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LMS/RUL/S08087

Screening Assessment of Potential Human-Health Risk from Future Natural-Gas Drilling Near Project Rulison in Western Colorado

Jeffrey I. Daniels
Jenny B. Chapman

February 2011

Publication No. 45237

Prepared by

Division of Hydrologic Sciences, Las Vegas, NV
Desert Research Institute, Nevada System of Higher Education

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S. M. Stoller Corporation, Office of Legacy Management
U.S. Department of Energy, Grand Junction, Colorado

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GLOSSARY OF TERMS

amsl	Above mean sea level (elevation)
ATSDR	Agency for Toxic Substances & Disease Registry (United States)
bgs	Below ground surface (i.e., at depth)
$\boldsymbol{BR_i}$	Breathing rate for [exposed] individual (*i*) for either occupational (*i* = worker) or public (*i* = resident) exposure
$\mathbf{CH_3T}_{gas}$	Tritiated (T = H^3) methane (natural) gas
C_{HTO_V-air}	Concentration of tritiated (T = H^3) water vapor in air (expressed as activity per unit volume)
CCR	Colorado Code of Regulations
CDPHE	Colorado Department of Public Health and Environment
CFR	Code of Federal Regulations (CFR)
COGCC	Colorado Oil & Gas Conservation Commission
DAC	Derived air concentration [equating to the quotient of the acceptable limit of intake and the exposure (by inhalation) -to-dose conversion factor for HTO_v]
derm	Dermal exposure pathway
$\mathbf{H^3}$	Tritium isotope (H^3) of hydrogen [half-life ($t_{½}$) equal to approximately 12.3 y]
$\mathbf{H_2O}$ **and HTO**	Water; and tritiated water (H^3H^3O or H^3HO; expressed as HTO)
HEAST	Health Effects Assessment Summary Table(s) prepared by the United States Environmental Protection Agency (USEPA)
$\mathbf{HTO}_{liquid}$	Tritated (H^3) liquid water
$\mathbf{HTO}_V$	Tritiated (H^3) water vapor (*v*)
inh	Inhalation exposure pathway
$\mathbf{k}_{derm}$	Dermal-absorption constant by which breathing rate (BR) is multiplied to account for absorption of HTO_v through exposed skin
LM	United States Department of Energy Office of Legacy Management
$M_{BY}RC_{HTO_v}^{inh}$	Morbidity (MBY = fatal and nonfatal) cancer risk coefficient (*RC*) for inhalation (inh) exposure to HTO_v [expressed as lifetime excess morbidity cancer risk (R) per unit activity]
MCL	Maximum contaminant level

PHA	Public Health Assessment (performed by ATSDR for accidental tritium released from the Lawrence Livermore National Laboratory between 1965 and 1970)
$R^{i}_{MBY\ HTO_v-inh+derm}$	Lifetime excess morbidity (*MBY*; fatal and nonfatal) cancer risk for an individual (*i*) exposed by inhalation and dermal contact to tritiated water vapor (HTO_v)
res	resident (applicable to public health risk)
SAP	Sampling and Analysis Plan (for Project Rulison)
SGZ	Surface ground zero (above working point for Project Rulison)
$t_{1/2}$	half-life of radionuclide
TE_i	Total exposure over lifetime [d/lifetime] for individual (*i*) for either occupational (*i* = worker) or public (*i* = resident) exposure
US	United States (also U.S.)
USAEC	United States Atomic Energy Commission
USDOE	United States Department of Energy
USEPA	United States Environmental Protection Agency
USNRC	United States Nuclear Regulatory Commission
wkr	worker (applicable to occupational health risk)

INTRODUCTION

The Project Rulison underground nuclear test was conducted in 1969 at a depth of 8,400 ft in the Williams Fork Formation of the Piceance Basin, west-central Colorado (Figure 1). The U.S. Department of Energy Office of Legacy Management (LM) is the steward of the site. Their management is guided by data collected from past site investigations and current monitoring, and by the results of calculations of expected behavior of contaminants remaining in the deep subsurface.

The purpose of this screening risk assessment is to evaluate possible health risks from exposure to Rulison contaminants so the information can be factored into LM's stewardship decisions. For example, these risk assessment results can inform decisions regarding institutional controls at the site and appropriate monitoring of nearby natural-gas extraction activities. Specifically, the screening risk analysis can provide guidance for setting appropriate action levels for contaminant monitoring to ensure protection of human health.

Human health and the environment are protected from radionuclides remaining in the deep subsurface from the Rulison test by three mechanisms, including 1) administrative directives and restrictions (institutional controls), 2) the geologic properties of the gas-bearing formation, and 3) monitoring.

Institutional controls restrict drilling below 6,000 ft in Lot 11 (where the nuclear test occurred), and restrict the removal of any material from within Lot 11 at those depths (Figure 2). As a result, contaminants would need to migrate through the subsurface for them to enter a gas well and reach the accessible environment.

The Williams Fork Formation is characterized by very low permeability sandstone lenses isolated by surrounding shale. Commercial production of natural gas requires hydraulic fracturing of these sandstones. Natural-gas production experience in the area shows that these hydrofractured wells can be located on 10-acre spacing without experiencing communication between wells (Williams Production Company, 2006).

LM and the Colorado Oil and Gas Conservation Commission (COGCC) have developed and implemented monitoring plans for natural gas wells near Project Rulison. The plans call for increased frequency in sampling of natural gas and produced water (i.e., water co-mingled with the natural gas stream) for wells close to the site. To date, no Rulison-related contaminants have been detected.

Geologic data from nearby production wells, current and historical monitoring data, historical nuclear-test information, and transport modeling calculations (Cooper *et al.*, 2007, 2009, and 2010; Ye *et al.*, 2009) indicate that contamination from the Rulison nuclear test is confined to the 40-acre lot (Lot 11) surrounding the test and will not migrate beyond the lot boundary in the future (see "Plan View" in Fig. 2). Nonetheless, LM has decided to determine the potential human health risk in the event that contaminant migration does occur. This will allow LM to consider the following sources of information while managing the site for protection of the public and environment: predictions of contaminant behavior, potential human health consequences in the event the predictions are incorrect, and monitoring data from nearby gas wells.

