# PRESCO, Inc.
# 2006 Gas Well Drilling Monitoring Report
# Battlement Mesa Area, Garfield County, Colorado

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# LIST OF ACRONYMS AND TERMS

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| AEC | Acronym for the Atomic Energy Commission, a forerunner of the DOE |
| ALARA | Acronym for "As Low as Reasonably Achievable" |
| ALI | Annual Limit on Intake for occupational exposures to radionuclides established by the United States Nuclear Regulatory Commission. The ALI is the derived limit for the amount of radioactive material taken into the body of an adult worker by inhalation or ingestion over a period of a year. |
| Alpha ($\alpha$) Particles | Radioactive particles consisting of two protons and two neutrons, the same as a helium nucleus. These particles can be shielded by a piece of paper and cannot penetrate the outer layer of dead skin cells, but pose a hazard if inhaled. |
| Analyte | A substance or chemical constituent undergoing analysis or the substance being measured by an analytical procedure. Any chemical, parameter, or radionuclide in a water sample with a concentration or activity capable of being measured by a laboratory. |
| Aquifer | A body of rock that is sufficiently permeable to conduct groundwater and yield significant quantities of potable water to wells and springs. |
| Background | Naturally occurring ionizing radiation from sources including cosmic radiation, terrestrial radiation, and indoor radon concentrations. |
| Becquerel (Bq) | The International System (SI) derived unit of radioactivity, defined as the activity of a quantity of radioactive material in which one nucleus decays per second. The older unit of radioactivity was the curie (Ci), defined as $3.7 \times 10^{10}$ becquerels or 37 gigabecquerels (GBq) |
| Beta ($\beta$) Particles | Radioactive particles consisting of electrons. Beta particles can travel no more than 10 meters in air or about 1 centimeter in tissue, and can be shielded by a pad of paper. Beta particles can cause damage to skin cells in high doses outside the body and can cause damage to cells and critical organs when emitted inside the body through ingestion or inhalation. |
| CDPHE | Acronym for the Colorado Department of Public Health and Environment |
| COGCC | Acronym for the Colorado Oil and Gas Conservation Commission |

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| Colloid | A particle-size of less than 0.00024 millimeters (mm), i.e. smaller than clay particle size (0.004 mm or 4 microns). An extremely fine-grained material in suspension or that can easily be suspended in water. |
| Connate Water | Water that is trapped inside a bedrock formation and was present at the time that the sediments were deposited, as opposed to meteoric water that has fallen as precipitation and percolated into the ground. |
| Confining Unit | A body of impermeable or distinctly less permeable material stratigraphically above or below one or more aquifers. |
| CPM | Counts per minute. A measure of radioactive disintegration. |
| Curie (Ci) | A unit of radioactivity measurement. One curie equals $3.7 \times 10^{10}$ disintegrations per second. One becquerel (Bq) is the International System of Units (SI) unit and equals 1 disintegration per second. |
| DAC | Derived Air Concentration. The DAC is the concentration of a radionuclide in air as the occupational exposure limit to that radionuclide in hours established by the United States Nuclear Regulatory Commission. |
| Darcy | A standard unit of measurement of permeability, equivalent to the passage of one cubic centimeter of fluid of one centipoises viscosity flowing in one second under a pressure differential of one atmosphere through a porous medium having a cross sectional area of one square centimeter and a length of one centimeter. |
| Decay Mode | Describes the way a radioactive atom decays and the forms of radiation |
| DOE | United States Department of Energy (formerly the AEC) |
| DRI | Desert Research Institute of Nevada |
| EIC | Eberline Instrument Corporation |
| EPA | United States Environmental Protection Agency |
| EPA Method | A specific method required by the EPA for laboratory analysis of a specific parameter or analyte and is followed by the method number. |
| Fission Products | Radionuclides created in the process of nuclear fission of uranium or plutonium. |

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| Gamma (γ) | Gamma radiation is electromagnetic radiation with high energy, similar to x-rays. Gamma radiation is given off by the nucleus of radionuclides, while x-rays come from outside the nucleus. Gamma rays and x-rays can travel long distances and penetrate through the human body. Gamma radiation is a hazard to all organs from both inside and outside the body. Gamma radiation can be shielded by heavy materials such as lead and concrete. |
| gpm | Gallons per minute |
| Half-life | The time it takes for half of the radioactive atoms of a radionuclide present to decay. The half-life is dependent on the radionuclide, some having half lives measured in seconds, days, years, or in millions of years |
| LANL | Los Alamos National Laboratory, located in Los Alamos, New Mexico |
| LLNL | Lawrence Livermore National Laboratory, located in California |
| MCi | A mega curie equals one million ($10^6$) curies. |
| MCL | Maximum Contaminant Limit(s) set by the EPA as the maximum concentration or activity concentration allowed in a municipal drinking water supply. |
| MDA | Minimum detectable activity is the minimum activity of a particular radionuclide that the laboratory can detect. |
| MDC | Minimum detectable concentration |
| MDL | Method Detection Limit is the same as the laboratory reporting limit or the minimum concentration of an analyte that the laboratory can accurately quantify using a particular laboratory method. |
| MeV | Mega electron volts, a unit of the energy given off during radioactive decay of a radionuclide, one million ($10^6$) electron volts (eV) |
| mg/L | Milligrams per liter. One milligram equals one thousandth ($10^{-3}$) of a gram per liter of water, and is approximately equivalent to parts per million. |
| microdarcies | A unit of fluid permeability measurement, equivalent to 0.000001 darcies, abbreviated µd. |

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| millidarcies | The customary unit of measurement of fluid permeability, equivalent to 0.001 darcy, abbreviated md. |
| MMCF | a million cubic feet of natural gas, unit of measurement |
| mrem | millirem (See "rem") |
| NERC | National Environmental Research Center, located in Las Vegas, Nevada |
| NORM | Naturally occurring radioactive materials |
| NRC | Nuclear Regulatory Commission, is an independent agency established by the Energy Reorganization Act of 1974 to regulate civilian use of nuclear materials, and is headed by a five member Commission. |
| NTS | Nevada Test Site |
| ppb | Parts per billion, approximately equivalent to micrograms per liter |
| ppm | Parts per million, approximately equivalent to milligrams per liter |
| pCi | Picocuries are a unit of radioactivity measurement equal to one trillionth of a curie (see definition of a curie). |
| pCi/cc | Picocuries per cubic centimeter as a measure of radioactivity per volume. |
| pCi/g | Picocuries per gram as a measure of radioactivity per unit weight. |
| pCi/L | Picocuries per liter is a measurement of radioactivity in a volume of liquid, usually used for water concentrations. |
| $pCi/m^3$ | Picocuries per cubic meter is a measure of radioactivity in a volume of air. |
| pMC | Percent modern carbon (pMC) is a unit of measurement for carbon-14. |
| permeability | The capacity of a porous rock, sediment, or soil for transmitting a fluid; it is a measure of the relative ease of fluid flow under unequal pressure. The customary unit of measurement is the millidarcy. |
| permeable | Said of a rock or sediment that allows water, oil, or gas to move through at an appreciable rate via super capillary openings. The antonym of permeable is impermeable. |

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| Project Rulison | An experiment conducted by the AEC and Austral Oil, a private oil company, on September 10, 1969 involving the detonation of a nuclear device to stimulate natural gas production from low permeability sandstone at a depth of 8,426 feet. |
| QA/QC | Quality Assurance/Quality Control is an evaluation of the accuracy and precision of laboratory analytical results. |
| Radiation | The emission of subatomic particles or rays from the nucleus of an atom |
| Radioactivity | The random decay of unstable atomic nuclei (nuclides) emitting subatomic particles and energy (radiation) to create a new daughter product nucleus. The emission of energetic particles and/or radiation during radioactive decay, involving the spontaneous disintegration of the atoms of certain nuclides into new nuclides which may be stable or undergo further decay until a stable nuclide is finally created. Represents emission of alpha particles, or beta particles, and usually accompanied by emission of gamma rays. |
| Radionuclide | A radioactive isotope of a particular chemical element |
| Radionuclides of Interest | Radionuclides which could possibly be entrained in the natural gas or have the remote possibility of being encountered during drilling activities. Concentrations of radionuclides related to Project Rulison are not expected to be encountered in the drilling area. |
| RAMS | Remote Area Monitoring Systems |
| rem | "roentgen equivalent man" is a measurement of radioactivity dose. A radiation dose is a measure of the amount of energy absorbed by body tissues. One mrem is one thousandth ($10^{-3}$) of a rem. |
| roentgen (R) | Measure of radiation exposure, or the amount of ionization produced by gamma radiation or x-rays in the air. An exposure of one milliroentgen (mR) would result in a dose of approximately one millirem (mrem). |
| Shielding | The use of a physical barrier, such as a lead apron, as protection from radiation. |
| Sievert (Sv) | The International System (SI) unit for dose equivalent equal to 1 joule/kilogram. 1 sievert = 100 rem. Named for physicist Rolf Sievert. |
| TENORM | Technologically enhanced naturally occurring radioactive materials. Concentrations of NORM at the surface that have been enhanced or |

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| | concentrated due to human activities such as mining and milling wastes or that inadvertently form as a result of human activities such as deposition of pipe scale containing radionuclides in oil and gas well piping and equipment. |
| TLD | Thermoluminescent dosimeter, a device used to measure whole body beta or gamma doses to onsite personnel. A TLD can contain a variety of different materials. When these materials are exposed to radiation, the absorbed energy is "trapped" and held indefinitely. When the materials are heated at a later time in a device known as a TLD reader, the trapped energy is released in the form of light, and the amount of light released is related to the radiation dose received. |
| Tritium | A radioactive form of hydrogen, $^{3}H$, forms naturally by reactions in the upper atmosphere with cosmic rays, and also by the detonation of nuclear devices. Tritium is a weak beta particle emitter. |
| TU | Tritium Units, an older unit of measurement of tritium equal to 3.21 pCi/L of tritium. |
| µg/L | micrograms per liter, or one millionth ($10^{-6}$) of a gram per liter of water, approximately equivalent to parts per billion |
| µCi/L | microcuries per liter, or one millionth ($10^{-6}$) of a curie, a measurement of radionuclide activity concentration per liter of water |
| Unconsolidated | A sediment that is loosely arranged, unstratified, or whose particles are not cemented together or "lithified" as a sedimentary rock, occurring either at the surface or at depth. Soil material that is in a loosely aggregated form. |
| USGS | Acronym for the United States Geological Survey |

# 1.0 Introduction

PRESCO, Inc. (PRESCO) developed natural gas resources on the north side of Battlement Mesa in Garfield County, Colorado. PRESCO owned both the surface land and the mineral rights in the vicinity of Battlement Mesa, Rulison Field, Colorado from 2004 to 2006. These resources are in proximity to where Austral Oil, a private company, and the United States Atomic Energy Commission (AEC), a predecessor agency to the United States Department of Energy (DOE), conducted Project Rulison, an experiment involving the detonation of an underground nuclear device designed to stimulate natural gas production from tight gas formations, or natural gas in dense, low permeability sandstone reservoir rock.

This report presents a summary of the historic monitoring that was conducted at the time of the Project Rulison experiment, and the monitoring efforts that PRESCO conducted in conjunction with the conventional natural gas well drilling in the area during 2006. What follows in this section is a brief description of the site geologic setting of the Battlement Mesa, a history of Project Rulison, and discussion of radioactivity. A general site location map is presented as Figure 1, and a map showing these gas wells in relation to the Project Rulison site is presented as Figure 2.

## 1.1 Battlement Mesa Geology

Battlement Mesa is located in central Garfield County, Colorado on the Colorado Plateau along the south-central part of the Piceance Basin, an irregularly shaped, geologic structural depression in the earth's crust created as a result of tectonic forces associated with the uplift of the Colorado Rocky Mountains and the Colorado Plateau. Rocks ranging from Precambrian to Cenozoic in age and having a total thickness of 15,000 feet are present within the central part of Garfield County; however, only rocks of the Cenozoic Era are exposed in the Rulison area as mapped on the Geologic Map of the Rulison Quadrangle (Yeend et al, 1988). Figure 3 presents a cross section of the geology of the area. A description of the Battlement Mesa geology is presented as Table 1.

Stratigraphy

Sedimentary rocks ranging in age from Late Cretaceous to Pliocene are exposed on Battlement Mesa. All are of terrestrial origin with the exception of the lower part of the Upper Cretaceous age Mesaverde Group. The Upper Cretaceous age Mancos Shale is a marine shale and underlies the Mesaverde Group. The Mesaverde Group was deposited in several near-shore environments, including coastal swamp, floodplain, and marine conditions. The action of streams meandering across this coastal floodplain deposited

sand and clay which became the discontinuous sand lenses from which the natural gas resources are produced today.

The Mesaverde Group consists an upper unit equivalent to the Lance-Lewis Formation, the Williams Fork Formation and the Isles Formation and is underlain by the Cretaceous Mancos Shale. The Mancos Shale is a marine shale that forms a confining unit in areas where the Mesaverde Group yields water to wells. However, the Mesaverde Group is not an aquifer in the Battlement Mesa area due to its great depth and does not supply water to wells in the area.

The Mesaverde Group under the test site consists mainly of sandstone and interbedded shale approximately 2,500 feet thick (Voegeli, West, and Cordes, 1970). The Williams Fork Formation that comprises the upper part of the Mesaverde Group is of special interest because it contains natural gas resources, and the Project Rulison nuclear device was detonated within this group, as an experiment to stimulate natural gas production from tight gas sands.

