period of one week in an occupational setting, the dose equivalent would be 0.15 mrem x (40 hours/2000 hours) = 3 x 10^{-3} mrem.

The ICRP in its "Reference Man" specifications (ICRP 74) has given a value of 1200 liters hr^{-1} (1.2 m^3 hr^{-1}) for the air inhaled by the average person. Thus, one can calculate the intake of tritium at this concentration for a person who works in such air for an entire year:

$$\frac{1.2\ \text{m}^3}{\text{hour}}\times\frac{2000\ \text{hours}}{\text{year}}\times 600\frac{\text{pCi}}{\text{m}^3}\times = 1.44\times10^6\ \text{pCi} = 5.33\times10^4\ \text{Bq}.$$

(EPA 99) gives a cancer morbidity rate of 1.52 x 10^{-12} Bq^{-1} for HTO in air. Thus the additional cancer risk for a person working in such air for a year is 8.1 x 10^{-8}. The risk for different exposure times would scale linearly according to the duration of the exposure.

Reference (EPA 99) gives the breathing rate for a "typical" person to be 17.8 m^3d^{-1} after averaging over age and gender dependencies and active times as well as sleeping times. This same quantity for a mature male person is 22.2 m^3d^{-1}. If one assumes that a person inhales such air on a full time basis for a period of one year, the following total amount of tritium in HTO would be inhaled:

$$600\frac{\text{pCi}}{\text{m}^3}\times17.8\frac{\text{m}^3}{\text{d}}\times\frac{365.25\ \text{d}}{\text{y}} = 3.90\times10^6\frac{\text{pCi}}{\text{y}} = 1.44\times10^5\frac{\text{Bq}}{\text{y}}.$$

Again, applying the morbidity coefficients, the result is a cancer risk of 2.2 x 10^{-7} per year of exposure in this improbable exposure scenario. The risk for exposures for exposure times would scale linearly with their durations.

HTO Released from the NuMI Ventilation Stacks

Here the hazard from the air released from the ventilation stacks associated with the NuMI beamline (EAV1, EAV2, EAV3 and SR3) will be evaluated. These are based on data collected during January to September 2006. The results presented here are preliminary values as the data is presently being checked and analyzed. These results are normalized to the full design intensity of the NuMI beamline of 4 x 10^{13} protons per pulse at a repetition rate of 1.87 seconds. A bank of dehumidifiers was installed in 2006 in the

Target hall to extract the tritiated air moisture and exhaust it through the SR3 stack. Measurements during the summer of 2006 indicate that the releases from SR3 dominate the ventilation of HTO (97%) in comparison with EAV1 (0.5%), EAV2 (0.5%) and EAV3 (2%). The present measurements lead to an estimated total activity of HTO released in a year[5] of 400 kW operations of 0.17 Ci. Table 1 gives the flow rates and the measured HTO concentration release rates from the stacks.

Table 1 Air flow rates out of the NuMI stacks during the periods of beam-on and beam-off operations.

	EAV1 (cfm)	EAV2 (cfm)	EAV3 (cfm)	SR3 (cfm)
Beam on	1900	750	500	700
Beam off	1900	3070	3500	700

Based on the above flow rates the worst case concentration found at the vent stack is estimated to be about 0.48 μCi m^{-3} at 400 kW, a value larger than the DCG_{air} (=0.1 μCi m^{-3}). Given the nature of the ventilation stacks, it is highly improbable that a member of the public would breathe this air for an extended period right at the stack release point. For purposes of this discussion the presence of other radionuclides released by these ventilation stacks which have been assessed separately (Grossman 04) has been ignored.

Offsite Hazard Due to HTO in Air Released from NuMI

CAP-88 PC, the computer code specified by the U. S. Environmental Protection Agency in 40 CFR 61 Subpart H to be used to calculate doses to members of the public near U. S. Department of Energy facilities has been used to calculate the dose equivalent due to HTO released from NuMI from all sources at the location of the maximally exposed person (Vaziri 2006). These calculations utilized the actual stack height (10.5 feet = 3.2 meters) and diameter (0.48 meters) of EAV2 and an entire year's worth of meteorological data. The location of the maximally exposed person is located 1500 meters directly east of the ventilation stack. Presently, the NuMI sump discharges at a rate of about 170 gallons min^{-1} of water that would have a concentration of typically 27 pCi cm^{-3}, without any collection of the condensate or any dehumidification systems operational. This discharge would amount to the following release of activity if all of the HTO were to be evaporated on site:

$$170\frac{\text{gal}}{\text{min}}\times 3785\frac{\text{cm}^3}{\text{gal}}\times 5.26\times 10^5\frac{\text{min}}{\text{year}}\times 27\frac{\text{pCi}}{\text{cm}^3}=9.14\frac{\text{Ci}}{\text{year}}.$$

[5] To be clear, this estimate does not include an additional HTO, such as chiller condensate, that might eventually be evaporated. If that method of handling the HTO is chosen, these measurements will need to be repeated and this analysis revised. The estimates presented here assume the beam to be operational 62 % of the time.

This value is probably characteristic of the amount of HTO produced by NuMI at half its design intensity, the operating conditions prior to the shutdown of spring 2006. If one can successfully evaporate this HTO, to calculate the dose equivalent and risk offsite, one must, conservatively, add to this the 0.17 Ci annual release from the ventilation stacks and so find that at the design intensity of 400 kW, 18.5 Ci yr^{-1} is likely to be a representative value. In doing this, to some degree, we are double-counting part of the emissions from SR3.

For a release of 18.5 Ci the CAP-88 result is a dose equivalent of 1.2×10^{-4} mrem at the location of the maximally exposed person. This corresponds to a total cancer risk of 5.6×10^{-9} from the morbidity coefficients of (EPA 99). These calculations were also done for a variety of other stack heights and stack diameters. If the stack diameter is increased from the present 48 cm to 4 meters while maintaining the present height, a situation perhaps representative of a large evaporator, the dose equivalent at the maximally exposed person is decreased by about 67%. If the stack diameter is held constant at 48 cm, while increasing its height up to 15 m, the dose equivalent at the location of the maximally exposed person decreases by about 78 %.

Acknowledgments

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