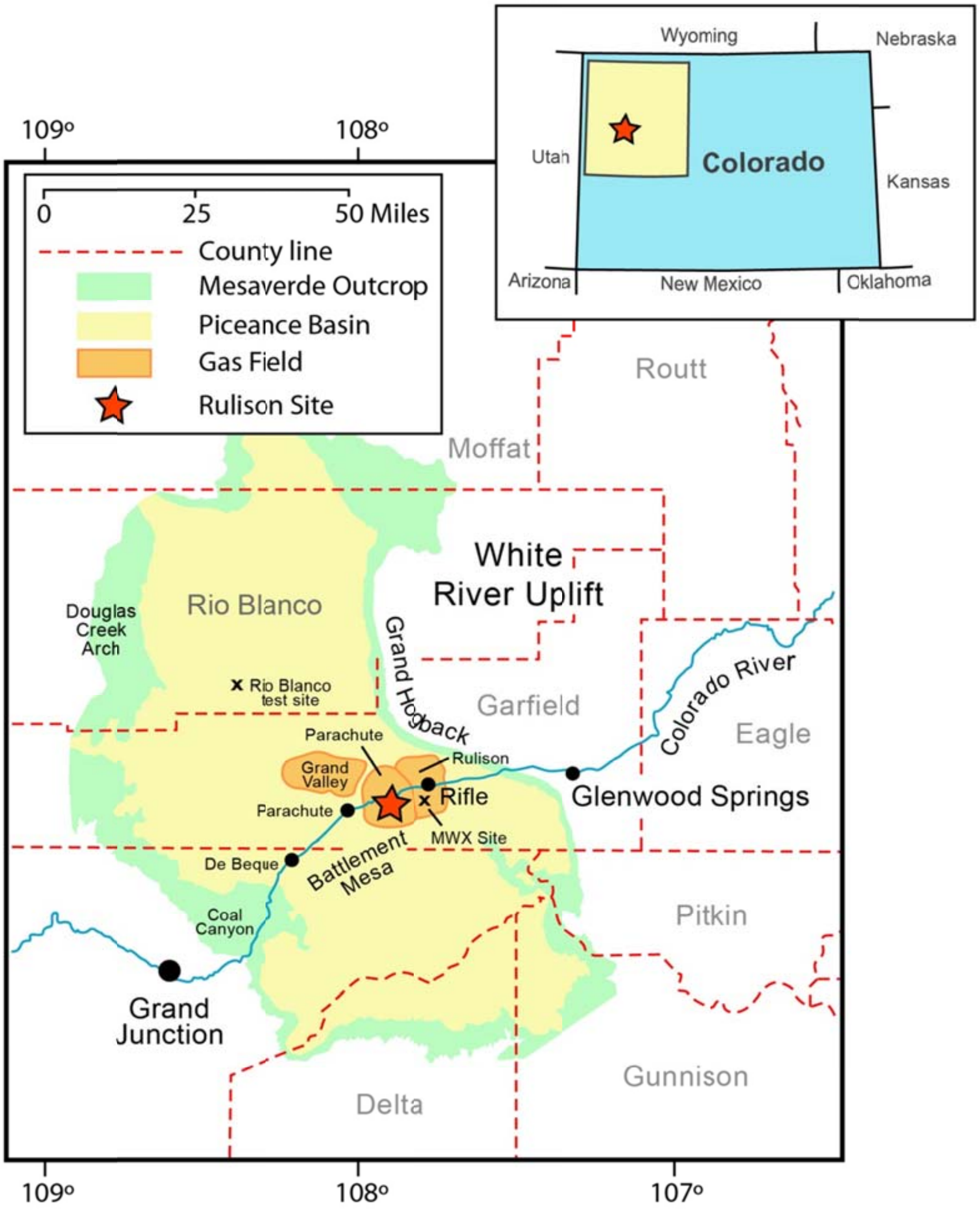

Figure 1. Location map for the Piceance Basin in northwestern Colorado. The Rulison nuclear test site is located in the Battlement Mesa area.

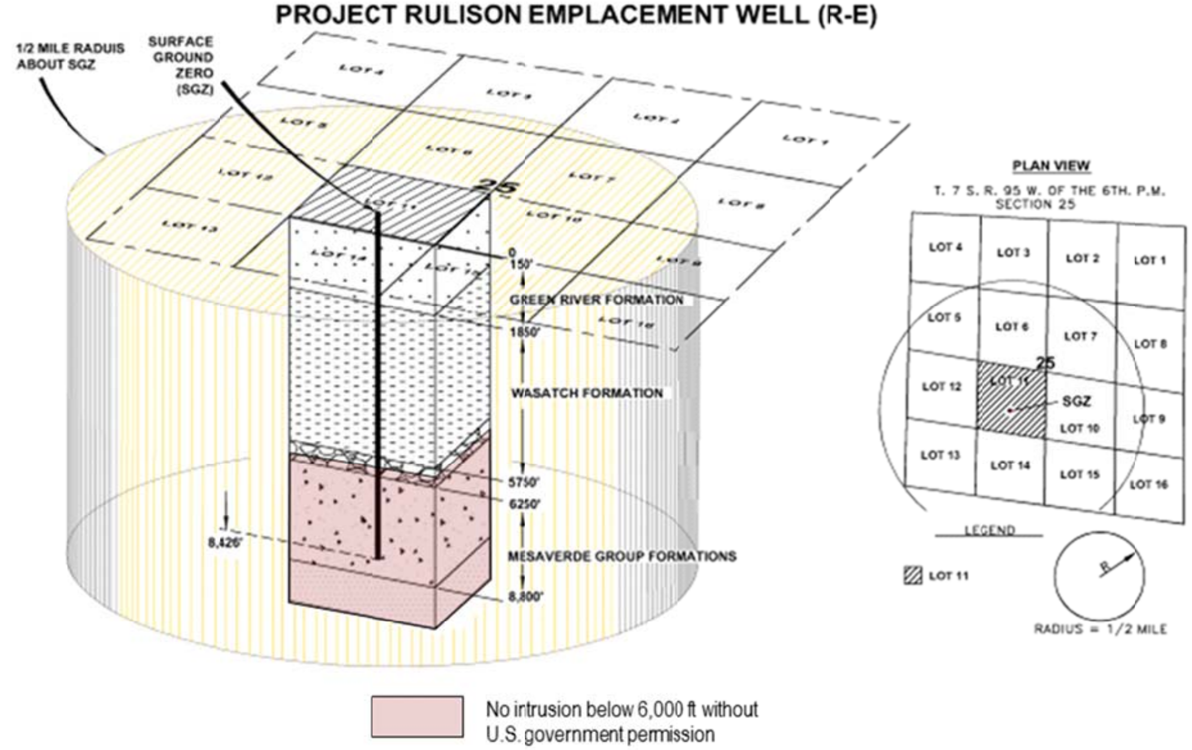

Figure 2. Cross section view of the Rulison nuclear test, denoted by the black line extending from surface ground zero to the detonation depth. The institutional controls restrict drilling in Lot 11 below a depth of 6,000 ft. From a presentation by the US DOE to COGCC on 7-15-09.

This screening assessment of potential human-health risk does not attempt to estimate the probability of exposure. The flow and transport modeling indicate that the geologic properties of the Williams Fork Formation, existing site management controls, and gas-well development practices will prevent migration of Project Rulison radionuclides beyond Lot 11 to future nearby gas wells, and then to the accessible environment. Based on that information, a classic risk assessment considering probability of exposure and consequence of exposure would result in no health risk because there is no probability of exposure. In order to provide decision makers with information about the consequences in the event the unexpected occurs, the risk evaluation simply assumes exposure occurs. This allows examination of possible human health impacts, but the reader must remember that all information (monitoring data and modeling calculations) indicates that exposures have not and should not occur.

Several recent publications have summarized historic information about the Rulison nuclear test and current activities in the area. The reader is directed to the "Rulison Path Forward" (USDOE, 2010a) and the "Rulison Monitoring Plan" (USDOE, 2010b) for concise descriptions of the site conditions, and to Cooper *et al.* (2007) and USAEC (1973) for more detailed discussions. These documents can be obtained from the LM internet site at http://www.lm.doe.gov/Rulison/Documents.aspx. The pertinent characteristics of the nuclear test are summarized in Table 1.

Table 1. Description of pertinent characteristics of Project Rulison[a]

Characteristic	**Description**
Sponsor/Purpose	• Joint industry/government sponsored experiment under the Plowshare Program (for peaceful uses of nuclear energy) of the United States Atomic Energy Commission [USAEC; and predecessor agency to U.S. Department of Energy (USDOE)]; • Proof-of-concept test of the economic and technical attainability of using underground nuclear explosions for natural-gas stimulation in low permeability, gas-bearing formations.
Location	• The Piceance Basin in western Colorado; • 40 mi (≈ 65 km) northeast of the city of Grand Junction; and about 6.3 miles southeast of Parachute, CO, above Battlement Creek, (Longitude 107°, 56′, 53″ *west*; and Latitude 39°, 24′, 21″ *north*).
Depth of working point	• Approximately 8,400 ft (about 2,600 m) below ground surface (bgs) in the low-permeability sandstones of the Williams Fork Formation of the Mesaverde Group; and • Emplacement-hole wellhead elevation ≈ 8,154 ft (2,500 m) above mean sea level (amsl).
Date and time of detonation	• September 10, 1969; at 15.00 h MDT.
Estimated yield	• 40 kiloton (kt) of TNT-explosive equivalent.
Structures and dimensions	• Cavity: radius ≈ 76 ft (23 m), and volume (expected value) ≈ 3.5×10^6 ft^3 (1×10^8 L); • Chimney: largest radius ≈ 78 ft (24 m), and height ≈ 275 ft (84 m)]; and • Fracture zone: high permeability region extending radially around cavity and chimney ≈ 209 ft (64 m).