The Mesaverde Group is also overlain by impermeable sedimentary rock including the Tertiary Wasatch Formation and Green River Formation. These thick sedimentary rock strata limit the downward migration of surface water. These units are not considered to be aquifers since they do not yield sufficient water volume to wells, and are considered confining units since they limit the migration of water.

The Wasatch Formation consists of brightly colored claystone, siltstone, and shale, interbedded with sandstone lenses. The Wasatch Formation is approximately 3,900 feet thick at the Project Rulison site. The Wasatch Formation generally is not a source of ground water in the Rulison area (Voegeli, West, and Cordes, 1970).

The Green River Formation is known for its oil shale, and also for deposits of sodium and calcium bicarbonate that have been mined for production of baking soda. In the central part of the Piceance Basin, a saline zone in the lower part of the Green River Formation limits the thickness of the freshwater found in the overlying Uinta-Animas Aquifer (Robson and Banta, 1995).

The sedimentary bedrock units are covered by younger, Quaternary, unconsolidated sediments and boulders of basalt eroded from the top of Battlement Mesa. These Quaternary age deposits range in size from clay and silt all the way up to boulder size particles and represent alluvium, terrace deposits, fan deposits, slump blocks, and debris flows derived from the bedrock units and basalt transported from higher elevations to the south. Water resources are utilized within this relatively thin layer of sediments. Permitted water wells in the Battlement Mesa area range in total depth from 98 feet to 250 feet below ground surface (bgs). Static water levels reported for these wells range from 43 feet to 173 feet bgs.

Structural geology

Battlement Mesa lies on the southern margin of the Piceance Basin, a broad structural and depositional basin trending northwest and formed during the late Cretaceous geologic period (145 million years ago to 65 million years ago). The sedimentary rocks dip gently (2° to 5°) or approximately 150 feet per mile, north toward the center of the basin. These low dip angles are responsible for the gently sloping structural terraces held up by sandstones in the Wasatch Formation in the area north of Plateau Creek.

Battlement Mesa has been uplifted, but structurally was relatively undeformed as there are no mapped faults or folds in the immediate area of Project Rulison. The Black Mountain anticline is a broad east-plunging anticlinal fold located to the west. The southern part of the Piceance Basin is characterized by a series of northwest trending folds. Apart from joints, the basin strata are cut only by scattered, minor thrust faults and small kink bands, products of late Laramide orogenic compression, and by later west-northwest trending normal faults of small to moderate throw (Grout and Verbeek, 1992). Several northwest trending faults are present north of Plateau Creek, bisecting the Wasatch Formation; however, the Geologic Map of the Rulison Quadrangle (Yeend et al, 1988) does not identify any folds or faults in the immediate vicinity of the Project Rulison site.

The absence of natural fractures coupled with the heterogeneous, discontinuous and limited sand bodies and impermeable nature of the Mesaverde Group in the area inhibits natural gas production by conventional methods. In fact, this was the reason that Project Rulison was conducted, i.e., to see if it was possible to stimulate natural gas production from these tight gas sands using a nuclear detonation. With advancements in technology and improvements in hydraulic fracturing, or "fracing," techniques it has become possible to complete economically viable gas wells in the Rulison Field and elsewhere in the Piceance Basin, where it was not economically feasible at the time of Project Rulison.

Hydrogeology

Drinking water supply wells and springs in the Project Rulison area produce water from shallow, unconsolidated aquifers, and consequently do not represent groundwater from the bedrock formations. This water in the bedrock formations is known as connate water. Connate water is trapped in the pore spaces and fractures within the sedimentary rock. The sedimentary bedrock in the vicinity of Project Rulison are not considered aquifers since the rocks lack sufficient permeability to allow this water to be produced in useful quantities. Connate water typically has much higher total dissolved solids (TDS), as salts, and may contain dissolved petroleum hydrocarbons or elevated metals concentrations.

Core samples of unfractured rock at the base of the Mesaverde Group collected elsewhere in the region have been tested and found to have very little ability to transmit groundwater. Core samples that have been analyzed are nearly incapable of vertically transmitting groundwater with permeability of less than $10^{-4}$ darcy and most samples have a matrix permeability of less than $10^{-3}$ darcy (Mayo and Kuntz, 2000). Porosity and permeability in the coal bearing sequences are variable with porosities ranging from less than 4% to greater than 12%, and permeabilities ranging from less than 0.1 millidarcy to 2.2 millidarcy. Much of the original porosity was reduced by compaction during burial of these sediments (Pitman et al, 1996).

The maximum flow rate of connate groundwater in the Mesaverde Group is estimated to be 0.3048 meters (1 foot) per day. The most probable rate is essentially negligible (Nork and Fenske, 1970, p 2). The permeability of Mesaverde sandstone samples from the Project Rulison area were measured under confined conditions and ranged from 1.4 microdarcies (µD) to 5.1 µD, and the water saturation percent of void volume ranged from 12 to 17 percent (Quong, 1972). Any connate groundwater flow is expected to be directed to the north-northwest into the basin following stratigraphic dip.

## 1.2 Project Rulison Location and History Summary

The Project Rulison site is located in Garfield County about six miles southeast of the town of Parachute, formerly known as Grand Valley, Colorado, on the north side of Battlement Mesa, and within the Battlement Creek drainage valley. The emplacement well, the Hayward #25-95, or R-E well, was located in the Northeast Quarter of the Southeast Quarter of Section 25, Township 7 South, Range 95 West of the Sixth Principal Meridian at an elevation of 8,154 feet above sea level. Figure 1 presents the general site location, and Figure 2 shows the location of Project Rulison site and the locations of PRESCO's natural gas wells drilled in 2005 and 2006.

The following information was obtained from the Project Rulison Manager's Report, April 1973 (AEC, 1973). Project Rulison involved the detonation of a 43 ± 8 kiloton yield nuclear device on September 10, 1969. The device was emplaced inside a 10 ¾ - inch steel casing in the Mesaverde Group at a depth of 8,426 feet. No radioactivity was detected on the surface either onsite or offsite as a result of the detonation (AEC, 1973, p. 53). The Mesaverde Group, reservoir rock, was estimated to contain eight trillion cubic feet of natural gas at depths ranging from 6,200 feet to 8,700 feet beneath 60,000 acres; however, the permeability of this rock is very low. At the time of the experiment the conventional production stimulation methods were not economic to produce the tightly held gas from low permeability reservoir rock.

The Rulison Site is located on privately owned surface land and is surrounded by privately owned surface land to the west, south, and east and by BLM land to the north. A summer residence is located on the site, approximately 1,400 feet from the former

drilling fluid overflow pond which has been remediated and converted to a fish pond. The site is used for livestock grazing and for recreation.

Subsurface use restrictions at the Rulison Site will remain in place in perpetuity. These restrictions are described on the permanent monument located at the site of the emplacement hole (R-E) and are as follows:

> "*No excavation, drilling, and/or removal of subsurface materials below a depth of 6,000 feet is permitted within Lot 11, NE ¼ SW ¼ Section 25, Township 7 South, Range 95 West, 6th Principal Meridian, Garfield County, Colorado without U.S. Government Permission. U.S. Energy Research and Development Administration September 1976."*

The Colorado Oil and Gas Conservation Commission (COGCC) has developed strict spacing rules which dictate how close a well can be drilled to an existing boundary. Additionally, the COGCC has agreed to notify the DOE of any permits for drilling oil and gas wells within an arbitrary 3 mile radius of the Project Rulison Site. It is not a limitation, only an area in which wells may be subject to environmental oversight measures as established by the COGCC and DOE for inclusion in a monitoring program. Additionally, the COGCC has established an area of half-mile radius from Project Rulison in which applications for drilling oil and gas wells requires a full hearing before the Commission. Project Rulison is covered in greater detail in Section 2.0; however, what follows in the rest of this section is a discussion of radioactivity.

### 1.3 Ionizing Radiation

Radiation is a form of kinetic energy, or energy in motion. Ionizing radiation has enough kinetic energy to strip electrons from atoms. Radioactive decay is the process by which a radioactive atom, or radionuclide, releases energy in the form of radiation to become more stable. A half-life is the time that it takes for half of the radioactive atoms present to decay. The half-life is dependent on the radionuclide and may be seconds, days, years, or even millions of years.

Not all ionizing radiation released during radioactive decay has the same amount of energy. The amount of energy released per decay is also dependent on the radionuclide. The three principal types of radiation include:

- alpha ($\alpha$) particles which consist of 2 protons and 2 neutrons, the same as a helium nucleus;
- beta ($\beta$) particles which are electrons; and
- gamma ($\gamma$) radiation and x-rays which are electromagnetic radiation, similar to light, ultraviolet light, and microwaves, but have more kinetic energy.

Exposure to these types of radiation may be from natural sources or may be the result of direct or indirect human involvement in the distribution of radioactive materials. Radiation used in medical and dental procedures, such as x-rays, magnetic resonance imaging (MRI), and chemotherapy are examples of beneficial radiation exposures. Control of radiation dose to the human body from direct exposure depends on the following factors:

1. Minimize the time of exposure to the source of radiation;
2. Maximize the distance to the source of radiation; and
3. Use shielding, or a physical barrier, to reduce the exposure to the human body.

Alpha radiation has the least amount of energy, traveling only about five centimeters in air, or 0.01 centimeters in tissue. Alpha particles can be shielded by a piece of paper and are not a hazard outside the body since they cannot penetrate the outer layer of skin cells. If inhaled, alpha particles can be a high hazard inside the body because they can cause substantial damage to cells in a small volume of tissue.

Beta particles, as electrons, are much smaller in size, and will travel no more than 10 meters in air or about 1 centimeter in tissue. Beta particles can be shielded by a pad of paper, and can cause skin damage at high dose levels from outside the body. They can cause damage to cells and critical organs when the beta particles are emitted inside the body when ingested or inhaled.

Gamma rays and x-rays are electromagnetic radiation with high energy. Gamma radiation is given off by the nucleus; whereas x-rays come from outside the nucleus. Gamma radiation can travel long distances and can penetrate through the body. Gamma radiation is a hazard to all organs from both inside and outside the body. Gamma rays can be shielded by heavy materials such as the cab of a vehicle, lead apron, barium compounds, concrete, or thick sedimentary rock sequences.

## 1.4 Background Radiation

Background radiation is ionizing radiation from natural sources including cosmic radiation and sources within the earth, and radionuclides incorporated in food and water, and in the human body tissues. Fission products released during the detonation of a nuclear device, such as the one used for the Project Rulison experiment, are not naturally occurring and are distinct from background radionuclides. The total annual natural background radiation exposure for the Rulison area is approximately 430 mrem from all sources. This radiation affects all living things on a daily basis and is omnipresent. A brief description of natural sources of radiation is presented in this section.

Cosmic Radiation

All living things on the earth are constantly bombarded by radiation from outside our solar system. This radiation interacts in the atmosphere to create secondary radiation that rains down on the earth. The dose rate from cosmic radiation varies in different parts of the world based largely on the geomagnetic field and land elevation. The amount of cosmic radiation to which people are exposed depends on altitude and location. At sea level, the amount of cosmic radiation is about 26 millirem (mrem) per year. The cosmic background radiation levels on the Colorado western slope range from 50 mrem to 100 mrem per year. During commercial air travel passengers are exposed to about 0.5 mrem per hour of cosmic radiation.

Terrestrial Radiation

Naturally occurring radioactive material is found throughout nature in the soil, rocks, water, air, and vegetation. The primary radionuclides responsible for terrestrial radiation are potassium, uranium, thorium, and their decay products. These radionuclides undergo a well documented radioactive decay process which yield naturally occurring daughter products.

## 1.5 Naturally Occurring Radioactive Materials

The primary radionuclides responsible for terrestrial radiation are potassium, uranium, and thorium. Naturally occurring radioactive materials (NORM) include naturally occurring terrestrial radiation at low background levels ranging to the elevated levels of radioactivity found in some rocks and soils as concentrated by geologic and chemical processes. The amount of terrestrial radiation to which people are exposed depends on the geology of the area.

Some oil and gas fields have elevated NORM associated with the produced petroleum hydrocarbons and produced water (connate water). This NORM precipitates out as a radioactive scale on the walls of pipe, production tubing, production equipment, vessels, and settles out in tank bottoms.

Some industrial processes, such as production, treatment, and separation of oil and saltwater (connate water) in the oil and gas industry, may concentrate radionuclides increasing the level of radioactivity. These radionuclides can become concentrated enough that they could pose a human health risk or a risk to the environment if not controlled. Such technologically-enhanced naturally occurring radioactive materials are referred to as TENORM.

The NORM radionuclides of most concern in the oil and gas industry are naturally occurring radium 226 ($^{226}$Ra), radium 228 ($^{228}$Ra), and radon 222 ($^{222}$Rn). The most abundant of these is radium 226. Radium is very soluble in connate water, or the

produced water/brine that accompanies oil and natural gas resources, but radium is not soluble in oil. Radium deposition occurs during changes in temperature and pressure and precipitated radium can be found in scale, sludge, produced waters, and produced sands. Radium is of concern not only because it is radioactive, but it is also toxic to the human body. Radium is carcinogenic and has been linked to leukemia and bone cancer. Radium 226 and radium 228 are the parent radionuclides of radioactive decay chains that include radioactive daughter products. The activation and fission products created by the Project Rulison experiment are unique and distinct from radionuclides that are the daughter products of NORM decay chains.

