
TENORM and the Blue Ridge Landfill

A summary of the dose and risk assessment process and results

BY RISK ASSESSMENT CORPORATION

Who are we and why did we perform this work?

Risk Assessment Corporation or RAC is a team of scientists who specialize in estimating radiation dose and risk to people from exposure to radioactive materials and chemicals released to the environment. John E. Till, Ph.D., is the President of RAC and created the company nearly 40 years ago. We are committed to performing high quality science and to communicating our results to people who may have been exposed and to our peers in an open and transparent way. More information about us can be found at www.racteam.com and at the end of this summary. We were asked by Advanced Disposal to perform this assessment once it learned that TENORM waste may have been disposed of at its Blue Ridge Landfill (BRLF) site.

What is the bottom line of our dose and risk assessment?

Our assessment has demonstrated that doses received by workers on the site and to the public from the assumed disposal of the TENORM materials are minimal when compared to radiation exposure they receive from natural and other man-made sources. The calculated inhalation and ingestion dose for the landfill worker during disposal was 1.9 millirem (mrem), and the external dose was 2.8 mrem for a total of 4.7 mrem. A millirem is a unit of radiation dose. The doses we calculated assume the same worker attended all 92 disposals. Doses to the public were less than one mrem while the waste was being disposed for all exposure scenarios we evaluated. Potential doses in the long term future to the public assuming the waste remains buried at the site are about one mrem per year. For perspective, the average member of the public is exposed to about 600 mrem each year from natural radiation, medical, and other sources.

What is TENORM?

TENORM, or Technologically Enhanced Naturally Occurring Radioactive Material, is naturally occurring radioactive material (NORM) that has been concentrated as a result of physical or chemical processing such as treatment of wastes generated during drinking and waste water treatment, oil and gas exploration and production, phosphate mining and production, and uranium mining and milling.

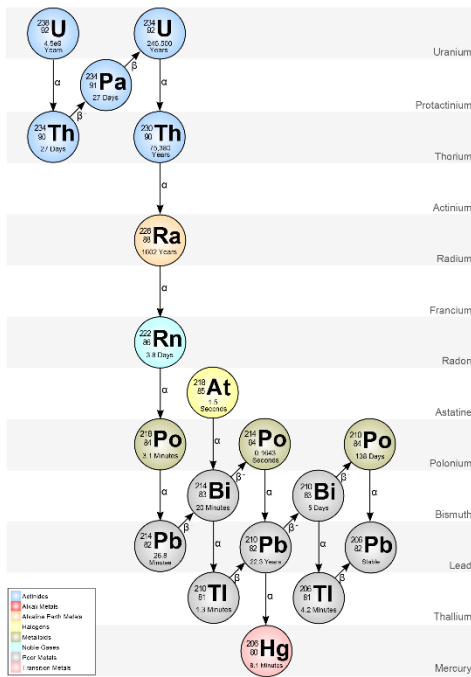
Most soil and rock contain naturally occurring radioactive materials such as uranium, radium, and thorium and their decay products that contribute to low levels of naturally occurring radiation in soil, biota, air, and water. These materials are present in varying concentrations across the United States.

TENORM

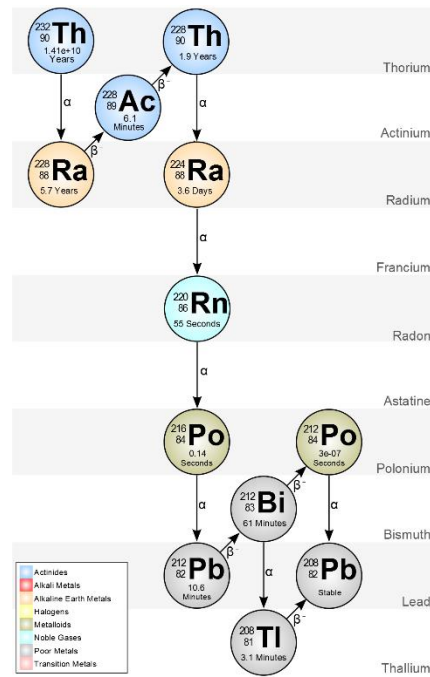
Technologically Enhanced Naturally
Occurring Radioactive Material

These are naturally radioactive materials that have been concentrated or exposed to the accessible environment as a result of human activities such as manufacturing, mineral extraction, or water processing.