[a] Compiled from data appearing in Nork and Fenske (1970); Fort *et al.* (1972); URS Corporation (2008); and USDOE (2010b).

The risk analysis contains the following sections. First the selection of tritium in water vapor as the hazard (constituent of concern) is discussed. Next, exposure scenarios are described that analyze pathways for Project Rulison tritium to reach humans. There are two basic scenarios; one for a worker on a gas well, and one for a resident. The risk calculation process is presented, along with the results. Uncertainty in the results is then examined for each parameter in the risk calculation. Implications of the risk results for environmental monitoring are explored. The conclusion summarizes the findings and puts them in context with health standards and regulations.

HAZARD IDENTIFICATION

This assessment is specific to hazards related to contaminant transport from the Project Rulison underground nuclear test. Significant health and safety hazards can be present in any exploration and production of natural gas from geologic reservoirs, but these are not considered here. Instead, the analysis focuses on determining what hazards are present as a result of radionuclides remaining in the Project Rulison nuclear chimney. Detailed descriptions of the underground nuclear test, its radionuclide products, and their disposition in the subsurface can be found in the "Project Manager's Report" (USAEC, 1973), with a more recent summary and analysis in Cooper *et al.* (2007). The following information is from these sources and the references they cite.

The vast majority of radionuclides produced by the nuclear test remain in the rubble-filled nuclear chimney created by the collapse of rock into the cavity void resulting from the nuclear detonation (this "chimney" at Rulison is estimated to be about 350 ft high and 152 ft wide), and most of these are entrained in solidified nuclear melt glass. Though some radionuclides may be present dissolved in liquid water, or have the potential to dissolve in water (H_2O), the very low permeability, partially gas-saturated environment of the lower Williams Fork Formation prevents effective liquid-phase movement. As a result, radionuclides that have a gas-phase are the only ones capable of migration from the nuclear chimney in timeframes of tens to hundreds of years. There was extensive production testing and removal of radionuclide-contaminated gas shortly after the nuclear test. Monitoring data from the produced gas shows that tritium is the only radionuclide remaining in significant quantities in the subsurface that has a gas phase, and the form of the tritium is as part of the water molecule. This means that tritium occurs in water vapor (mixed with the methane gas), and also in liquid water.

Tritiated methane (natural) gas (CH_3T_{gas}) was essentially all removed during the production testing, with measurements indicating that gas produced toward the end of production testing from the chimney was uncontaminated, formation gas.

As a result of the measured radionuclide concentrations in fluids removed from the nuclear chimney, and the measured characteristics of the Williams Fork Formation, the hazard identified is for exposure to tritiated water originating from the Rulison chimney. Migration of the tritiated water (HTO) through the Williams Fork Formation can only effectively occur in the vapor (gas phase) of water; however, the exchange of tritium between gas and liquid phases is rapid. This means that tritiated water vapor (HTO_v) that travels through the subsurface will equilibrate with liquid water (HTO_{liquid}) it contacts, such that tritiated water may be found in either phase. The subsequent analysis therefore considers possible exposure to tritiated water as a result of gas exploration and production near the Rulison test.

EXPOSURE SCENARIOS

Assessing potential impacts to human health from drilling near the Rulison site requires determining the conditions of exposure. One challenge is that there is no current exposure, so these factors in the assessment must be inferred or assumed rather than directly measured. This entails an unavoidable level of subjectivity in selecting parameter values to implement a conceptual exposure scenario. The parameter values applied in this assessment are described below, but it is important to note from the outset that other scenarios may be equally valid. The objective in the selections made here is to realistically represent current practices in the gas industry while including reasonable conservatism (erring on the side of overestimating exposure). A later section examines uncertainty in the scenario parameters.

Two fundamental exposure scenarios are developed; one regarding a worker and another regarding a resident. Each scenario must define what the person is exposed to (concentration and form) and for how long. The tritiated water is currently located in the deep subsurface of the Williams Fork Formation at a depth in excess of 8000 ft. The exposure scenarios thus rely on drilling and production of natural gas to provide a pathway for the tritium, to reach land surface. Both scenarios begin with the assumption that a new well drilled adjacent to Lot 11 encounters HTO originating from the Rulison test. It is important to note here that CH_3T_{gas} is not considered because it was largely removed as a result of post-detonation production and flaring of gas from 1970 to 1971.

This conceptual pathway is as follows:

1. A new well is drilled for the development of natural gas from the lower portion of the Williams Fork Formation;
2. The well is hydrofractured and, due to some unexpected coincidence of formation properties and hydrofracture engineering, a fracture connection is made with the Rulison nuclear chimney;
3. The well undergoes a development process to remove hydrofracturing fluids and optimize well performance. Some liquids removed in this process are captured in tanks on the surface (most of this liquid was initially injected during hydrofracturing). Initially, natural gas along with some entrained liquids typically are discharged into the atmosphere by combustion as a consequence of flaring (burning); and
4. The production phase of the well begins, with sealed piping systems moving gas from the wellhead and eventually to distribution systems. At several points along that pathway, beginning at the wellhead, there are dehydrating steps to remove water vapor (and other impurities) from the natural gas. These dehydrating processes will effectively remove tritiated water vapor from the natural gas during the industrial production process, preventing transfer of tritium to gas customers. There is also mixing with natural gas from many other locations that occurs along the way from wellhead to distribution pipeline.

The method of radioactive decay for tritium is by means of the release of a beta particle, which is a relatively low-energy emission with a range in air of about ten feet. Penetration of this beta particle is blocked effectively by materials such as plastics, clothing, or safety glasses. As a result, health concerns for exposure to tritium arise when there is a route that brings the tritium inside the body into proximity with internal organs, or externally into contact with unprotected skin and eyes. With the pathway described above, the primary opportunity for internal exposure is by means of inhalation during the flaring activity, when a person could inhale HTO_v released to the atmosphere with the natural gas.

Ingestion of HTO_{liquid} is not considered a viable pathway. The quality of produced liquid water is non-potable (due to high salinity, the presence of other hydrocarbons, and hydrofracturing compounds) and it is handled and disposed of per Colorado regulations. The same is true of liquid water condensed and removed from the natural-gas stream.

Given the pathway described above, both the worker and resident exposures are based on inhalation and dermal absorption by exposed skin. The dermal absorption is by virtue of absorption of HTO_v from the humid air surrounding the body. A worker could also experience occasional dermal absorption of HTO_{liquid} as a result of incidental splashes or similar incidents managing liquids during the industrial process.

Worker Exposure Scenario

Several types of workers are considered: a driller/rig worker, a production testing worker, and a compressor station/dehydrator maintenance worker. The production testing worker is likely to have the maximum exposure and thus the conditions particular to that worker are the focus of the worker-risk calculations. The assumptions for each worker type are described below.

Well development generally consists of hydrofracturing, well conditioning, and production testing. Liquids are removed from the well during this process, though the vast majority of these liquids originate from injection in the well during hydrofracturing, in contrast to native-formation fluid. Flaring of development fluids into the atmosphere can occur for about 30 days and it is assumed that the production testing worker is onsite during that entire period, breathing the flared HTO_v, with exposed skin absorbing HTO_v from the humid air. This worker may also have incidental contact with HTO_{liquid}, but this is expected to be minimal as a result of industrial health and safety practices for liquid management (e.g., clothing requirements such as long-sleeved shirts; work gloves; safety glasses). Thus, the exposure duration for the production testing worker is 30 days.