The Rulison natural gas field, and other natural gas fields within the Piceance Basin, are not known to have a significant NORM problem. Elevated concentrations of NORM are present in parts of the Gulf Coast region of Louisiana and Texas. The natural gas in the Rulison field is reportedly dry, with relatively little produced water generated.

## 1.6 Evaluation of Background Radiation and NORM in the Rulison Area

In order to evaluate NORM in Garfield County, Cordilleran obtained a copy of the Colorado Geological Survey's Bulletin 40, Radioactive Mineral Occurrences of Colorado "A Complete Listing with Locations, Production, Geologic Setting and Bibliography" (Nelson-Moore et al, 1978, 2005). Bulletin 40 is available on a compact disk, and a review of the documents indicate that the only occurrences of radioactive minerals in Garfield County are associated with uranium and vanadium deposits in much older sedimentary rock formations (the Wingate Sandstone, Entrada Sandstone, and the Chinle Formation) near the town of Rifle, Colorado. These units lie stratigraphically below the Mesaverde Group, at significant depth, and will not be encountered in drilling activities in the area of Project Rulison.

Cordilleran contacted Dr. James Otton with the USGS Energy Resource Surveys Program to inquire about NORM in Garfield County. According to Dr. Otton, the Green River Formation locally contains some uranium; however, he was not aware of any elevated radioactivity levels in the Wasatch Formation or the Mesaverde Group in the area (Otton, personal communication).

The Tertiary Green River Formation is present near the surface of some of PRESCO's well sites; however, it is not a zone of production. Published geochemistry information also indicates that there are local zones within the Green River Formation where elemental uranium concentrations associated with organic materials in oil shale are reported at 4.5 ppm, as compared to uranium in petroleum at 0.06 ppm, and uranium in coal at 1.6 ppm (Fish, 1983). Drilling activities on Battlement Mesa will go through part of the Green River Formation at some well locations, but this interval will be cased and cemented off and therefore will be isolated from the wells where it is present.

Additionally, the gas wells are cased and cemented through the Wasatch Formation. There are some uranium deposits in the Wasatch Formation in Wyoming, but a search at the USGS Library and Colorado Geological Survey information revealed no occurrences in Colorado.

The USGS and Colorado Geological Survey have evaluated coal resources in northwestern Colorado including the collection of samples for geochemical analysis. Chemical analyses of 100 coal samples and 17 coal-associated rock samples from the Williams Fork Formation were collected from parts of Garfield, Moffat, Pitkin, Rio Blanco, and Routt Counties (Hildebrand et al, 1981). The following tables present the statistical analysis of the data for potassium, reported in percent, and for uranium and thorium, reported parts per million (ppm), obtained for coal samples from the Williams Fork Formation in Garfield County Colorado, as adapted from USGS Open-File Report 81-1348.

| Element | Arithmetic Mean | Minimum (%) | Maximum (%) | Geometric Mean | Geometric Deviation |
|---|---|---|---|---|---|
| **Grand Hog Back Coal Field, Garfield County, Colorado – Six Coal Samples** | | | | | |
| Potassium (K) | 0.038 | 0.022 | 0.071 | 0.034 | 1.6 |
| **Carbondale Coal Field – Garfield and Pitkin County, Colorado - Nine Coal Samples** | | | | | |
| Potassium (K) | 0.027 | 0.01 | 0.048 | 0.024 | 1.6 |

(Adapted from Hildebrand et al, 1981) Potassium was analyzed by x-ray fluorescence analysis.

It should be noted that the potassium values, reported as percentages, represent total potassium concentrations in the coal samples. Since the natural abundance of stable (non-radioactive) potassium isotopes is 99.99% ($^{39}$K is 93.26%, and $^{41}$K is 6.73%) and the radioactive isotope potassium 40 ($^{40}$K) has a natural abundance of 0.012%, the amount of activity from radioactive potassium 40 in the Williams Fork coal is expected to be very low, based on the low percentages of total potassium.

All rocks contain some minerals with naturally occurring radioactive isotopes, which is the source for terrestrial NORM. The most common of these isotopes is potassium 40, found in potassium containing minerals. Because clay minerals, such as illite and smectite, generally contain significant amounts of potassium, rocks such as shale or claystone tend to emit gamma rays at relatively high rates. Gamma-ray logs are frequently used in oil and gas drilling to detect this gamma radiation (Brenner and McHargeue, 1988).

In contrast to potassium, uranium and thorium do not have stable isotopes. Thorium and uranium and their daughter products also emit gamma rays and are also more common in

shale or claystone than in sandstones or limestone. Therefore these radionuclides tend to reinforce the gamma-radiation distribution results from the presence of the potassium.

Coal is largely composed of organic matter, but also contains inorganic matter, as minerals and trace elements, including potassium, uranium, and thorium, and their decay products. Shales and other argillaceous rocks are usually associated with coals, occurring either stratigraphically above or below the coal.

According to USGS Open-File Report 81-1348 the Geology and Chemical Analyses of Coal and Coal-Associated Rock Samples, Williams Fork Formation, (Upper Cretaceous) Northwestern Colorado (Hildebrand et al, 1981), statistical comparisons of the same means and variance of 35 elements (whole coal basis) for 100 Williams Fork Formation coal samples with 295 coal samples from the Rocky Mountain province show that the Williams Fork Formation samples have significant higher content of potassium, but that the contents of uranium were not significantly different. The report did not provide a comparison of thorium content between the Williams Fork coal samples and Rocky Mountain province coal samples, but did present thorium data for the Williams Fork samples collected in northwestern Colorado. The values represent naturally occurring concentrations of these elements reported in parts per million (ppm). The following table presents the uranium and thorium data for the Williams Fork from the USGS Open-File Report 81-1348.

| **Element** | **Arithmetic Mean** | **Minimum (ppm)** | **Maximum (ppm)** | **Geometric Mean** | **Geometric Deviation** |
|---|---|---|---|---|---|
| **Grand Hog Back Coal Field, Garfield County, Colorado – Six Coal Samples** | | | | | |
| Thorium (Th) | 2.4 | 1.0 | 4.6 | 1.8 | 2.1 |
| Uranium (U) | 1.0 | 0.4 | 2.3 | 0.8 | 2.0 |
| **Carbondale Coal Field – Garfield and Pitkin County, Colorado - Nine Coal Samples** | | | | | |
| Thorium (Th) | 2.0 | 0.7 | 3.8 | 1.8 | 1.7 |
| Uranium (U) | 0.6 | < 0.2 | 1.2 | 0.2 | 4.0 |

(Adapted from Hildebrand et al, 1981) Uranium and Thorium were analyzed by delayed neutron activation.

The following presents some useful conversion factors to relate elemental concentrations to activities.

According to the Health Physics Society to convert becquerels per gram (Bq/g) to ppm for uranium (U), thorium (Th), and potassium (K) in rocks, you use the following conversions:

| | |
|---|---|
| Uranium ($^{238}$U): | 1 ppm = 0.33 pCi/g |
| | 1 pCi/g = 3 ppm; |
| Thorium ($^{232}$Th): | 1 ppm = 0.11 pCi/g; |
| | 1 pCi/g = 9.1 ppm; and |
| Potassium ($^{40}$K) | 1 ppm = 0.000817 pCi/g; |
| | 1 pCi/g = 1,224 ppm. |

One picocurie (pCi) = 0.037 becquerels (37 Bq/m$^3$) or 2.22 disintegrations per minute

One Becquerel (Bq) = 1 disintegration per second

0.1 percent = 1,000 ppm

1 percent = 10,000 ppm

# 2.0 PROJECT RULISON

The following section describes the objectives of the Project Rulison experiment, the historic monitoring and sampling efforts that were undertaken, and the results of the monitoring and sampling during the detonation, reentry drilling, and flaring operations from 1969 to 1972, as well as monitoring and remediation activities that have occurred since that time.

## 2.1 Project Rulison Objectives and Chronology

Prior to conducting the Project Rulison experiment, the USGS collected water samples from wells, springs, and surface water sources in the area to evaluate baseline conditions. The USGS logged the emplacement well and evaluated the bedrock formations encountered in the boring for the presence of groundwater, and found that the formations did not yield water. Project Rulison occurred on September 10, 1969, with the detonation of a 43 ± 8 kiloton yield nuclear device. The technical objectives of the experiment were:

1) to measure changes in gas production caused by a nuclear explosion;
2) to measure effective flow capacity to the nuclear fracture zone with time and decreasing reservoir pressure;
3) to determine the gas quality with regard to contamination by radioactivity and techniques utilized in reducing this contamination;
4) to identify the effective height and volume of the chimney and the effective fracture zone radius as determined by volumetric measurements during production testing; and
5) To evaluate seismic effects produced by the detonation, to provide information on appropriate yields for any future development.

Austral Oil and the AEC waited seven months before commencing reentry drilling, where a second borehole, R-EX, was drilled into the underground cavity created by the blast. Austral Oil and the AEC waited to allow the radioactivity to decrease to less than one thousandth of that present 12 hours after the detonation occurred, before beginning reentry drilling.

Postshot re-entry site preparations began in April 1970. Directional drilling started toward the chimney of the cavity on June 29, 1970, and also involved cementing a 5½ inch diameter casing in place to a depth of 7,624 feet. Directional drilling was completed to a total measured drill string depth of 8,354 feet, or 192 feet above the detonation point, on July 28, 1970.

Approximately 456 million cubic feet (MMCF) of natural gas were produced in 108 days of flow testing between October 1970 and April 1971. At the time, this was the equivalent of approximately 10 years of production from a conventionally stimulated well drilled in the Rulison Field (AEC 1973, p.20). Calibration flaring was scheduled to start August 18, 1970; however, the hole plugged after initial flow tests were made on August 18 and August 22, 1970. A drill rig was brought back on site to clean out the borehole and operations were initiated on September 11, 1970 and completed September 29, 1970. Calibration flaring resumed October 4, 1970, and was completed on October 7, 1970 with the flaring of 12.9 million cubic feet (MMCF) of gas during this period.

High production flow testing began October 26, 1970, and continued to November 3, 1970, when the well was shut in for a short term buildup period. A total of 109.5 MMCF was flared during this test. Intermediate production flow testing began December 1, 1970, and was completed on December 20, 1970. A total of 99.9 MMCF of natural gas was flared to the atmosphere. The third, and final, flow test began on February 2, 1971, and ended on April 23, 1971, with a total of 233 MMCF of gas having been flared to the atmosphere.

### 2.2 Explosion Phenomenology

The detonation of an underground nuclear device releases an immense amount of energy. The extreme temperatures from the blast vaporized much of the rock, oil, water, and gas surrounding the emplacement hole resulting in an underground cavity, with an estimated radius of 76 feet. Immediately after the explosion, compressive shock waves fractured or altered the formation beyond the cavity wall. However, rebounding compressive stresses retain most radionuclides near the cavity region (Maxwell et al, 1999). At the Project Rulison site shear fractures were estimated to extend 276 feet from the cavity, and the maximum extent of fracturing was 433 feet out from the cavity. These estimated figures are consistent with the cavity radius of 78 feet as calculated from the recovered krypton-85, and the fluid loss encountered 275 feet above the working point in the re-entry well (AEC, 1973).

Within approximately one minute of the detonation, the formation pressure dropped and returned to pre-detonation lithostatic pressure of the formation. Melted rock puddled at the bottom of the cavity, cooling to form a glass several feet deep at the bottom of the cavity. When the pressure within the cavity dropped the roof could no longer support the weight of the fractured rock above and the roof collapsed into the cavity, forming a porous rubble column called a “chimney.” Within several days of the detonation, the cavity cooled, and condensation of steam occurred (Cooper et al, 2006). Formation gas and connate water flowed back into the cavity, eventually filling the cavity region

(Maxwell et al, 1999). Due to the impermeable nature of the surrounding rock, the connate water is likely to remain in the cavity.

The radionuclides produced as a result of the underground detonation are derived from the original materials of the device, nuclear reactions connected with the explosion, and activation products created in the surrounding geologic materials. Complex and dynamic processes occur within milliseconds to hours after detonation and control their chemical nature and spatial distribution (Tompson et al, 1999).

As the cavity cooled, radionuclides were distributed into four phases: 1) the melt glass, 2) as surface deposits on rubble in the chimney, 3) dissolved in water, and 4) in the gas phase (Cooper et al, 2006; Borg et al, 1976). Most of the heavier fission products from the detonation are refractory and are incorporated into the glass having condensed first. The melt glass does not have time to form a regular crystal lattice, and is therefore metastable due to its rapid quenching which means the glass will slowly break down and dissolve over long periods of time. Though surface-deposited nuclides are more readily dissolved into groundwater than those in the melt glass, many are reactive and tend to adsorb strongly onto mineral surfaces.

Most radionuclide vapors will be retained in the immediate cavity region by rebounding compressive stresses, although in some cases, small amounts of radionuclides may escape the cavity region as a result of pressure-driven "prompt-injection" (Tompson et al, 1999). Lighter radionuclides, such as tritium ($^{3}H$) as a radioactive form of hydrogen, condense later within a "radioactive" or "exchange volume" surrounding the cavity, within the fracture zone of two to five times the radius of the cavity. Other radionuclides will partially condense both within the melt and the rubble zone, and some radionuclides, such as krypton-85 ($^{85}Kr$) may exist only as noncondensible gases and move outside the immediate vicinity of the cavity/chimney system (Tompson et al, 1999).

## 2.3 Project Rulison Radionuclides of Interest

According to the January 2005 Rulison Site Environmental Management End State Vision Report, (US DOE, 2005) groundwater and natural gas in the immediate vicinity of the test cavity are contaminated with radionuclides. The migratory potential of these radionuclides via natural gas from the test cavity is being modeled. Table 2 presents the representative source term of radionuclides potentially present in the immediate vicinity of the Project Rulison cavity as adapted from Table 1.1 on page 6 of the End State Vision report. Table 3 presents radionuclides of interest, or those fission products that were included with the natural gas flared to the atmosphere and which remotely could be encountered in the natural gas resources during exploration and production today. The radionuclides possibly entrained in natural gas present within the cavity or in the

surrounding fracture zone include tritium, carbon-14, and krypton-85 (Cooper et al, 2004, 2006). These are discussed in more detail in the following sections.

Tritium

Tritium is a radioactive form of hydrogen. Most hydrogen is made up of one proton, and an orbital electron; however, tritium has two extra neutrons in the nucleus. Tritium is unstable because it contains these two extra neutrons in its nucleus which gives tritium an excess amount of energy. Tritium has a half-life of 12.3 years which means that half of the tritium present will decay every 12.3 years by slowly releasing the excess energy in the form of beta radiation and an anti-neutrino leaving a stable helium atom.

In nature, tritium is produced in small quantities when cosmic rays interact with nitrogen ($^{14}N$) or oxygen ($^{16}O$), causing spallation from the nuclei, forming tritium ($^{3}H$) and carbon ($^{12}C$), or when cosmic rays interact with hydrogen in the form of deuterium ($^{2}H$). These interactions primarily occur in the upper atmosphere and the resulting tritium falls to earth as precipitation, i.e., as either rain or snow. Therefore, tritium is present in small quantities as a naturally occurring radionuclide.

High levels of tritium are formed as a result of a nuclear detonation. Prior to atmospheric nuclear testing, the global equilibrium tritium inventory was estimated at 80 megacuries (MCi). Surface waters such as lakes and streams are estimated to have had a concentration of 5 to 10 pCi/L. Post World War II atmospheric testing caused an increase in atmospheric input rate of about 6 to 7 MCi per megaton yield. The United States and former Soviet Union stopped their above-ground tests in the early 1960s; however, China did not stop until much later. With rapid hydrosphere mixing, a half-life of 12.3 years, greater than natural level concentrations of man-made tritium can now be found worldwide in surface and shallow groundwater. These tritium levels have been declining back to the natural background levels with the reduction in aboveground nuclear weapons testing. The USGS and EPA data indicate the presence of naturally occurring or atmospheric tritium in surface water samples and samples from shallow aquifers and springs closely connected to shallow aquifers in the vicinity of Project Rulison.

Since tritium has a half-life of 12.3 years, meteoric tritium cannot be present in the Mesaverde Group, and if tritium were found within the Mesaverde Group in elevated quantities it could only be from a man-made source such as the Rulison cavity, or as background concentrations levels of naturally occurring tritium introduced from the surface in drilling fluids. Due to the time lapsed since the test in September 1969, any tritium remaining is approximately one-eighth of the original amount generated during the Project Rulison test, and the extremely low permeability of the formation inhibits migration of the tritium away from the cavity.

Tritium is almost always found as water, or "tritiated" water, rather than in a gaseous hydrogen state. Tritium found in underground nuclear test cavities is expected to be in the form of free water in the cavity or as water vapor entrained in natural gas, or possibly as part of the methane molecule within the natural gas (Copper et al, 2006). Since tritium may be present in water molecules, it is mobile and is expected to be the first radionuclide to migrate from a test cavity and surrounding fracture zone. Therefore, tritium is the primary radionuclide analyzed by the EPA at underground nuclear test sites which can serve as an indicator of radionuclide migration and can be used to age date groundwater.

Tritium is one of the weakest beta particle emitters known with a maximum beta decay energy of 0.019 mega electron volts (MeV), forming helium-3 as the decay product. The range of the most energetic tritium beta particles is only about 5 millimeters in air or 0.005 millimeters in water or soft tissue, making it nonhazardous outside the body, but its lack of energy presents a detection problem. Where other radionuclides can be detected by their penetrating radiation, tritium has to be introduced directly inside a detector or liquid scintillation counter in order to be measured. Therefore, water samples must be sent to a laboratory to detect the presence of tritium using a liquid scintillation counter under clean laboratory conditions.

Concentrations of tritium are reported in picocuries (pCi), or one-trillionth of a curie, in a liter of water. The laboratory is capable of measuring extremely low levels of tritium radioactivity. The EPA has established a drinking water standard for tritium of 20,000 pCi/L, expected to result in a total body dose of 4 millirems (mrem) per year. The derived air concentration (DAC) is 0.00002 microcuries per cubic centimeter ($\mu Ci/cm^3$), or 20 $pCi/cm^3$, and the annual limit intake (ALI) for tritium is 80 millicuries (mCi) or 80,000,000,000 pCi (Idaho State University and NRC website). The maximum permissible body burden for tritium to the whole body is 1 mCi, or 1,000,000,000 pCi (Worcester Polytechnic Institute, Radiation Safety Office website).

Once tritium enters the body it disperses quickly and is uniformly distributed throughout the body. Since tritium is in the form of water and disperses through the body, the entire body is of concern rather than target organs as is the case with other radionuclides. However, tritium is excreted through urine within a month or so after ingestion. Organically bound tritium can remain in the body for a longer period. While not impossible, ingesting a large enough dose of tritium to cause any significant harm to a person is unlikely (Idaho State University, Physics Department website, 2005).

Tritium can be used in combination with a chemical phosphor that emits light in the presence of radiation, causing it to "glow in the dark." Tritium is commonly used in applications that require a dim light source, but where using batteries or electricity is not possible. Some examples include exit signs, containing 10 curies of tritium, gun sights

which contain 0.012 curies, and luminescent dials on wrist watches which contain 0.8 millicuries (mCi) to 41 mCi. These common items contain concentrations of tritium that are many times to orders of magnitude higher that of what the laboratory is capable of measuring in water samples. Documentation of concentrations of tritium in radioluminescent devices was obtained from (Semkow et al, 2002) and Idaho State University Physics Department radiation information website.

Krypton-85

Krypton is a chemical element with the symbol Kr, and atomic number 36, that occurs as a colorless gas found in trace amounts in the atmosphere with a concentration of about one part per million (ppm). Krypton is isolated by fractionating liquefied air and is often used with other rare gases in fluorescent lamps. Krypton is referred to as a noble gas, similar to helium, argon, neon, xenon, and radon, so called because of their low chemical reactivity. Due to this limited interaction with other elements, krypton is considered chemically inert; however, krypton can form clathrates with water when atoms of krypton-85 gas are trapped in a lattice of water molecules (Wikipedia, 2006).

Krypton-85 ($^{85}$Kr) is a radioactive isotope of krypton with a half-life of 10.76 years and is naturally occurring in small quantities by the interaction of cosmic rays with the stable krypton 84 isotope. Krypton-85 forms in much larger quantities as a product of nuclear fission (Wikipedia, 2007). Krypton-85 has a beta decay energy of 0.687 MeV, and decays to form rubidium 85 ($^{85}$Rb) which is stable with 48 neutrons. Since krypton-85 is a beta particle emitter, the EPA drinking water standard is 4 mrem/year. The NRC has not established an ALI for Krypton, but has established a DAC of 0.0001 µCi/ml, which is equivalent to 100 pCi/ml.

Carbon-14

Carbon is a chemical element, with the symbol C, and atomic number of 6. Carbon-14, ($^{14}$C), or radiocarbon, is a naturally occurring radioactive isotope of carbon that was originally discovered by Martin Kamen and Sam Ruben on February 27, 1940 (Wikipedia, 2006). Its nucleus contains 6 protons and 8 neutrons. Its presence in organic materials is used extensively as a radiocarbon dating method to date wood and other organic samples or archaeological samples. Radiocarbon dating can be used to determine the age of carbonaceous materials up to 60,000 years.

Carbon-14 is produced naturally in the upper layers of the atmosphere (troposphere and stratosphere) by thermal neutrons absorbed by nitrogen atoms. When cosmic rays enter the atmosphere, they undergo transformations, including the production of neutrons.

The natural relative abundance of carbon-14 is one part per trillion (0.0000000001%) of all naturally-occurring carbon on Earth. The half-life of carbon-14 is 5,730 years, and it decays to stable nitrogen 14 ($^{14}$N) through beta decay, with a decay energy of 0.156 MeV.

The NRC has established an ALI for compounds containing carbon-14 of 2,000 µCi/ml, or (2,000,000,000 pCi/ml), and a DAC for compounds containing carbon-14 of 0.000001 µCi/ml, (1 pCi/ml or 1 pCi/cc).

Gamma Emitting Radionuclides

Gamma radiation is produced in association with the release of alpha particles and beta particles during decay of certain radionuclides; therefore, gamma emitting radionuclides are also of interest.

In the absence of nuclear testing, ambient gamma radiation rates naturally differ among locations since rates vary with altitude (cosmic radiation) and with radioactivity in the soil (terrestrial radiation). Ambient gamma radiation will also vary slightly at a location due to changes in solar radiation, weather patterns, and other environmental factors.

Project Rulison Radionuclide Estimated Activities

According to the Project Rulison Manager's Report, the following radionuclide activities were created as a result of the detonation:

- Tritium: A theoretical 10,000 curies of tritium were estimated to have been created, of which 2,824 curies of tritium were produced during the flow tests. Most of the gaseous tritium was removed from the cavity by the end of the testing (AEC, 1973 p. 25-26). An accounting of all of the tritium created could not be made because of the large quantity of tritiated water that was recovered at the conclusion of the testing, and an unknown volume of tritiated water remaining in the cavity. A significant portion of the tritium remains in the solidified melt zone. A boron carbide shield surrounding the nuclear explosive may have been effective in reducing the tritium produced by the explosion to less than 10,000 curies, but a lack of tritium balance made it difficult to evaluate the actual quantity.

- Krypton-85: A theoretical 800 curies of $^{85}Kr$ were estimated to have been produced as a result of the explosion. However, the volume of the cavity was calculated based on an observed release of 1,064 curies of $^{85}Kr$ as well as the observed reservoir pressure and temperature which indicated a radius of 78 feet. The yield of the device was subsequently calculated at $43 \pm 8$ kilotons based on the creation of approximately 1,113 curies of krypton-85 (AEC, 1973 p.25).

  It has been suggested that the difference between total and recovered $^{85}Kr$ suggests that 19% of the radioactive gas escaped due to prompt injection into the surrounding reservoir rock. The Project Manager's report, based in large part on data from Smith, 1971, indicates that all of the $^{85}Kr$ produced by the nuclear device was accounted for in the flaring. Four separate estimates of $^{85}Kr$ production by the nuclear device, ranging from 1005 to 1112 Ci. Smith himself

uses 1100 curies for the production amount in calculations, although the average of the estimates is 1066 ± 20 Ci. Without decay-correcting the amounts produced during the post-shot reservoir testing, 1065 Ci of $^{85}$Kr were removed from the subsurface (AEC, 1973). Decay correcting the amounts produced during the post-shot reservoir testing would only increase the portion of the original mass removed. The precise amount of $^{85}$Kr created cannot be determined given the error bounds. The Project Rulison radiochemical analysis data presented as Figure 9 in the Project Manager's report shows the $^{85}$Kr going to zero (AEC, 1973 Figure 9, pg 26) as concentration vs. cumulative gas produced.

- Carbon-14: The estimated inventory of carbon-14 is 2.2 curies (DOE End State Vision, 2006) produced by the Project Rulison detonation. The carbon-14 is likely to be incorporated in the carbon dioxide ($CO_2$) molecule. Most of the carbon dioxide was initially formed at the time of the detonation and possibly some generated from the heat of the rock melt. Carbon dioxide concentrations were found to increase as the well produced, whereas the hydrogen concentration in the gas declined (AEC, 1973 p. 28).

These radionuclides are also identified as being the most mobile and therefore most likely to be present in the gas in the DOE Project Rulison End State Vision document dated January 2006. Table 2 presents:

1) A list of the "estimated inventory" of other radionuclides present within the cavity, including the radionuclides of interest and those trapped in the glass within the cavity based on Rulison data and data from the Nevada Test Site;
2) the half-lives of these radionuclides;
3) the primary type of radioactive decay mode,
4) the natural abundance of each radionuclide; and
5) the radiation energy and daughter products produced by each of the radionuclides adapted from the End State Vision Document. A copy of the DOE End State Vision Document is included as Appendix A.

## 2.4 Project Rulison Environmental Surveillance

Samples of water, soil and vegetation were collected prior to the detonation to establish background radiological conditions of the site. Preshot and postshot precipitation samples were collected by the USGS. Samples of water, soil, and vegetation, were also collected prior to, during, and after completion of the drilling operations, and prior to the start of flaring, during calibration flaring, and periodically during and after each production test. Continuous air samples were collected during the drilling operations.

Precipitation samples were collected during both the calibration flaring and production testing.

## 2.5 Project Rulison Radiological Monitoring

The AEC oversight included onsite radiological safety monitoring conducted during the Project Rulison detonation phase, reentry drilling, and the flaring operations. Several different methods were employed to monitor for the presence of radionuclides. The AEC contracted the Eberline Instrument Company (EIC) to provide onsite radiological safety support for Project Rulison which included;

1) Installation and operation of Remote Area Monitoring Systems (RAMS) around the site for effluent documentation and hazards evaluation (during the detonation phase only);
2) Around the clock site surveillance by certified radiation monitors;
3) Environmental sampling;
4) Operation of onsite sample preparation and radiological measurement trailers;
5) Installation and operation of continuous effluent monitoring systems during post detonation activities;
6) Radiation area access control;
7) Personnel dosimeters;
8) Instrument maintenance and calibration;
9) Control of radioactive and contaminated materials and equipment;
10) Report preparation, including daily reports to open file during postshot activities; and
11) Maintaining the capability to respond to radiation incidents in case of an emergency (AEC, 1973, p.85).