For a driller/rig worker, exposure would occur as a well is drilled. Though it requires about 90 days to drill a Williams Fork well, the majority of this time is drilling through overlying formations. The vertical extent of the nuclear chimney in the subsurface is approximately 350 ft. At a relatively slow drilling rate of 100 ft/day, there would be approximately four days during which fluids coming up hole on the rig could originate from the depth of the nuclear test chimney. Though fluids (gas and liquid) will be coming to the surface from the depth of concern for these four days of drilling, the worker does not necessarily have sustained exposure to HTO_v over that entire timeframe and any direct contact with liquids would only be incidental. Nonetheless, if four days of sustained exposure is assumed conservatively, this duration still represents a much smaller exposure duration than that of the production testing worker described above.

A compressor station/dehydrator maintenance worker is not usually in contact with the fluids involved at these facilities. Liquids are removed from the natural-gas stream at several locations in the process (e.g., at the wellhead, at compressor stations) but maintenance of these facilities is automated such that workers do not spend time in contact with the liquids or in enclosed spaces with water vapor equilibrated with the liquids. Gas and liquids at compressor stations and similar facilities also represent the accumulation of fluids from many wells such that any contaminant concentrations would be diluted and thereby prove to be insignificant with respect to exposures and relative to concentrations possible at the source well. As a result of these factors, the other worker scenarios entail higher potential exposure.

Resident Exposure Scenario

Tritiated methane (natural) gas (CH_3T_{gas}) was confirmed removed from the Rulison chimney by measurements made during the production testing in 1970 and 1971 (USAEC, 1973). Consequently, today natural gas use by the public does not represent a route of exposure. Additionally, as already described, any residual HTO_{liquid} that might be present in the gas would be insignificant, as a result of removal by dehydration equipment and dilution by gas from multiple wells prior to distribution. Therefore, any residential exposures as a result of distribution of the gas to a home would be of no consequence.

The resident that is the receptor of concern here is an individual living near the site of the newly drilled well. The resident exposure scenario parallels that of the worker in that flaring activities during well development and production testing are assumed to release tritium to the atmosphere and it is assumed that the resident inhales it and absorbs humid air through exposed skin. The exposure duration is 30 days, coinciding with the typical length of time for flaring during well development and production testing in the area.

Any exposure of the public to HTO_{liquid} removed from the gas stream is considered to be much smaller than the scenario involving exposure to flared gas. Water removed by dehydrators represents liquids from many gas wells, only a small fraction of which could be located adjacent to the Project Rulison test. In the unlikely event that tritium is present in water produced from one of the wells, it would be significantly diluted by liquids collected from other wells. Atmospheric dispersion of water vapor originating from collection ponds, and mixing with water vapor in the atmosphere from other sources, would cause additional reductions in concentration that would result in lower contaminant levels than would be present in flared gas.

Exposure Concentration

The worker and resident scenarios identified above describe inhalation and dermal exposure to HTO_v released during flaring. The concentration of that HTO_v cannot be measured because there is no current release. Calculations to predict future concentrations cannot be used because they have concluded that no migration of tritium above background concentrations will occur beyond the Lot 11 boundary (Cooper *et al.*, 2009, 2010). Instead of speculating about concentrations of HTO_v during flaring from a future well, measurements of HTO_v in atmospheric moisture from the flaring of gas at Project Rulison are used.

After the detonation, the nuclear chimney was intercepted by a well and production testing was conducted to assess the effectiveness of the test for enhancing natural-gas production. The produced gas was flared into the atmosphere and air sampling was conducted by project personnel, with independent atmospheric sampling conducted by the Colorado Department of Health (USAEC, 1973).

The highest atmospheric tritium concentration reported in the Rulison Manager's Report (USAEC, 1973) is 290 pCi/m^3, measured at the beginning of flaring operations at a sampling pad about a half mile from the flare stack. Using the value of 290 pCi/m^3 as the concentration of HTO_v that can be inhaled and absorbed through exposed skin by both a worker and a resident is considered to be a conservative assumption. This HTO_v concentration is an atmospheric measurement resulting from gas produced directly from the nuclear chimney. Concentrations of radionuclides measured in the gas flared from the Project Rulison chimney in 1970 and 1971 decreased from this value as gas was produced and replaced by uncontaminated formation gas. Additionally, radioactive decay has reduced remaining radionuclide amounts. For example, the half-life of tritium ($t_{½}$) is approximately 12.3 years, such that radioactive decay would reduce the 290 pCi/m^3 concentration measured in the atmosphere in 1971 to a value today (after 40 years) of about 30 pCi/m^3.

Scenario Summary

The exposure scenario assumes that HTO_v is encountered during drilling a new gas well adjacent to the Rulison nuclear test. It is assumed that HTO_v is released to the atmosphere for 30 days as a result of flaring during production testing operations at the well. The concentration of tritium in atmospheric HTO_v is assumed to be 290 pCi/m^3, based on the highest measurement reported during the flaring of gas produced directly from the chimney during Project Rulison. Workers and residents are assumed to inhale air containing 290 pCi/m^3 tritium concentration, and to absorb it through their exposed skin from humidity in the air. Workers may also have incidental splashes of HTO_{liquid}, but that absorption is assumed minor compared to the skin absorption of atmospheric tritium. Though the worker and resident scenarios are similar, the risk calculations differ as a result of different assumed breathing rates. The details of these worker and resident risk calculations are presented in the next section.

SCREENING ESTIMATES OF HUMAN-HEALTH RISK

A screening calculation is performed for determining prospectively the occupational and public human-health lifetime excess morbidity (i.e., includes both fatal and nonfatal) cancer risks that could result from estimates of exposures to activity concentrations of HTO_v in air described in the exposure scenarios above.

Based on expert recommendations, the Agency for Toxic Substances & Disease Registry (ATSDR) in a public health assessment (PHA) focusing on tritium released into the atmosphere and subsequent exposures chose to account for dermal absorption conservatively, by multiplying the breathing rate exposure by a factor of 2 (ATSDR, 2003).[*] Although others, such as Hamby (1993), used a factor of only 1.5 for this purpose, in this screening assessment breathing rate will be multiplied by the more conservative dimensionless constant of 2.0 in order to account for potential dermal absorption of HTO_v. Although this approach for addressing the dermal exposure pathway is simplistic and semi-quantitative, it is nevertheless conceptually valid and sufficiently conservative to conform to the precautionary nature of a screening risk assessment. Further, the daily-average breathing rates selected for a prospective worker (30 m^3/d) and for a prospective resident (20 m^3/d) are considered to be representative of upper limits for adults. The occupational breathing rate exceeds the residential one because the level of activity and metabolism required by adults performing drilling, production, and maintenance activities in the field are certain to be more demanding more consistently than in the case of an average healthy adult in a residential setting.

Occupational and public human-health morbidity (i.e., fatal and nonfatal) cancer risk from exposures to HTO_v in air are estimated for worker and residents by multiplying together the following factors: 1) a concentration of HTO_v in air, 2) an estimate of the age-averaged lifetime excess cancer morbidity risk coefficient, 3) a daily breathing rate for either a worker or a resident, 4) the dermal absorption factor that accounts for penetration of the skin by HTO_v, and 5) the total duration of lifetime exposure.

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[*] Based on results of discussions between the authors M.W. Evans, PhD, and P. Charp, PhD, in the Division of Health Assessment and Consultation at the Agency for Toxic Substances & Disease Registry (ATSDR) in the United States and subject-matter experts [R.V. Osborne, PhD, at *Ranasara Consultants, Inc.*, Deep River, Ontario, Canada (and former Director of the Health & Environmental Sciences Division at Chalk River Laboratories, Ontario, Canada); and K. Eckerman, PhD, Leader of the Dosimetry Research Team at Oak Ridge National Laboratory, Oak Ridge, TN].

This calculation is expressed mathematically and symbolically by Eq. (1), with the symbols and the units explained immediately following:

$$R^{i}_{MBY\ HTO_v - inh+derm} = C_{HTO_v - air} \times M{\scriptstyle BY}RC^{inh}_{HTO_v} \times (BR_i \times \mathrm{k}_{derm}) \times TE_i \qquad \text{Eq. (1)}$$

where

$R^{i}_{MBY\ HTO_v - inh+derm}$ = Lifetime excess morbidity *(MBY)* cancer risk for individual worker (*I* = *wkr*) or resident (*i* = *res*) from both inhalation (*inh*) and dermal (*derm*) exposure to tritiated water vapor (HTO$_v$) — expressed in units of lifetime attributable radiation cancer incidence (fatal and nonfatal);

$C_{HTO_v - air}$ = activity concentration of HTO$_v$ in air — expressed in units of activity per unit volume of air (pCi/m^3);

$M{\scriptstyle BY}RC^{inh}_{HTO_v}$ = Central estimate of the age-averaged lifetime excess cancer morbidity *(*MBY*)* risk coefficient[†] (*RC*) for inhalation of tritiated water vapor (HTO$_v$) — expressed in units of lifetime attributable radiation cancer incidence (fatal and nonfatal) per unit of HTO$_v$-[radio]activity inhaled (e.g., $R^{inh\text{-}HTO_v}_{MBY} / \mathrm{pCi}_{HTO_v}$) and calculated to be equal to 5.62 × 10^{-14} R/pCi (as expressed in the Health Effects Summary Table (HEAST)[†].

$BR_i \times \mathrm{k}_{derm}$ = Breathing rate for *i* = *wkr* or *i* = *res*—expressed in units of volume of air inhaled daily (m^3/d) and multiplied by a dimensionless constant (k$_{derm}$) that is equal to a factor of 2 to account conservatively for dermal absorption of HTO$_v$ through the skin at a rate equal to the breathing rate (ATSDR, 2003).

TE_i = Total exposure over lifetime for *i* = *wkr* or *i* = *res* — expressed in units of days over lifetime (d/lifetime)

The representative activity concentration for HTO$_v$ in air used in Eq. (1) is obtained from values measured during gas recovery operations for Project Rulison. Table 2 contains the results for the worker and resident from application of Eq. (1), along with the selected parameter values. Lifetime excess morbidity cancer risk was computed for both the worker and resident based on a 30-d exposure duration.

[†] Morbidity risk coefficient is described in *Federal Guidance Report No. 13* and associated "*HEAST* User's Guide" (see USEPA, 1999) as the probability of both fatal and nonfatal radiogenic cancers per unit activity inhaled of a given radionuclide, and is expressed for tritiated water vapor (HTO$_v$) in Table 2.1 of the *Federal Guidance Report No. 13* (see USEPA, 1999) as "1.52E−12 (Bq^{-1})" and transformed in the "*HEAST* Radionuclide Table" (*op. cit.,* USEPA, 1999) into a value of "5.6200e-14 Risk/pCi" (by multiplying units of *R*/Bq by 3.7 × 10^{-2} Bq/pCi).

Table 2. Estimated occupational and public carcinogenic morbidity risk (R/lifetime) from inhalation and dermal exposure to a hypothetical concentration of tritiated-water vapor (HTO_v) in air represented by the maximum reported atmospheric concentration of HTO_v measured during flaring operations conducted as part of natural-gas recovery at Project Rulison.

Exposed individual	**Hypothetical exposure concentration for HTO_v in atmosphere (C_{HTO_v-air}; pCi/m^3)[a]**	**Estimated total exposure for individual over lifetime (*TE_i*; d/lifetime)**	**Estimated daily breathing rate for exposed individual (*BR_i*; m^3/d)**	**Constant by which *BR_i* is multiplied in order to account for dermal absorption of HTO_v (k_{derm}; dimensionless)**	**Inhalation morbidity risk coefficient for HTO_v (Mby*RC*; *R*/pCi)**	**Estimate of risk per lifetime (*R*/lifetime)**
Worker	$2.9 \times 10^{+02}$	30	30	2	5.62×10^{-14}	3×10^{-08}
Resident	$2.9 \times 10^{+02}$	30	20	2	5.62×10^{-14}	2×10^{-08}

[a] C_{HTO_v-air} is the maximum concentration of HTO_v reported in air on October 5, 1970, during flaring operations, and was obtained at a sampling pad about 0.5 mi (≈ 800 m) from the Project Rulison surface ground zero (SGZ) (USAEC, 1973; p. 107).

Worker Risk

Worker risk is calculated for hypothetical inhalation and dermal exposures to a HTO_v concentration of 290 pCi/m^3. This concentration is the maximum reported from measurements during production testing and flaring of gas from the Project Rulison nuclear chimney (USAEC, 1973), and is not reduced to account for radioactive decay during the 40 years since the measurement was obtained.

An appropriate respiratory rate is identified (30 m^3/d) for metabolism associated with activities on a drilling platform or in performing activities related to production testing. However, dermal absorption of HTO_v through exposed skin is also possible and it is necessary to account for that pathway of exposure too (Peterson, 2008; and Hamby, 1993). As noted previously, it is considered conservative to assess the dermal absorption of HTO by the skin as being equal to that occurring in the lungs as a result of inhalation. Consequently, the breathing rate is multiplied by a dimensionless constant of 2 (see Table 2).

The risk coefficient considered applicable is taken from Federal Guidance No. 13 (USEPA, 1999). The dimensions of this parameter are lifetime excess morbidity (both fatal and nonfatal) cancer risk per unit activity of HTO_v (see Table 2).

The highest estimated worker lifetime excess morbidity cancer risk for inhalation and dermal exposure over 30 d to the atmospheric concentration of HTO_v of 290 pCi/m^3 is presented in the last column of Table 2. The resulting risk value is 3×10^{-08} (3 per 100,000,000).

Resident Risk

For a resident, the exposure concentration for HTO_v in air is again based on the maximum concentration of HTO_v measured in the atmosphere during flaring operations conducted for Project Rulison (USAEC, 1973). This concentration is not decayed from the time of measurement.

For the resident, the applicable breathing rate is multiplied by a factor of 2 (ATSDR, 2003) in order to account conservatively for dermal absorption of HTO_v by exposed skin. As noted earlier, the respiratory rate of 20 m^3/d is less than for a worker because the resident is not considered to be performing the same degree of continuous activity and exertion workers are certain to experience in executing field tasks daily.

As in the case for the worker, the risk coefficient considered applicable is taken from Federal Guidance No. 13 (USEPA, 1999). The dimensions of this parameter are lifetime excess morbidity (both fatal and nonfatal) cancer risk per unit activity of HTO_v (see Table 2).

The estimated resident lifetime excess morbidity cancer risk based on inhalation and dermal exposure over 30 d to the atmospheric concentration of HTO_v of 290 pCi/m^3 appears in the last column of Table 2. The resulting risk value is 2×10^{-08} (2 per 100,000,000).

For the same exposure duration as the worker (30 d) the value for risk for a resident is about 1.5 times lower, the reason being that the BR_{res} and BR_{wkr} differ by exactly a factor of 1.5 (i.e., 20 vs. 30 m^3/d; for resident and worker, respectively).