Beginning with the detonation phase, and during all operations through completion of the production testing, one or more AEC representatives were present at the Rulison location. Radiological monitoring and sampling programs were conducted both onsite and offsite. No fresh fission products attributable to Project Rulison were found in any of the air, water, milk, feed, soil, vegetation, animal, precipitation, or natural gas samples analyzed following the detonation phase (AEC, 1973, p. 106).

**Detonation Phase Monitoring**

During the detonation phase, eight RAMS detectors were installed in a circular array around the Project Rulison test site at a distance of approximately 300 feet, and one was placed on the R-E wellhead unit. All of the RAMS units, including the one on the wellhead reportedly survived the ground shock, and no radiation above normal background was detected by any of these units.

Weekly readings were recorded by a gamma scintillation detection system equipped with a strip chart readout installed on the wellhead, prior to the site being placed in a caretaker status. Action guidelines were established for indicated radiation levels of 3 milliroetgen per hour (mR/hr) above background (AEC, 1973, p.85).

**Reentry Drilling Monitoring**

EIC installed monitoring systems and analyzed drilling fluids for radioactivity during reentry drilling of the R-EX borehole. EIC installed and calibrated systems to continuously monitor all drilling mud, chips, and gas prior to the start of drilling. Remote monitors for explosive gas mixtures around the drill rig, tanks, and exhaust air ventilation system were installed and operated continuously by EIC personnel.

Radiological analyses were performed in an onsite laboratory trailer equipped with gamma scintillation detectors with a multichannel analyzer, a gas flow proportional alpha and beta counter, and a liquid scintillation spectrometer. Sample preparation was conducted in a separate trailer onsite. An oxidizer was used to combust samples of organic materials and natural gas from which the water of combustion was collected and analyzed for tritium (AEC, 1973, p.86).

Portable radiation detectors and industrial hygiene hazard detection equipment for toxic and explosive gases were also provided by EIC. Detection of contaminated fluids, consisting of oily rig wash water, rain or snow melt, diesel oil, and mud, was accomplished by:

1) periodically checking mud samples for tritium and gross gamma activity,
2) continuously analyzing off-gas for tritium and krypton-85; and
3) using a gamma detector over the shaker table capable of detecting krypton-85.

As an added precaution, all water was assayed and contained in two 500-gallon capacity tanks and one 9,000-gallon capacity tank. Samples, swipes, and air and vapor samples in the work area were analyzed and all found to be at background levels. No detectable activity was found in the mud or water displaced from the borehole annulus between the production tubing and the casing (AEC, 1973, p.87).

**Calibration Flaring Monitoring**

During calibration flaring radiological data were collected from samples obtained in the downwind trajectory of the plume, as well as from rain-out data, plume rise data, and actual concentrations of tritium and krypoton-85 in the effluent plume. Concentrations obtained with onsite instruments were compared with actual isotopic concentrations found in the downwind samples. After the drill rig was removed, remote monitors were deactivated or were moved to different locations such as the flare line to monitor effluent

flow. A fraction of the gas was diverted, dried, and passed through a special chamber known as a STALLKAT, an acronym for "system to analyze low-level krypton and tritium." The one-of-a-kind, experimental instrument was developed for use with Project Gasbuggy in New Mexico, the first underground nuclear test designed to liberate natural gas from tight gas sands. Although using the STALLKAT had drawbacks, not the least of which was poor sensitivity to tritium, it was the best available technology for its time. However, its lack of tritium sensitivity required assuming a constant tritium-krypton ratio for many of the smaller release estimates (AEC 1973, pg 67).

Tritium and krypton-85 concentrations were measured using the STALLKAT and the results were recorded during the flaring. Liquids, including water and hydrocarbons, were separated from the sampled gas and were analyzed for tritium and fission products to document the condition of the gas going to the flare stack. The larger portion of these liquids was removed by a separator and stored in steel tanks, and was sampled and analyzed for tritium, gross beta, and gamma emitters before being re-injected into the flare. A gross gamma scintillation detector was also mounted on the flare line and set to alarm if any unexpected release of fission products occurred (AEC, 1973 p.87-90). None were detected.

No air samples taken in work areas showed activities above background, except for tritium water vapor during flaring periods. The highest air concentration observed was 100,000 ($10^5$) times less than the level established by AEC Manual 0524 for occupational workers. Analysis of onsite vegetation and soil samples showed only worldwide fallout and natural activity, except for areas with known spills, and the close-in area contaminated with fallout or snow out from the flare stack (AEC, 1973, p.76).

During the first production test, or high-rate flaring, approximately 420 curies of krypton-85, 620 curies of tritium, 0.9 curies of carbon-14, and 0.00004 curies of mercury-203 were released to the environment (AEC, 1973, p. 95). Radioactivity concentrations in the natural gas sampled after the separator are included in the following table.

Flaring at 2 MMCF per day was conducted on October 4, 1970. Of the numerous samples collected, only four atmospheric moisture (tritium) samples were significantly above background: 1) 50 picocuries per cubic meter ($pCi/m^3$) on Morrisania Mesa and 2) 12 $pCi/m^3$, 46 $pCi/m^3$, and 170 $pCi/m^3$ on Holmes Mesa. Radioactivity concentrations guides in air for the general offsite population were 67,000 $pCi/m^3$ for tritium and 100,000 $pCi/m^3$ for krypton-85 (AEC, 1973 p. 106). The EPA and NERC failed to detect any offsite levels significantly above background following the October 5, 1970 flaring at 10 MMCF per day. The EPA/NERC samples indicated tritium levels in the offsite area ranged from background, 5 to 10 $pCi/m^3$, to a maximum of 290 $pCi/m^3$ at a sampling location about ½ mile from the flare stack (AEC, 1973 p. 107). All of the Colorado

Department of Public Health and Environment samples were within the range of background.

Project Rulison Gas Testing Monitoring Results

| Radionuclide | Testing Event | Initial Flaring Concentration In the Gas (pCi/cc) | Final Flaring Concentration In the Gas (pCi/cc) |
|---|---|---|---|
| Tritium | First Production | 185 | 160 |
| | Second Test | 150 | 100 |
| | Third Test | 90 | 3.3 |
| Krypton-85 | First Production | 145 | 125 |
| | Second Test | 125 | 90 |
| | Third Test | 80 | 2.8 |
| Carbon-14 | First Production | 0.35 | 0.30 |
| | Second Test | 0.28 | 0.23 |
| | Third Test | 0.19 | 0.07 |

pCi/cc – picocurie per cubic centimeter (about the volume of a sugar cube) equivalent to one picocurie per milliliter (pCi/ml)

The isotope mercury-203 was also detected in the Rulison gas samples following the experiment. Chemical analysis of the formation rock near the point of detonation indicated that sufficient mercury was present naturally to produce the minute concentrations of mercury-203 observed in the Rulison gas (AEC, 1973, p.25). Approximately 0.00003 curies of mercury 203 were observed in the Rulison gas following the third production test.

Snow samples collected at the time of production flaring were analyzed for tritium concentrations. They indicated tritium levels ranging from background to a maximum of 1,800 picocuries per milliliter (pCi/ml) during the first production test, and a maximum of 5,100 pCi/ml of moisture, during the second production test, both collected as single day samples 20 yards from the flare stack. The maximum readings resulted from short term rainout of tritiated water from the flare, after accidental extinguishing of the flame (AEC, 1973, p. 95). At no time during the entire production testing did onsite radiation surveillance detect any Rulison-related radioactivity in the environment, other than tritium (AEC, 1973, p. 96).

During site cleanup conducted and completed in July 1972, soil and vegetation samples were collected to determine the distribution and concentration of residual tritium impacts.

All soil samples were below the tritium cleanup concentration guide of 30,000 picocuries per gram (pCi/g). The maximum concentration observed in soil was 20,000 pCi/g. The maximum tritium concentration in vegetation was 150 pCi/g (wet). Tritium concentrations were not detected above background levels in samples of site spring water and site air moisture. The concentrations of tritium in the produced water remained essentially constant throughout the flow testing indicating no influx of new water from the producing formation (AEC, 1973, p. 27).

## 2.6 Project Rulison Personnel Dosimetry

Film badges were issued to personnel involved during the initial reentry drilling. Urine samples were also collected from ten EIC personnel prior to detonation to establish individual background levels. No urine samples were collected after the detonation, since there was no release of radioactivity.

During the reentry drilling, calibration flaring, and production testing all personnel entering controlled areas at the Rulison site were issued thermoluminescent dosimeters (TLDs). No onsite personnel received whole body beta or gamma doses during the report period as measured by TLDs. Urine assays for tritium showed no positive results (AEC, 1973, p.75-76, and 96).

## 2.7 Project Rulison Environmental Oversight

Project Rulison site cleanup activities were conducted from 1972 to 1976. The following sections describe environmental oversight activities conducted since that time which have included annual groundwater sampling, an aerial survey, and surface radioactivity survey.

Groundwater Sampling

The EPA has been conducting long-term monitoring of groundwater resources from area wells, springs, and surface water locations since July 1972. The results of the water sampling have not indicated the presence of tritium or gamma emitting radionuclides related to Project Rulison.

Cordilleran submitted Freedom of Information Act (FOIA) letters requesting the groundwater radiochemistry data from 2005 and 2006 in March 2007. Cordilleran received a response dated August 13, 2007 from the DOE which included both reports. Copies of these reports are included as Appendix B. The results for the Rulison area indicate that concentrations of gamma radiation emitting radionuclides were not detected in any of the samples collected during 2005 or 2006. Concentrations of tritium analyzed by the conventional method indicated that tritium was not detected. Concentrations of tritium analyzed using the enriched tritium method are consistent with values found in current precipitation.

Surface Area Cleanup

In May 1986, Reynolds Electrical and Engineering Company under the direction of the DOE Nevada conducted a Hazardous Waste Installation Assessment to identify and evaluate areas at the Rulison site where hazardous substances may have been released into the environment. The assessment was to comply with the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). Desert Research Institute prepared a CERCLA Preliminary Assessment of Project Rulison in 1988. However, the CERCLA Hazard Ranking System score calculated for Project Rulison was well below the score required for a site to be placed on the National Priorities List (NPL). The DOE's Office of Environmental Management cleaned up the surface of the site to meet the Colorado Department of Public Health and Environment (CDPHE) Water Quality Control Standards.

In 1994 and 1995, four pond samples were collected from the effluent pond located approximately 1,312 feet (400 meters) north-northwest of the Project Rulison emplacement hole (R-E). The drilling effluent pond was used to store non-radioactive drilling fluids generated during the drilling of the device emplacement hole (R-E). The assessment found residual impacts from drilling wastes remaining in the pond consisting of concentrations of diesel range total petroleum hydrocarbons, benzene, toluene, ethylbenzene, and xylenes, barium, chromium, and lead were found in pond sediment samples. Based on the results of the 1994-1995 sampling, the DOE decided to conduct a voluntary cleanup action at the pond to address the impacts in the pond sediments (Appenzeller-Wing and Mellington, 1997). The pond cleanup was completed in November 1995. The assessment included the installation of seven shallow groundwater monitoring wells to evaluate groundwater impacts associated with the pond within the unconsolidated alluvial and colluvial deposits. The assessment and cleanup activities were completed in November 1998. The monitoring wells were plugged and abandoned in 2001.

Aerial Radiological Survey

An aerial radiological survey was conducted by EG&G Energy Measures over the Project Rulison site from July 6 through July 12, 1993. Parallel lines were flown at intervals of 250 feet over a 6.5 square mile area at an altitude of 200 feet surrounding the Battlement Creek Valley. The gamma energy spectra obtained were reduced to an exposure rate contour map overlaid on a high altitude aerial photograph of the area. Terrestrial exposure rate varied from 3.5 µR/hr to 12.5 µR/hr, excluding cosmic radiation at one meter above ground level. This is consistent with area background radioactivity levels. No anomalous or man-made radionuclides were found (Hopkins, 1995).

Surface Radioactivity Study

The DOE and EPA have conducted other investigations of the Project Rulison site as well as at two other Plowshare underground nuclear test sites, Project Rio Blanco, Colorado, and Project Gasbuggy, New Mexico. The EPA conducted surface soil characterization at these sites and the results were reported in January 1995. According to the report abstract, the abundances of man-made and naturally occurring radionuclides were determined with their contributions to total exposure rates. Cesium 137 ($^{137}$Cs) was the only fission related radionuclide detected. The highest concentrations were detected in undisturbed forest litter which is known to accumulate fallout of radiocesium. The highest concentrations of $^{137}$Cs were reported in samples collected off-site at the Project Gasbuggy and Project Rio Blanco locations. The amounts observed were consistent with radiocesium fallout concentrations observed in other parts of the United States (Faller, 1995).

Therefore, this radiocesium appears to be related to global fall-out from aboveground nuclear tests conducted at the Nevada Test Site since the reported activities are consistent with those observed at other locations in the United States with similar amounts of precipitation (Faller, 1995). Exposure rates due to $^{137}$Cs in the environment are typically less than 1 µR/hr (Hopkins, 1995). The following table for surface readings is adapted from the January 1995 report (Faller, 1995).

| Location | Cosmic (µR/hr) | $^{40}$K (µR/hr) | $^{232}$Th (µR/hr) | $^{238}$U (µR/hr) | $^{137}$Cs (µR/hr) | Sum γ (µR/hr) | PIC (µR/hr) |
|---|---|---|---|---|---|---|---|
| Well R-E (Emplacement Hole) | 9.7 | 3.3 | 3.3 | 2.3 | 0.07 | 18.6 | 17.0 |
| Well R-EX (reentry Hole) | 9.7 | 3.9 | 3.0 | 2.0 | 0.05 | 18.6 | 17.5 |
| Effluent Pond (Hayward 96 Ranch) | 9.3 | 4.5 | 3.6 | 2.0 | 0.18 | 19.7 | 17.5 |
| 32 Kilometers North | 8.6 | 2.9 | 2.7 | 1.7 | 0.04 | 16.0 | 15.7 |

µR/hr - microroentgen per hour

PIC – portable ion chamber

The sums of the deduced exposure rates and total rates measured with the PIC were within the uncertainties expected of the analytical methods used. The relative collection efficiency of the high purity Germanium (HpGe) detecting device was about 30 percent. Exposure rate contributions from Potassium 40 ($^{40}$K) and the Thorium 232 ($^{232}$Th) and Uranium 238 ($^{238}$U) series were calculated assuming a uniform distribution in the ground. No reduction in rate due to the de-emanation of radon gas was assumed. Also the rate from Cesium 137 ($^{137}$Cs) was calculated using a depth distribution parameter, $\alpha/p$ of 0.05 as no core samples were collected as part of the study (Faller, 1995).

Desert Research Institute Natural Gas Radiochemistry Samples

According to an October 10, 1997 DOE press release, LLNL completed radiation analysis of natural gas samples collected from production wells near Project Rulison. According to Mr. Peter Sanders – DOE Nevada, Rulison Site Project Manager, all analytical results for total activity were well below the lower limit of detection. Copies of the sample results were not provided.

On May 5, 2005, the Desert Research Institute (DRI), under contract to the DOE, sampled five commercial gas wells producing from near the site of the Project Rulison gas stimulation test site were sampled and analyzed for tritium. Four of the wells sampled were located just within the three-mile notification radius to the northwest of the Project Rulison site, and the fifth well was located approximately five miles to the northeast of the Project Rulison site. The gas wells sampled included,

- The 28-31 South Parachute Federal;
- The 15-34 Clem-Warren;
- The 11-43 Bentley;
- The 11-34 Bentley; and
- The 10-11 Savage.

The samples were collected and contained in five new 20-pound steel propane bottles, filled with wellhead gas, and were purged three times to ensure representative samples.

The samples were obtained directly at the wellheads with pressures limited to less than 30 pounds per square inch (psi), as specified by the analytical facility. The samples were sent to Isotech® Laboratories, Inc. (Isotech®) in Champaign, Illinois, for compositional analysis, $\delta^{13}$ carbon analysis of methane, carbon-14 ($^{14}C$), and tritium ($^{3}H$) by beta spectrometry. Tritium and carbon-14 were not detected in any of the five samples. A copy of the DRI report is included as Appendix C.

In January 2005, the DOE Environmental Management Office published the Rulison End State Vision document. This document was designed as a tool to communicate individual site end state to involved parties, i.e., the DOE, regulators, and public stakeholders. It states that it was not designed to be a decisional document. The Project Rulison surface area has been remediated; however, the DOE/Nevada Site Office (NSO) does not plan to remediate the subsurface because of the lack of feasible technologies for removing the materials within the subsurface cavity. Subsurface characterization of the Rulison site was scheduled to begin in the fiscal year 2005. According to the End State Vision document, the DOE has identified plutonium, tritium, and mixed fission products as compounds of concern in the subsurface, with gaseous radionuclides (tritium, carbon-14, and krypton-85) being the most mobile in the environment. The End State Vision

document states that at the present time, the hazard extent has not been defined; however, the DOE will continue to investigate and model subsurface contamination. According to the Life-Cycle Baseline Revision 5, subsurface closure of the Rulison site is scheduled for completion in fiscal year 2011.

According to the FY 2005 DOE Congressional Budget request, the DOE requested $1,438 for laboratory costs for Project Rulison. According to the DOE FY 2006 Congressional budget request, Volume 5, February 2005, no budget was allocated for the fiscal year 2006; however, the narrative states on pages 157 and 158 that

"…o*ffsite closure at eight former nuclear testing sites in Alaska, Colorado, Mississippi, Nevada, and New Mexico. Off-site surface closure eliminates potential access to contamination by removal and clean closure or closure in place, capping and establishing appropriate use restrictions. The focus for most off-site surface closures will be to allow unrestricted use by site landlords. Subsurface closure includes completing predictive flow models and establishing monitoring networks where necessary to ensure that contaminated groundwater remains within expected boundaries – associated use restrictions and institutional controls will be in place within the predicted contaminant boundaries to preclude inadvertent contact with subsurface contaminants*."

"*For the Rulison, Colorado, subsurface, the flow and transport analysis and radioactive risk analysis will be completed*."

The Responsibility for DOE management of the site was transferred to the DOE Office of Legacy Management in Grand Junction, Colorado as of October 1, 2006. Prior to this Project Rulison had been managed by DOE Nevada Office of Environmental Management.

## 2.8 Project Rulison Radionuclide Transport Modeling

The DOE has proposed two possible radionuclide release scenarios for groundwater contamination which include 1) surface contamination from site activities conducted at the time of the experiment and 2) subsurface contamination resulting from radionuclides from the cavity. Monitoring was conducted at the time of the re-entry drilling and flaring activities, the site surface has been remediated, and subsequent investigations have not identified any Project Rulison related radioactivity. Therefore, the first scenario has been eliminated. The second scenario is considered highly unlikely as it requires continuous fractures to be formed through thousands of feet of cement since the two wells drilled for Project Rulison were plugged and abandoned after the experiment was concluded further reducing the probability they could act as conduits for the flow of radionuclides from the cavity to the surface (Earman et al, 1996).

Using the total radiologic source term is an overestimation of the possible hydrologic source term to the Mesaverde Group because it is known that significant amounts of radioactivity remain essentially immobile in the cavity and chimney after a nuclear test. Some radionuclides are unable to migrate from the cavity because they are entrapped in the melt glass. Additionally, production testing for the natural gas conducted from 1970 to 1971 removed portions of the gaseous radionuclides from the cavity (Earman et al, 1996).

The Desert Research Institute and DOE have prepared preliminary computer model simulations for tritium migration through the low permeability Mesaverde Group natural gas reservoir. Gas diffusion was found to be important in the overall transport, with only limited additional migration driven by advection from assumed gas production from a well. Other parameters affecting tritium migration include variable permeability and gas production rates, gas saturation, and tortuosity model (the circuitous pathway of pores and fractures in the rock through which the gas must travel). Of importance in all simulations are the exchange and decay processes. While tritium migration occurs essentially only in the gas phase, exchange into liquid water serves to effectively trap tritium mass along the gas pathway, while tritium decay also allows for significant mass decay over the time scales considered for the production from nearby gas wells, i.e., 30 years (Cooper et al, 2006).

The preliminary computer model simulation shows tritium migration due to diffusion only for the first 36 years since the experiment as the first gas wells were not drilled in the area until 2005. Approximately three tritium half-lives have lapsed during this time meaning that one-eighth of any of the original tritium produced, minus the tritium which was removed during flaring of gas from the re-entry well, is still present. The results show that for the initial and boundary conditions modeled that a concentration of 1 pCi/L nearly reaches the drilling exclusion zone (Lot 11) after 10 years of pumping (Cooper, 2004) assuming that all the simulation parameters are correct. For comparison, atmospheric tritium concentrations typically range from 0.4 $pCi/m^3$ to 1.3 $pCi/m^3$, tritium concentrations in precipitation typically ranges from 2.7 pCi/L to 91.9 pCi/L, and the EPA drinking water standard for tritium is 20,000 pCi/L.

For the most part tritium migration is unaffected by pumping and is controlled only by diffusion in the gas phase, as the pumping rate is so low. The simulation suggests that after 30 years of pumping, near the end of the production life of the natural gas production well, the edge of the theoretical tritium "plume" has traveled approximately 180 meters (590 feet), but is still 280 meters (918 feet) from the hypothetical production well. Radioactive decay of tritium is responsible for the decline in concentrations at the center of the plume and also is responsible for controlling the growth of the plume, with little lateral migration 45 years after the Rulison test (Cooper, 2004).

# 3.0 PRESCO MONITORING ACTIVITES

PRESCO conducted the following monitoring activities during the drilling of natural gas wells on Battlement Mesa in the proximity of Project Rulison, during 2006, as part of the first phase of natural gas well development:

1) Screening the BM 35-12 well pad using a Ludlum Model 3 Survey Meter and pancake probe. The BM 35-12 well pad is located in Section 35, T7S, R95W, southwest of the Project Rulison site and outside the ½ mile radius. Screening of the well pad was conducted on August 24, 2006 prior to initiation of drilling and again on September 13, 2006 while the drill rig was onsite;
2) Screening the BM 35-12 drill cuttings using the Ludlum Model 3 Survey Meter. Recording the Model 3 Survey Meter drill cutting screening results for the BM 35-12 to assess background radioactivity levels for each of the geologic formations encountered;
3) Using Landauer® Environmental TLD badges posted on location to continuously evaluate potential gamma radiation exposures;
4) Collecting samples of natural gas for isotopic analysis including tritium and carbon-14; and
5) Collecting samples of produced water for radionuclide analysis including tritium and gamma spectroscopy.

PRESCO and Cordilleran developed a Work Plan in October 2004, and finalized the Work Plan on May 26, 2005. The Work Plan included protocols for the collection of water samples from area wells, springs, and surface water (creeks). The data obtained from these activities was presented in a report dated March 2006 that was sent to PRESCO and copies were also provided to the COGCC.

The Work Plan also outlined monitoring activities during gas well drilling activities. These monitoring activities were based on what the AEC had done during the Project Rulison experiment. The Work Plan took into consideration that

1. PRESCO's activities were located outside the 40 acres surrounding the Project Rulison, as set aside by the AEC/DOE, also described as Lot 11 located in the Northeast Quarter of the Southwest Quarter of Section 25, Township 7 South, Range 95 West, of the Sixth Principal Meridian;
2. PRESCO's activities during 2005 and 2006 were conducted outside the ½ mile radius set by the COGCC;
3. the impermeable nature of the Mesaverde Group and overlying sediments; and
4. the estimated inventories of the radionuclides produced by the explosion, their chemical and radiological properties, and the half-lives of the radionuclides possibly entrained in the gas in developing the monitoring activities employed.

The individual monitoring and sampling activities PRESCO conducted are described in the following sections.

## 3.1 Work Plan Deviations

The purpose of the Work Plan was to conduct sampling and monitoring activities for wells that PRESCO drilled within the COGCC ½ mile radius surrounding Project Rulison. There were no additional requirements or restrictions for any operator drilling outside the ½ mile radius. It is important to meet the objectives identified in the Work Plan; however, a Work Plan should be flexible to allow for changes in the sampling and monitoring program, based on new information as it becomes available, and allow for the collection of meaningful data.

Laboratory Radiochemistry Analysis of Drill Cuttings

Since the wells PRESCO drilled and completed in 2005 and 2006 were all outside the COGCC ½ mile radius from Project Rulison, no drilling mud or drill cutting samples were submitted for laboratory analysis. There is no mechanism by which radionuclides related to Project Rulison could come into contact with drilling muds or cuttings from the gas wells PRESCO drilled during 2005 or 2006. The Ludlum Meter readings did not indicate the presence of radioactivity above natural background levels.

The COGCC agreed to notify the DOE of applications within a 3-mile radius of Project Rulison. The COGCC notified the DOE of the drilling applications for these wells. The DOE in Nevada responded to the COGCC in August 2003 pursuant to PRESCO's BM 27-44 and indicated that did not plan to sample natural gas from this well, but they might collect a gas sample in the future, and that they were relying on existing data to create a flow and transport model for the Project Rulison site.

Ludlum Meter Screening

The Work Plan originally stated that readings were to be recorded in milliroetgens per hour (mR/hr); however, in 2005 after reviewing the protocols with Janet Johnson, Ph.D, Senior Scientist Health Risk Assessment with Tetra Tech, Inc., (formerly MFG, Inc.) the Ludlum model 3 survey meter and pancake probe (model 44-9) do not provide an accurate exposure rate in mR/hr, only a relative reading using this scale. Dr. Johnson suggested that using the counts per minute (CPM) would be more meaningful with this type of meter. She also indicated that radiation levels should be evaluated for each formation to establish background conditions.

In 2005 the earlier readings were converted to CPM by reading them off the corresponding meter scale. These readings establish site specific background values.

The drill cuttings were generally screened on 30 foot intervals. In 2005 the Ludlum meter screening consisted of screening drill cuttings from the entire boring intervals of the BM 26-42 and BM 36-13, whereas for wells BM 36-23 and the BM 34-24 only drill cuttings from the Mesaverde Group were screened. In 2006, the only well PRESCO drilled in the vicinity of Project Rulison was the BM 35-12. Drill cuttings from the BM 35-12 were screened for the entire boring interval, and in some cases were screened more frequently than every 30 feet.