SENSITIVITY OF RISK RESULTS TO PARAMETER UNCERTAINTY

The values of each parameter in the equation used to compute excess lifetime morbidity cancer risk (Eq. 1) have some uncertainty associated with them. One approach for including that uncertainty in the analysis is to define a range for each parameter and perform the calculation hundreds or thousands of times, randomly selecting values from all the parameter ranges, resulting in a statistical distribution of possible risk values. This quantitative approach is not employed here, but instead uncertainty is evaluated in each parameter individually and the sensitivity of the computed risk is assessed. This is consistent with the screening nature of this analysis. One consequence of this simpler approach is that the focus is only on the upper bound of uncertainty, meaning values that would increase the calculated risk. It is important to recognize that the uncertainty in parameters also includes values that would result in risk much lower than reported here. Each individual parameter—atmospheric exposure concentration, breathing rate, dermal-absorption multiplier, risk coefficient, and exposure duration—is examined below, along with the significance the upper bound of uncertainty could have on the outcome of excess lifetime morbidity cancer risk.

Atmospheric Concentration

The atmospheric concentration of HTO_v considered a realistic upper limit is 290 pCi/m^3, the maximum concentration of HTO_v reported in air on October 5, 1970, during flaring operations, and obtained at a sampling pad about 0.5 mi (≈ 800 m) from the Project Rulison surface ground zero (SGZ) (see USAEC, 1973; p. 107). Although this is the highest reported value from either onsite or offsite monitoring, records question the validity of some of the onsite monitoring measurements, but note that the true values will not be higher than an order of magnitude above the reported measurements (USAEC, 1972). Of these measurements, the highest reported is 83 pCi/m^3 near the flare stack. Applying the order of magnitude correction, it is possible that the highest monitoring value for HTO_v during site flaring activities was 830 pCi/m^3 (ten times the measurement of 83 pCi/m^3), rather than 290 pCi/m^3. This difference is about a factor of three. Even after multiplying the worker and resident levels of risk appearing in Table 2 by this degree of uncertainty, the resulting risk outcomes remain well below a value of 1×10^{-6}.

Risk Coefficient

According to Pawel *et al.* (2007), " … most risk coefficients for inhalation of radionuclides are determined within a factor of 5 or less by current information." This conclusion applies specifically to the risk coefficients for inhaled HTO_v (based on the assignment of the mortality risk coefficient for inhaled tritium vapor to the narrowest of the relatively broad, semi-quantitative "uncertainty categories" used to address uncertainty in the risk coefficient for this radionuclide and exposure mode). Therefore, on the basis of this uncertainty analysis for the risk coefficient for inhalation of tritium vapor, the value of Mby*RC* appearing in Table 2 might be greater by at most a factor of 5, based on the application of the models used for its derivation. Accordingly, an increase by a factor of 5 in the value of the Mby*RC* would yield a corresponding lifetime excess morbidity cancer risk for both worker and resident that would still be less than 1×10^{-6}.

Breathing Rate

The worker and resident breathing rates used to compute worker and resident excess lifetime morbidity cancer risk are 30 m^3/d and 20 m^3/d, respectively. According to OEHHA (2000), a maximum overall breathing rate equivalent for a 63 kg (139 pound) human is estimated to be 43.7 m^3/d. This breathing rate is a factor of about 1.5 times greater than the worker estimate and about 2.2 times greater than the resident estimate. Therefore, even if the worker and resident estimates of risk per lifetime that appear in the last column of Table 2 are multiplied by a factor of 1.5 and 2.2, respectively, the result in each case remains a risk level that does not exceed 1×10^{-6} .

Dermal-Absorption Constant

The dermal-absorption constant is already at its maximum value of 2 (a factor of 1.5 has been used by others). Consequently, this value is not considered to be associated with any uncertainty relative to an alternative less realistic maximum.

Exposure Duration

The exposure duration is estimated based on the typical amount of time a gas well completed in the Williams Fork Formation undergoes well development and production testing involving flaring of gas in the atmosphere. Estimated at 30 days, the duration of that activity may vary from well to well based on formation characteristics and hydraulic fracturing specifics. However, with natural gas as a commercial commodity, there is business interest in limiting the duration of flaring such that it is unlikely to continue more than two or three times the 30 days assumed here.

Another aspect of exposure duration is the assumption that only one contaminated well is encountered. Given recent drilling intensity in the area, many wells could be drilled in the area surrounding Lot 11. The potential wells of most interest, considering current drilling practices and the predominant east-west fracture trend controlling reservoir drainage, are four wells in each of the lots due east and west, and two wells in each of the six lots north and south of lot 11 [this is coincident with the more intense monitoring frequency zone proposed by LM (DOE, 2010b), Figure 3].

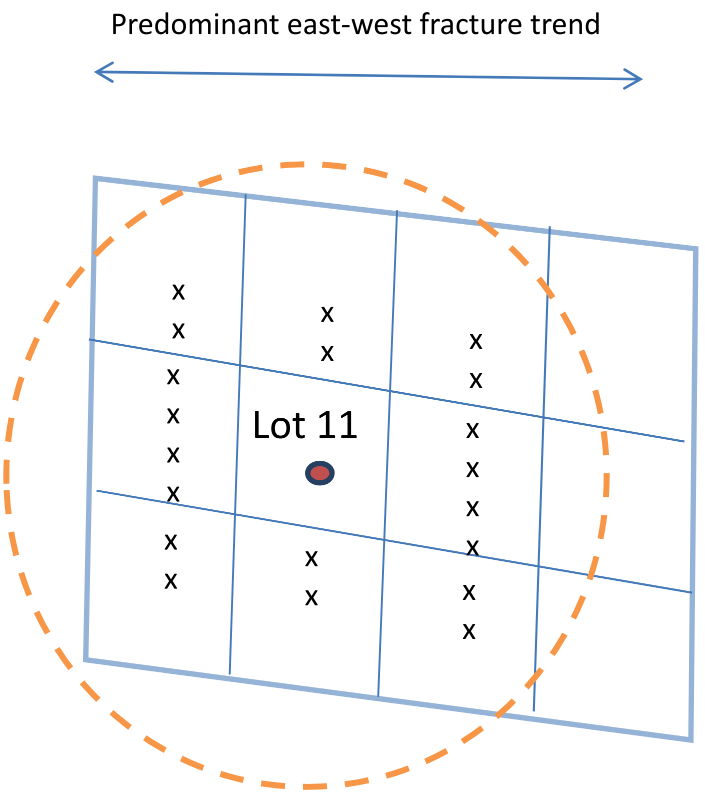

Figure 3. Sketch map of the Rulison nuclear test location, shown as the red circle in Lot 11. Lot boundaries are in blue and a half-mile radius from the test is shown in orange. Hypothetical new gas wells are shown by an "x" in the surrounding lots, located per current well drilling practice in the area.

The concentration of HTO_v used in the exposure scenarios relates to that measured during production testing directly from the Project Rulison nuclear chimney. This concentration can reasonably be applied only to a single well drilled directly into the chimney. If multiple wells encountered tritium, the possible increased exposure time would be offset by the lower concentration of HTO_v. For example, if all the surrounding wells encountered tritium, were flared for 30 days one after another, and the same worker was present throughout, the exposure duration would increase by 20 times (an exposure duration of 600 days). However, the concentration of HTO_v from a well not completed in the nuclear cavity can reasonably be expected to be orders of magnitude lower than the 290 pCi/m^3 assumed here as a result of dispersion during subsurface transport, dilution by uncontaminated gas contributing to the wellbore, and radioactive decay from the time of the measured concentrations 40 years ago. Consequently, a multiple well scenario would present less risk than the single well scenario developed here, and the uncertainty in exposure duration is related only to uncertainty in the length of time for flaring a single well. If a factor of 3 increase in the exposure duration for a worker and a resident occurred, related to uncertainty in flaring duration, the corresponding level of risk for both receptors would remain less than 1×10^{-6}.