Wipe Samples

Since PRESCO's 2006 drilling activities were outside the ½ mile radius from the Project Rulison site and PRESCO was not flaring any natural gas, tritium wipe samples were not collected from drill rig surfaces or other structures and equipment onsite. Since no flaring of natural gas was conducted there was no pathway for tritium as water vapor to be released to the atmosphere. Samples of the natural gas and samples of produced water were collected and submitted for laboratory analysis of tritium for each 60 MMCF volume of gas produced from the four wells closest to Project Rulison.

Gas Samples and Produced Water Samples

The gas samples were submitted to Isotech® for the same analysis as performed on natural gas samples collected from area gas wells by the DOE/EPA. The work plan originally stated that the gas samples would be analyzed for krypton-85; however, Isotech® is not able to perform this analysis on the gas samples, and the work plan was revised.

Produced water samples have been collected from the BM 26-42, BM 27-44, BM 34-24, BM 36-13, and the BM 36-23 beginning in late 2005 through 2006. These wells are located outside the COGCC ½ mile radius of the Project Rulison site and are located to the south and west. The BM 36-13 is located 200 feet outside the ½ mile radius to the south and the BM 27-44 is located approximately 1½ miles to the west.

Produced water sample were submitted to Paragon Analytics for analysis of tritium and gamma emitters, but Paragon is not able to analyze for the presence of carbon-14 or krypton-85. The tritium analysis and gamma spectroscopy analysis conducted is consistent with that the DOE/EPA has been conducting for samples collected from area water wells, springs, and surface water locations, and is consistent with the analysis PRESCO has been conducting for their baseline and ongoing water monitoring.

Tritium has only been analyzed using the conventional method, which typically has a method minimum detectable activity (MDA) of 300 pCi/L to 400 pCi/L. The DOE/EPA has used an enriched method for tritium analysis on a few of their annual well and spring groundwater samples. The enriched method uses an electrolysis concentrate and distillation process to achieve a lower detection limit of 5 pCi/L. The EPA currently

analyses all of the water samples by the conventional method and then selects 25% to be analyzed by the enriched method in areas where migration is possible. Tritium analysis performed by the enriched method is only performed by a few laboratories nationwide, is more expensive, and requires a long time to receive the results. The MDA for the conventional method are well below the EPA drinking water standard of 20,000 pCi/L.

### 3.2 Ludlum Model 3 Survey Meter Screening

Cordilleran used the Ludlum model 3 Survey meter equipped with a Ludlum model 44-9 pancake Geiger-Mueller probe to conduct area screening of the BM 35-12 well pad prior to drilling, screening again during the drilling, and to screen drill cuttings from the BM 35-12 well. PRESCO did not drill any other gas wells in the area of Project Rulison during the 2006 field season.

The Ludlum model 3 survey meter and Geiger Mueller pancake probe do not detect tritium but the survey meter was used to screen for radioactivity since the instrument is able to detect alpha, beta, and gamma radiation. The instrument detects beta radiation with high efficiency; however, since tritium is a weak beta radiation emitter the instrument is not sensitive enough to detect tritium. Field detection of tritium is difficult because tritium has a low beta particle energy, and due to potential interference from other radionuclides. In order to analyze for tritium there is a need for large equipment, such as a liquid scintillation counter, and a clean work area free of dust and engine exhaust to be able to adequately prepare and analyze the samples to obtain accurate tritium concentration results.

The Ludlum model 3 survey meter was used to screen the drill cuttings from the gas well pads for radiation and the results were recorded in counts per minute (CPM). During 2005 Cordilleran revised the Work Plan and had the Pason Systems Inc. (Pason) geologist performing the mudlogging record the readings of subsequent wells in CPM. The readings reported in mR/hr for the first two wells were converted to CPM by comparing the instrument scales.

During 2005, the Pason geologist screened drill cuttings from the BM 26-42 and the BM 36-13 gas wells from the surface to the total depth drilled, which included readings from the Green River Formation, the Wasatch Formation, and from the Mesaverde Group. The Pason geologist screened drill cuttings from the BM 36-23 and the BM 34-24 only from the Mesaverde Group since this is the production interval, and the interval in which Project Rulison was conducted.

During 2006, PRESCO did not hire Pason or anyone else to perform mudlogging services. Cordilleran received drill cuttings from the BM 35-12 well and screened them with the Ludlum Model 3 meter and probe. Copies of the screening logs, statistical data

evaluation, comparison with previous wells, and calibration records are provided in Appendix D.

### 3.3 Landauer® Dosimetry Badges

Environmental, low-level dosimetry badges were obtained from Landauer® of Glenwood, Illinois to evaluate personnel dosimetry and area environmental monitoring. These type of Landauer® badges were selected since they are rugged enough to be used outdoors and tolerate environmental extremes, and are sensitive enough to provide accurate reporting to 0.1 millirem (mrem) or 1 microSievert (µSv).

Landauer® designed these thermoluminescent dosimetry (TLD) badges for environmental and low level dosimetry applications which are significantly improved over previous dosimeters. The environmental/low-level dosimeter can be used indoors or outdoors, and is designed to withstand extremes in temperature, humidity, precipitation, and other environmental conditions. The holder is constructed of opaque, matte black polypropylene plastic, sealed within a heavy-duty vinyl tamper resistant pouch and has multiple slots to permit several methods of attachment for easy deployment.

The technical specifications for the TLD badges are as follows:

- Fully meets ANSI N545 performance, testing, and procedural specifications;
- Thermoluminescent element is aluminum oxide ($Al_2O_3$:C);
- Favorable atomic number (10.2) compared to calcium based TL materials (14-16);
- Two TLDs per dosimeter;
- Minimum detectable dose is nominally 0.1 mrem (1 µSv); reporting to tenths of a mrem ambient dose equivalent;
- Maximum Dose (linear range) 100 mrem (1 Sv); if exposure at a level of 25 rem (0.25 Sv) or higher is suspected, Landauer® can specially process the TLD; and
- Fade – during a full year of deployment, fade is negligible under normal indoor conditions and less than 10% for most extreme environmental conditions over a three month use period.

Landauer® suggests the following applications for the Environmental/low-level TLD badges:

- Environmental monitoring including site characterization, site boundaries, off-site, and compliance with administrative and regulatory requirements;
- Low-level exposure studies, including area monitoring, shielding studies, special studies. Low minimum detectable dose permits shorter exposure period and faster study; and

- Determining exposure to members of the public by ensuring compliance with current guidelines and 10 CFR 20 limiting dose for non-occupationally exposed persons to 100 mrem annually.

Since the drilling for each gas well was completed within a month or less, Cordilleran requested that Landauer® provide monthly TLD service. During 2005 PRESCO had two drill rigs operating; however, during 2006, PRESCO only had one drill rig, the Exp 12 rig used to drill the BM 35-12, operating in the vicinity of Project Rulison. Figure 4 shows a typical drill rig layout and the site locations where the TLD badges were deployed, and Figure 5 shows the locations of the Landauer® badges and Ludlum meter screening results on the BM 35-12 well pad.

Sets of Landauer® TLD badges were deployed to the field in August, September, and October, 2006 during PRESCO's drilling and well completion activities. Badges were principally used as area monitors, attached to locations with the greatest potential for exposure on the rig platform, above the shale shaker(s), over the mud mixing tanks, and one near the reserve pit. Due to the distance from Project Rulison, personnel were not issued TLD badges. Some badges were not recovered due to construction activities on the well pad. Annual drilling activities had concluded by November 2006 due to onset of winter weather conditions and access issues, so Cordilleran stopped the TLD badge service once the drilling had been completed.

Two controls were provided with each shipment; one for field deployment and retrieval, used to measure exposures during shipment for placement and collection, and the other for transit used to measure exposure during shipment to and from Landauer® only. The deployment/retrieval control is used to calculate the net exposure. The deployment/ retrieval control was placed in an aspen tree onsite along with another badge. The shipment control was kept in a desk drawer in Cordilleran's Arvada, Colorado office until it was time to ship the monthly TLD badges back to Landauer®.

The Landauer® TLD badge results are presented in Table 4. Copies of the Landauer® TLD badge reports are presented in Appendix E.

### 3.4 Natural Gas Sampling

Cordilleran collected natural gas samples from the Battlement Mesa gas wells that have been completed and are currently in production outside the ½ mile radius of Project Rulison. Samples were collected soon after the well was first brought into production in the fall of 2005, and PRESCO planned to sample the four closest producing gas wells for every 60 million cubic feet (MMCF) of gas that was produced. The gas samples were analyzed for tritium and carbon14. According to Steven Pelphrey (personal

communication), Laboratory Manager, Isotech® is not able to analyze the samples for krypton-85.

PRESCO established the sampling interval of 60 MMCF based on production data for other gas wells producing from the Williams Fork Formation in the Rulison field. The wells that PRESCO had proposed to test are shown on Figure 6. Approximately 80% of wells drilled on ten-acre spacing show no production interference with one another, and wells drilled on 40-acre spacing show no interference with one another (PRESCO, 2005). Therefore, gas production drainage curves were plotted based on a uniform drainage model, and anisotropic drainage models, the latter expected to be more representative of natural conditions as a function of time. This means that over time the produced gas is migrating laterally into the well from areas a greater distance away from the well bore and may flow preferentially in some directions, forming an elliptical radius of influence rather than a circular radius of influence expected in a uniform drainage model.

The gas samples collected from PRESCO's wells were collected in 20-pound steel propane tanks that were under vacuum and provided by Isotech®. Since the tanks were purged by Isotech® and were received under vacuum, it was not necessary to purge the tanks three times. Since samples were collected soon after the well was brought into production, and periodically when production records indicated that the wells have produced 60 MMCF, the gas samples are representative of the natural gas in the well. PRESCO's natural gas production interval volumes for individual wells and the dates gas samples were collected are presented in Table 5.

Samples were collected from the BM 26-42 and the BM 27-44 on December 7, 2005. The BM 26-42 was sampled again on January 27, 2006, because when the December sample arrived at Isotech®, it was still under partial vacuum, and the tritium and carbon-14 analysis could not be run with the limited sample amount. The initial gas sample was collected from the BM 36-13 well on January 27, 2006 when the BM 26-42 well was re-sampled. Subsequent samples were collected from the BM 34-24, the BM 36-13, and the BM 36-23. Copies of the Isotech® analytical results are presented in Table 6 and as Appendix F.

### 3.5 Produced Water Sampling

Produced water samples, or connate water, from the Mesaverde Group were collected from the same gas wells from which natural gas samples were collected. The produced water samples were analyzed for the presence of tritium using the conventional method and also gamma spectroscopy. According to Paragon Analytics, they are not able to analyze the produced water samples for the presence of krypton-85. There is a possibility of running a total activity on liquid scintillation counting; however, this would not be

specific for krypton-85 (Lance Steere - Laboratory Manager, personal communication 2007).

The first sample was collected from a discharge pipe into the reserve pit at the BM 26-42 well pad. The produced water sample was collected using a gallon capacity plastic bucket while the separator was discharging to the reserve pit. The sample was transferred in one 250-milliliter amber bottle for conventional tritium analysis, and one liter poly bottle preserved with a ten percent nitric acid solution for the gamma emitters.

The only other well, the BM 36-13, that had been completed at that time was still flowing back, and the water was not representative of produced water in the formation. Access to the site became difficult due to snow accumulation and therefore, no initial produced water sample was collected from the BM 36-13.

Subsequent produced water samples were collected from the tubing on the separator units at each location, or from the production tanks. Produced water samples were subsequently collected from the BM 26-42, BM 34-24, BM 36-13, and the BM 36-23. Analytical results for the produced water samples are included in Appendix G.

### 3.6 Gamma-Ray Logs

PRESCO ran gamma-ray logs on some of the wells that they drilled. The gamma-ray log measures natural radiation emitted by a rock formation as a scintillometer-containing sonde is lifted up the borehole. The scintillometer detects natural gamma rays emitted by radioactive isotopes within rock units. Measurements are recorded in standard American Petroleum Institute (API) units, or in grams per ton, on a strip chart (Brenner and McHargue, 1988). These readings plot out as “curves” or “tracks” with the amount of gamma radiation increasing from left to right. Since the printouts are normalized, it is difficult to correlate the readings to other units of radioactivity measurement. However, if a significant source of gamma radiation were encountered in the subsurface, it would be logged. Cordilleran was not provided with copies of the gamma logs; however, these may be found in the COGCC database.

# 4.0 MONITORING ACTIVITY RESULTS

The following section provides the results of each of PRESCO's 2006 monitoring activities conducted during natural gas well drilling and samples collected from producing wells in proximity to the Project Rulison site.

## 4.1 Ludlum Model 3 Survey Meter Screening Results

Cordilleran performed a statistical evaluation of the data to establish site specific background levels of radioactivity. The results indicate that the majority of readings recorded ranged from 100 CPM to 140 CPM, and that relatively few readings exceed 260 CPM for each of the wells. This is consistent with surface survey readings that Cordilleran has observed at the well pad sites including surface survey data obtained at the BM 35-12 conducted prior to drilling and during drilling activities.

These wells were drilled outside Lot 11 and the COGCC established ½ mile radius surrounding Project Rulison, and there is no mechanism by which these cuttings could be impacted with radionuclides related to Project Rulison. The readings are generally consistent from the top of each hole to the total depth drilled; therefore, these readings represent background conditions. The background range has been established at four standard deviations, with a maximum of 260 CPM using the model 3 meter and pancake probe on the 0.1x setting.

Cordilleran evaluated data for each bedrock formation based on the expected top of formation elevations PRESCO reported for each well. All of the formations show very consistent results, as do the readings for each well. Cumulative frequencies and histograms showing the cumulative percentages of readings, as well as the data for each of the wells is presented in Appendix C.

## 4.2 Landauer® Dosimetry Badge Results

The Landauer® environmental dosimetry badge results indicate radiation exposures consistent with background radiation. The transit control badges were stored in Cordilleran's Arvada, Colorado office away from radiation sources. Landauer® reported similar gross readings for the monthly transit control badges as for those deployed in the field. The deploy controls were kept onsite either in the company man's trailer or were post onsite with another badge for results comparison, and were stored away from potential radiation sources. Several of the September 2006 badges were destroyed or lost as a result of construction activities on the BM35-12 well pad.

The results for the deploy badges are also consistent with the other monthly badges that were deployed in the field. The highest gross reading was 19.6 mrem and an average reading of 13.78 mrem. The TLD badges were used to monitor drilling activities from August, September, October 2006, with the last set of badges collected on November 15, 2006. The rig had moved off of the BM 35-12 well pad by that time and some of the badges were collected from the dismantled rig located at the Una yard.

Dose limits to workers should be no greater than 5,000 mrem/year above background. Dose limits to members of the public should be no more than 100 mrem/year above background (10 CFR 20.1201 Subpart C). The average person is exposed to 294 mrem/year from natural background radiation; however, the dosage range from background is from 75 mrem to 5,000 mrem due to geographic and other factors (University of Florida, Environmental Health and Safety website). Based on the EPA website calculator (http://www.epa.gov/radiation/students/calculate.html) the average annual dose from all natural sources in the Rulison area may be as high as 435 mrem per year.

Landauer® provided cumulative exposure results in mrem for these location ID numbers for the calendar quarter, year to date, and permanent. The highest net result was 1.0 mrem, the highest calendar quarter result was 1.0 mrem, and the highest cumulative year-to-date was 1.0 millirem. The TLD badge results are presented in Table 4 and, copies of the Landauer® reports are presented in Appendix D. A diagram of the drill rig and equipment on which the TLD badges were placed is shown as Figure 4 and locations of the badges on the BM 35-12 well pad are shown on Figure 5.

### 4.3 Natural Gas Sampling Results

The results of the natural gas samples that DRI collected from area gas wells at a distance of approximately 3 miles from the Project Rulison site indicated that activities for carbon-14 and tritium were not detected in any of the five gas samples. These samples were collected from wells owned by EnCana Oil & Gas (USA), Inc. with one gas well located to the southwest, three gas wells located to the north-northwest, and one gas well located to the northeast of the Project Rulison site. A copy of the DRI Rulison: Gas Sampling of Proximate Producing Wells Report is presented as Appendix E.

Isotech® reported that concentrations of carbon-14 were not detected with a detection limit ranging from 0.4 percent to 1.0 percent modern carbon (pMC) for gas samples collected from the EnCana wells outside the 3 mile radius of Project Rulison. Isotech® reported that concentrations of tritium were not detected in any of the five gas samples with a detection limit of 10 tritium units (TU) to 15.2TU, or approximately 32.1 pCi/L to 48.8 pCi/L.

Concentrations of tritium and carbon-14 were not detected in gas samples collected from PRESCO's wells. The results of the natural gas samples collected from PRESCO's wells included three samples from the BM 26-42 gas well, the first of which was not able to be analyzed due to insufficient sample volume. Subsequent gas samples were collected from the BM 26-42, BM 27-44, BM 34-24, BM 36-13, and the BM 36-23. A gas sample was not colleted from the BM 34-4 due to its distance from Project Rulison and because gas samples were collected from wells that were between it and Project Rulison.

For gas samples from PRESCO's wells Isotech® reported that concentrations of carbon-14 were not detected with detection limits ranging from 0.4 pMC to 0.6 pMC. Concentrations of tritium were not detected above detection limits of 10 TU to 12 TU, or approximately 32.1 pCi/L to 38 pCi/L.

PRESCO's natural gas production volumes and the dates gas samples were collected are presented in Table 5. The Isotech® laboratory analytical results for gas samples collected from PRESCO's wells are included on Table 6 and copies of the Isotech® laboratory reports are included as Appendix F. Gas samples were to be collected from the four closest gas wells to the Project Rulison site with gas samples analyzed for tritium and carbon-14, every 60 MMCF production volume.

### 4.4 Produced Water Sampling Results

The produced water samples were submitted to Paragon Analytics (PAL) in Fort Collins, Colorado for laboratory analysis of tritium for analysis by liquid scintillation counting and gamma emitting radionuclides for analysis by gamma spectroscopy. Produced water samples were collected at the same time as the natural gas samples unless weather conditions or site conditions did not permit for samples to be collected. PRESCO's monthly produced water volumes and sample dates are presented as Table 7.

According to the PAL Condition of Sample Upon Receipt Form, the sample coolers had external readings ranging from 12 µR/hr to 17 µR/hr and background readings ranged from 12 µR/hr to 15 µR/hr. These screening results indicate that the level of radioactivity was equivalent to background or were within Department of Transportation (DOT) acceptance criteria.

Tritium

The laboratory analytical results indicate that concentrations of tritium were not detected, above the minimum detectable concentration (MDC). The laboratory results for tritium are presented in Table 8. The MDC ranged from 320 pCi/L to 350 pCi/L and all results were reported as "U" indicating tritium concentrations were not detected.

Gamma Spectroscopy

The PAL analytical results for the gamma spectroscopy analysis indicated that no gamma radiation emitting radionuclides were detected above the respective MDC, with the exception of potassium-40 in one sample. All of the remaining results were reported as "U" indicating gamma emitting radionuclides were not detected. Potassium 40 was detected at 152 ± 96 pCi/L, and a MDC of 146 pCi/L in the initial produced water sample collected from BM 26-42, but was not detected in subsequent samples collected from BM 26-42. As stated in Section 1.6, potassium 40 is a common, naturally occurring radionuclide found in food, human muscle tissue, and has been reported in coal samples and coal-associated rock samples collected from the Williams Fork Formation from Garfield County and in the region. It has been used to age date the basalt on top of Battlement Mesa.

The only consistent comment in the PAL summary of the gamma spectroscopy results was that PAL has determined a significant low bias for bismuth-214 and lead-214. Therefore, PAL has estimated concentrations of bismuth-214 ($^{214}$Bi) and lead-214 ($^{214}$Pb) below the MDC and flagged these with a "J" qualifier.

> *"Paragon Analytics has found there to be a significant low bias to $^{214}$Pb and $^{214}$Bi results when using a mixed nuclide gamma source for efficiency calibrations. The magnitude of this bias has been determined to be approximately 32% for $^{214}$Bi, and 23% for $^{214}$Pb. Therefore, any reported results for $^{214}$Pb and $^{214}$Bi are flagged with a "J" qualifier, indicating the activity values to be an estimated value. Results are reported without further qualification."*

The results for the produced water sample collected from the BM 26-42 well do not suggest the presence of radionuclides associated with Project Rulison, especially since potassium 40 has not been detected in subsequent produced water samples from this well and was not detected in samples collected from other gas wells sampled during 2006. The gamma spectroscopy results are presented in Table 9. Copies of the PAL reports for the produced water samples are included as Appendix G.

# 5.0 SUMMARY

The results from PRESCO's 2006 monitoring and sampling activities do not indicate the presence of elevated radiation levels associated with NORM or with fission products related to Project Rulison. Based on the information contained in the Project Rulison Manager's Report, April 1973, the End State Vision Document, (January 2005) and discussions with Los Alamos and MFG, Inc. it is very unlikely that any radionuclides related to Project Rulison would be present in natural gas or produced water from PRESCO's Battlement Mesa gas wells. It is even less likely that radionuclides would be able to contaminate drill cuttings, given the impermeable nature of the Mesaverde Group and overlying bedrock formations, and based on the observations and results of the re-entry drilling and natural gas flaring performed as part of the Project Rulison experiment.

PRESCO and Cordilleran developed a Work Plan for monitoring drilling activities inside the COGCC ½ mile radius of Project Rulison. The proposed monitoring activities were based on the monitoring activities performed by the AEC at the time of the Project Rulison experiment and on the DOE/EPA monitoring activities that have been conducted since that time. The radionuclides of interest are those that were identified by these agencies relating to Project Rulison and similar underground test sites.

PRESCO conducted voluntary monitoring and sampling activities in 2006 outside the half-mile radius that were reasonable considering the distance from the Project Rulison site, the impermeability of the geologic formations, the findings obtained by the AEC during the re-entry drilling into the cavity chimney, and the time lapsed since the Project Rulison was conducted. Approximately 28 percent of the tritium estimated to have been produced by the detonation of the Rulison device was consumed during the flaring activities (AEC, 1973 p. 25). Most of the gaseous tritium was removed from the cavity by the end of the testing. The remaining tritium is expected to be in the form of tritiated water in the cavity, or incorporated within the vitrified rock (glass) lining the cavity. The tritiated water is immobile because of the impermeable characteristics of the Williams Fork Formation and the Mesaverde Group in general.

Thirty-six years, roughly three tritium half-lives, have lapsed since Project Rulison was conducted; therefore, the concentration of any tritium remaining is approximately one-eighth of that produced. Tritium migration is driven by gas diffusion and is not expected to be significantly affected by the low pumping rates of natural gas wells in the area. All simulations must consider the exchange and decay processes. While tritium migration occurs essentially only in the gas phase, exchange into liquid water serves to effectively trap tritium mass along the gas pathway. Tritium decay also allows for significant mass decay over the time scales considered for the production from nearby gas wells, i.e. 30 years.

Krypton-85 has a half-life of 10.76 years and the yield of the Rulison explosive was calculated based on the measured concentrations of krypton-85 in the gas and was shown to have all been produced. The concentrations of tritium and krypton-85 were shown to decrease over time with the amount of cumulative gas produced as based on the Project Rulison radiochemical data. Most of the krypton-85, if not all, is expected to have been removed from the cavity by the end of the Project Rulison production testing. Any remaining krypton-85 may be trapped by water within the cavity, or as pockets within the glass or in the chimney, but is not likely to be detected in gas from wells outside Lot 11. Isotech® and Paragon Analytics are not able to analyze the gas samples or produced water samples, respectively, for the presence of krypton-85.

Carbon-14 was present in low-levels in the gas tested during the Project Rulison production testing, and based on the estimated inventory of 2.2 curies from the End State Vision document, it is theoretically possible to be present in natural gas. Carbon14 is a naturally occurring radionuclide commonly used to age date organic materials less than 60,000 years old. Due to the relatively small amount of carbon14 reportedly produced during the experiment from the source term it is unlikely that any carbon14 related to Project Rulison would be detected. Natural gas samples were analyzed for the presence of tritium and carbon-14.

The Ludlum model 3 survey meter and Geiger Mueller pancake probe screening of drill cuttings evaluated site specific background levels of radioactivity for wells drilled outside the half-mile radius of Project Rulison. The Ludlum model 3 survey meter readings indicate that the majority of readings on the 0.1x setting typically range between100 CPM to 140 CPM, with the upper range of background at 260 CPM. These background readings are consistent for drill cuttings from the Green River Formation, Wasatch Formation, and Mesaverde Group.

The Landauer® TLD badge results do not indicate elevated levels of radioactivity were encountered during the drilling of the BM 35-12 gas well located to the west outside the half-mile radius from the Project Rulison site. The badges were posted in locations where radioactivity would likely be detected if it were present. These locations included badges posted on the shale shaker, mud mixing tanks near the reserve pit, and also on the rig platform. Readings were consistent with the transit and deploy control TLD badges. Drilling activities took approximately one month to complete a well; Landauer® provided a monthly badge service. Therefore, badges were deployed around the BM 35-12 well site prior to drilling and also during drilling activities.

Due to the low permeability of the Mesaverde Group, fluid movement is restricted. Project Rulison was conducted because of limitations of the conventional gas well drilling technology at that time to produce gas from tight gas sand formations. The Mesaverde Group in the vicinity of Battlement Mesa is not considered an aquifer. Natural gas moves through these formations more readily than connate water. Some connate water is produced as a waste product during natural gas separation process.

Water vapor entrained in the natural gas is separated from the gas before it can be transported by pipeline or truck for further refining. Gas samples were collected for analysis of tritium and carbon-14 by Isotech®. Samples of the produced water were collected for analysis by PAL.

The Isotech® results from the natural gas samples collected from the wells sampled by DRI in May 2005, and the compositional ranges of other components in the PRESCO gas samples were similar to the results obtained by DRI for gas samples collected from EnCana gas wells in May 2005. Analytical results for natural gas samples collected from the PRESCO gas wells indicate that concentrations of tritium and carbon-14 were not detected.

The analytical results for the produced water sample collected from BM 26-42 in December 2005 and analyzed by PAL indicated that tritium and gamma emitting radionuclides were not detected, with the exception of potassium 40 detected at 152 ± 96 pCi/L. Potassium 40 is a common, naturally occurring radionuclide and was not detected in subsequent samples collected from the BM 26-42 gas well. Concentrations of tritium and gamma emitting radionuclides were not detected in the produced water samples collected from the other PRESCO gas wells sampled from December 2005 through December 2006.

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**Online Resources**

Aragonne National Laboratory, EVS
www.ead.anl.gov/

Colorado Department of Public Health and Environment – Radiation Services
http://www.cdphe.state.co.us/hm/rad/radiationservices.asp

Health Physics Society – Paul W. Frame, CHP, PhD
http://hps.org/publicinformation/ate/q2345.html

Idaho State University
www.physics.isu.edu/radinf/tritium.htm

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www.doe.gov/

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