Effect of Compounding Upper Bounds of Parameter Uncertainties

The effect of compounded parameter uncertainties on excess lifetime morbidity cancer risk outcomes is determined by multiplying together the respective risk estimates computed in Table 1 by the product of the estimated uncertainties for each parameter with respect to an upper bound. This factor is 1.5 times larger for the resident than the worker because of the difference between selected breathing rates (e.g., for worker the product of compounded uncertainties is ≤ 3 for $C_{HTO_v\text{-}air}$ × ≤ 5 for Mby*RC* × ≤ 1.5 for BR_{wkr} × ≤ 3 for TE = 68; and for the resident the product of compounded uncertainties is ≤ 3 for $C_{HTO_v\text{-}air}$ × ≤ 5 for Mby*RC* × ≤ 2.2 for BR_{res} × ≤ 3 for TE = 100). The multiplication of both worker and resident risk by even the maximum of these compounded values—a factor of 100—reveals from a screening perspective that the resulting risks, which now must be considered extremely overly conservative, remain within the risk range considered by regulatory agencies to be virtually safe or *de minimis* (i.e., from 10^{-4} to $\leq 10^{-6}$).

IMPLICATIONS FOR MONITORING

The activity concentration in air of HTO_v can be related to the activity concentration of tritium (as HTO) in associated liquid-phase water in order to establish health protective risk-based action levels for monitoring production water, as discussed in the "Rulison Monitoring Plan" (USDOE, 2010b). This is possible as a result of the rapid equilibrium obtained between tritiated water vapor and liquid water. By measuring the concentration of one phase, the concentration in the other phase can be determined. For example, the concentration of HTO_v in air that corresponds to a human health risk of 1×10^{-6} in the exposure scenario can be converted to an equivalent concentration of tritium in liquid water (HTO_{liquid}), using the equations presented in the Appendix. If a valid measurement of tritium in product water (HTO_{liquid}) from a well near Project Rulison were to exceed a risk-based action level (i.e., activity concentration), then the well in question can be shut-in until the situation can be assessed further, and nearby wells might have their sampling frequency increased.

Solving for the concentration of HTO in formation water associated with a given level of health risk provides information that may be useful for developing monitoring detection limits and action levels. The maximum activity concentration of HTO_v in air that is associated with a 1×10^{-6} lifetime excess morbidity cancer risk for the worker exposure scenario is 9.9×10^3 pCi/m^3. Similarly, the activity concentration of HTO_v in air that is associated with a 1×10^{-6} lifetime excess morbidity cancer risk for the resident exposure scenario is 1.5×10^4 pCi/m^3 (see Table A-1 in the Appendix).

By converting these concentrations of HTO_v in air for the worker and the resident that correspond to a 1×10^{-6} risk to their equivalent concentrations of tritium as liquid water (HTO_{liquid}), a maximum contaminant level (MCL) for the water can be determined that can be used conveniently and effectively for monitoring purposes to establish action levels that would prevent concentrations in air that could lead to health consequences. Thus, concentrations of HTO_v in air for the worker and the resident that correspond to a 1×10^{-6} lifetime excess morbidity cancer risk can be converted into activity concentrations for HTO_{liquid} that range from 6.6×10^5 pCi/L to 1.9×10^6 pCi/L for a worker during summer and winter atmospheric conditions, respectively, at Rulison; and from 9.8×10^5 pCi/L to 2.8×10^6 pCi/L for a resident during summer and winter atmospheric conditions, respectively, at Rulison (see Table A-1 in the Appendix). Accordingly, the lowest concentration in water identified here, 6.6×10^5 pCi/L for the worker under summer atmospheric conditions, is one option for an action level during monitoring. Even though produced water from natural-gas recovery near Project Rulison is not suitable as drinking water, for purposes of comparison, the maximum contaminant level (MCL) for tritium in the National Primary Drinking Water Regulation (NPDWR) is 2×10^4 pCi/L.

A similar analysis was performed for the Gasbuggy underground nuclear test site (another natural-gas stimulation test). The Gasbuggy results (USDOE, 2010c) derived different HTO_{liquid} concentrations associated with a worker and resident risk level of 1×10^{-6}. The primary reason for this difference is that the exposure scenarios defined for Rulison and Gasbuggy differ, particularly in the number of days of exposure, and the atmospheric conditions used to derive a concentration of HTO_{liquid} were different. Also, Rulison includes a dermal exposure route that is absent from the Gasbuggy analysis.

Interestingly, the Gasbuggy analysis also includes consideration of dose-based limits for HTO_v exposure, which is not performed in this assessment. The Gasbuggy dose-based limits correspond to higher HTO_{liquid} concentrations than those derived from Gasbuggy risk calculations, supporting the cautious nature of the risk-based approach.

CONCLUSIONS

A probability range from 10^{-4} to $\leq 10^{-6}$ of excess lifetime morbidity cancer risk generally is considered by regulatory agencies to be negligible or too small to be of societal concern (and is equated with the *de minimis* principal or "virtually safe" concept). While some may argue that the notion of negligible risk is vague and should not be subject to literal interpretation, the principle is based on selecting a sufficient threshold of improbability so that risks at or below that level can be ignored for purposes of decision making (Martin, 2002). The concept of *de minimis* risk has been adopted by the USEPA (2010; 40 CFR 300) for managing responsibly environmental, health, and safety risks for compliance, and so it will be used here for considering the magnitude of risk for the worker and resident scenarios with respect to potential emissions of HTO_v into air. Accordingly, the results in Table 2 demonstrate that for both the worker and resident, concentrations of HTO_v in the atmosphere based upon inhalation and dermal exposures to the highest reported measurement of HTO_v in the atmosphere during post-shot production testing at Project Rulison in 1971 would present lifetime excess morbidity cancer risk at magnitudes well below 1 per million (i.e., $<< 1 \times 10^{-6}$). In fact, the computed risk levels appearing in the last column of Table 2 for both worker and resident would increase at most only by two orders of magnitude (from just over 1×10^{-8} to just over 1×10^{-6}), if they are multiplied by the compounded uncertainty in all parameters . Although unrealistically high, these resulting worker and resident values for lifetime excess morbidity cancer risk from inhalation and dermal exposure to HTO_v under the conditions described would still remain within the range of values the regulatory community consider to be virtually safe or *de minimis*.

Also worth mentioning is that during Project Rulison activities after the nuclear detonation, including drill back, gas sampling, gas-production testing, and gas flaring, human health and safety monitoring revealed " … no personnel radiation exposures" (USAEC, 1973).

It is informative to compare the concentrations used for performing these screening calculations of risk with those that are considered health protective and published in the regulatory literature. For workers, the USDOE (2009), USNRC (2007), and State of Colorado Department of Public Health and Environment (CHPDE, 2005) all indicate that occupational exposure to tritium in air should not exceed the derived air concentration (DAC) of 2×10^7 pCi/m^3, a value much higher than 2.9×10^2 pCi/m^3, which was used in this screening analysis.

For residents, the atmospheric exposure concentration of HTO_v used in the screening analysis of 2.9×10^2 pCi/m^3 also is well below regulatory concentration limits for public health protection. For example, for members the public, USDOE (1993), USNRC (2007), and CDPHE (2005) set guidance at a concentration in air of 1×10^5 pCi/m^3. Even more importantly, the concentration used in this screening analysis is also below the more restrictive concentration limit of 1.5×10^3 pCi/m^3 specified by USEPA (1989) for HTO_v in air as part of the National Emission Standards for Hazardous Air Emissions (applicable to radionuclides emitted from federal facilities of this category).

In conclusion, this screening assessment of human-health risk indicates that worker and resident health risk from inhalation and dermal exposure to tritium in water can be considered *de minimis* as a result of any future natural-gas drilling near Project Rulison in Western Colorado. Additionally, monitoring of product water at a concentration limit consistent with such *de minimis* risk will ensure that the future recovery of natural gas near Project Rulison will be protective of occupational and public health. These findings provide a human health perspective to consider along with data from past site activities, forecasts of predicted contaminant behavior, and ongoing monitoring, for site stewardship.

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APPENDIX: DERIVATION OF HEALTH-PROTECTIVE OPTIONS FOR TRITIUM CONCENTRATIONS IN LIQUID WATER (HTO_{LIQUID}) BASED ON A TRITIUM VAPOR (HTO_V) CONCENTRATION IN ATMOSPHERE ASSOCIATED WITH WORKER AND RESIDENT EXPOSURE SCENARIOS, A LIFETIME EXCESS CANCER MORBIDITY RISK ≤ 1×10^{-6}, AND LOCAL CLIMATE CONDITIONS

The concentration of tritium in liquid water (HTO_{liquid}) can be determined from the concentration of tritium in water vapor (HTO_v) in air using Eq. A-1.

$$C_{\mathrm{HTO}_{liquid}} = C_{\mathrm{HTO}_v} \times \rho_{\mathrm{H_2O}} \times \left(\frac{1}{\mathrm{AH}} \times u\mathrm{CF}\right), \text{ where} \qquad \text{Eq. (A-1)}$$

$C_{\mathrm{HTO}_{liquid}}$ = Activity concentration of tritium in liquid water $\left(\mathrm{pCi}/\mathrm{L}_{H_2O}\right)$;

C_{HTO_v} = Activity concentration of tritiated water vapor (HTO_v) in air $\left(\mathrm{pCi}/\mathrm{m}^3_{air}\right)$;

AH[**] = Absolute humidity of air $\left[\left(\mathrm{g_{H_2O}}/m^3{}_{\mathrm{air}}\right)_{\mathrm{H_2O}_v @T\,^\circ\mathrm{C};\ \mathrm{RH}\ \%}\right]$, with respect to a given temperature (T °C) and relative humidity (RH %).

$\rho_{\mathrm{H_2O}}$ = Density of water $\left[\left(\mathrm{g_{H_2O}}/\mathrm{cm}^3{}_{\mathrm{H_2O}}\right)_{\mathrm{H_2O}@T\,^\circ\mathrm{C};\ \mathrm{Salinity}\ \ \mathrm{mg/L}}\right]$, and representing the mass-to-volume conversion factor with respect to a given temperature (T °C) and salinity (mg/L);

uCF = Units conversion factor (i.e., $\mathbf{10^{+03}\ cm^3_{\mathit{H_2O}}/L_{\mathit{H_2O}}}$ = $10^{+06}\ \mathbf{cm^3_{\mathit{H_2O}}}/\mathrm{m}^3_{H_2O} \times 10^{-03}\ \mathrm{m}^3_{H_2O}/\mathbf{L_{\mathit{H_2O}}}$).

Table A-1 contains a comparison of product-water tritium concentrations corresponding to summer and winter atmospheric conditions (i.e., representative of extremes) of temperature, relative humidity, absolute humidity, and water density near Project Rulison surface ground zero (SGZ), and associated with different concentrations of atmospheric HTO_v. The values for HTO_v are derived using respective worker and resident breathing rates, a worker and resident excess cancer morbidity risk equal to 1×10^{-6}, and an exposure duration of 30 days per lifetime for both workers and residents.

[**] For comparison, absolute humidity (AH) was determined for both minimum and maximum temperatures and corresponding percentiles of relative humidities (RHs) in Rifle, CO (see URL: http://www.city-data.com/city/Rifle-Colorado.html), which is near Project Rulison. These AH values occur in winter and summer and range from 5.4 g/m^3 (at 5 °C and 80% RH, during winter) to 15.2 g/m^3 (at 30 °C and 50% RH, during summer). The AH values were computed from temperature and humidity using approximations in the "Climate/Humidity Table" available from *Transportation Information Service (TIS) of German Marine Insurers* [© Gesamtverband der Deutschen Versicherungswirtschaft e.V. (GDV), Berlin, Germany] and available January 2011 at URL: http://www.tis-gdv.de/tis_e/misc/klima.htm].

Table A-1. Comparison of product-water concentrations of tritium (HTO_{liquid}) corresponding to summer and winter atmospheric conditions of temperature, relative humidity, absolute humidity, and water density near Project Rulison surface ground zero (SGZ), and associated with different concentrations of atmospheric HTO_v, which were derived using respective realistic upper-limit exposure parameters for worker and resident, total lifetime exposure durations of 30 d and a *de minimis* excess cancer morbidity risk equal to 1×10^{-6}.

Atmospheric conditions		**Summer**[a]	**Winter**[a]
Temperature (T =° C)		30	5.0
Relative humidity**[a]** (RH = %)		50	80
Absolute humidity (AH = g/m^3)		15.2	5.4
Water density**[b]** (ρ_{H_2O} = g/cm^3)		1.008	1.013
Exposed individual	Atmospheric concentration of HTO_v corresponding to a *de minimis* 1×10^{-6} lifetime excess morbidity cancer risk (pCi/m^3)	Produced water concentration of HTO_{liquid} (pCi/L)	Produced water concentration of HTO_{liquid} (pCi/L)
Worker	$9.9 \times 10^{+03}$	$6.6 \times 10^{+05}$	$1.9 \times 10^{+06}$
Resident	$1.5 \times 10^{+04}$	$9.8 \times 10^{+05}$	$2.8 \times 10^{+06}$

[a] Summer and winter atmospheric conditions available for Rifle, CO (see "Average Climate in Rifle, CO," available December 2010 at URL: http://www.city-data.com/city/Rifle-Colorado.html), the city nearest to the Project Rulison surface ground zero (SGZ) for which such data are available.

[b] The density of water (ρ_{H_2O}) at 5 °C and 30 °C was determined using the "Water Density Calculator" created with the assistance of the University of Michigan and the National Oceanic and Atmospheric Administration (NOAA) and available from the *Computer Support Group Network* (at URL: http://www.csgnetwork.com/h2odenscalc.html). The calculation is made with respect to a representative formation-water salinity equal to 16,236 mg/L (which is consistent with the salinity for groundwater in the Mesaverde aquifer of the Piceance Basin in Colorado that is reported by USGS to exceed 10,000 mg/L; see "Ground-Water Quality" in Mesa Verde Aquifer section of *USGS Groundwater Atlas of the United States for Arizona, Colorado, New Mexico, and Utah, HA 730-C* available December 2010 at URL: http://pubs.usgs.gov/ha/ha730/ch_c/C-text8.html).

The water concentrations of tritium (H_2O_{liquid}) in the last two rows of Table A-1 represent concentrations in product water that could, for a worker or resident exposure scenario, under the described atmospheric conditions and noted exposure durations, yield atmospheric concentrations that could produce a lifetime excess cancer morbidity risk $\leq 1 \times 10^{-6}$. Accordingly, the lowest produced-water concentration (shaded in the "Summer" column of Table A-1 and equal to 660,000 pCi/L) constitutes a monitoring option that would be a health-protective indicator of potential consequences for both workers and residents should drilling or production continue to other wells without further assessment. Even though product water from natural-gas recovery near Project Rulison is not considered to be suitable as drinking water (e.g., salinity is significant > 10,000 mg/L), for purposes of comparison, the maximum contaminant level (MCL) for tritium that is the National Primary Drinking Water Regulation (NPDWR) for this radionuclide is 20,000 pCi/L[††].

[††] See United States Environmental Protection Agency (USEPA). 2010. *Derived Concentrations (pCi/l) of Beta and Photon Emitters in Drinking Water Yielding a Dose of 4 mrem/y to the Total Body or to any Critical Organ as defined in NBS Handbook 69,* available at website of the Office of Water, United States Environmental Protection Agency, Washington, DC [see "TOOLS—Limits for Beta Particles and Photon Emitters at 4 millrems [sic]/year (PDF)" at URL: http://water.epa.gov/lawsregs/rulesregs/sdwa/radionuclides/compliancehelp.cfm; December 2010].