Radioactivity is the result of the breakdown or transformation of these materials to produce new elements or decay products that may also be radioactive and continue to decay. This decay process continues until the sequence ends with a stable element, frequently lead. Radiation is emitted as each radioactive element or radionuclide decays. A common, naturally occurring decay product of uranium that is present in many areas of the country is radon gas. There are three naturally occurring decay series, and the most important in TENORM are the uranium-238 and thorium-232 decay series, depicted below (images taken from <http://metadata.berkeley.edu/nuclear-forensics/Decay%20Chains.html>).



Uranium-238 decay series



Thorium-232 decay series

Exposure to NORM is responsible for about 50% of the average person's radiation dose in a year, and is not considered to be a health or safety concern. An example where NORM could be a problem is where natural radon in homes may be higher than recommended levels. In addition to NORM, other sources of background radiation include radioactive materials used in medicine and some consumer products. For more information on TENORM visit the EPA's website at: <https://www.epa.gov/radiation/technologically-enhanced-naturally-occurring-radioactive-materials-tenorm>.

Exposure to NORM accounts for about 50% of the average person's radiation dose in a year. The other 50% comes from medical, consumer products and other sources.

What material was put in the Blue Ridge Landfill?

We had no means to directly verify that TENORM waste was actually disposed of at the Blue Ridge site. For the purposes of this assessment we assumed that the materials disposed of at the site were TENORM. Based on our review of available documents, we assumed that 92 loads of waste material (totaling approximately 1,157 US tons) from fracking activities associated with oil and gas exploration in the Marcellus and Utica shale deposits in Ohio and West Virginia were brought into the Blue Ridge Landfill

between July 20, 2015, and February 3, 2016. These waste materials were classified as TENORM because the extraction process concentrates naturally occurring radionuclides in the wastes generated. The wastes were trucked into the landfill, compacted, and covered with soil.

What environmental sampling for radioactive materials has been performed at the Blue Ridge Landfill and surrounding areas?

Seven different on-site environmental sampling events have been conducted between February 10, 2016, and May 8, 2016. Additionally, a scan involving 328,306 discrete readings across the entire landfill to measure radioactivity in the landfill (referred to as a gamma scan) was completed on March 3, 2016. The number of samples collected from each media type are summarized in the table below.

Media	Sample Count
Air	30
Soil	30
Surface water	53
Ground water	15
Sediment	27
Sludge	1
Leachate	8
TOTAL	164

The environmental measurements and gamma scans indicated that the mixing of TENORM materials into the municipal waste stream resulted in radionuclide concentrations consistent with the natural background of the area. The concentrations from the 92 disposals in question were low enough that they were not detectable by the gamma scan on the surface of the buried waste. The geologic region where the landfill is situated appears to have high natural background radiation, likely from the shale deposits in the area, and this is reflected in some of the surface water samples and surface gamma exposure rates.

Environmental sampling performed at the landfill indicates that radionuclide concentrations are consistent with the natural background of the area.

What is radiation dose and risk?

Radiation dose is the amount of radiation an individual is exposed to externally and internally and that is absorbed by an organ or tissue. In the United States, radiation dose is usually measured in units of millirem (mrem)¹ where 1,000 millirem = 1 rem. Once we know the radiation dose to people, we can estimate what this means in terms of risk of causing cancer to a person exposed. Risk is the chance of getting cancer from the dose received. Risk is expressed as a probability or percentage.

Radiation dose is the amount of radiation energy absorbed in body tissue.

¹ In other countries of the world, the units used for dose are millisieverts (mSv), where 100 mrem = 1 mSv. For this summary we use units of millirem (mrem).

According to the National Cancer Institute, the background incidence of cancer from all sources in the United States is about 40%. That is, about 4 persons in 10 will get cancer of some type during their lifetime.

Numerous studies performed over several decades have confirmed that radiation is a weak carcinogen compared to other substances we may be exposed to such as asbestos, and many chemicals.

Generally, excess radiation dose can lead to an increase in risk for certain types of cancer. Risk estimates that are used to predict public health effects are based on detailed epidemiological studies of exceedingly well-defined populations.

How do we calculate dose and risk?

Radiation dose is a function of many parameters, including the source of the radioactive material, its movement or transport in the environment, how an individual is exposed, and the type and energy of radiation emitted. Scientists use both measurements and mathematical models to estimate a person's radiation dose.

To estimate the dose and risk to people from burial of the waste at the Blue Ridge Landfill, we must first know how much material was disposed. This is known as the source. The source describes the amount and type of radioactive material of concern. In the case of the landfill, the source of radioactive material is approximately 1,157 tons of TENORM, consisting primarily of uranium-238 (U-238), thorium-230 (Th-230), thorium-232 (Th-232), radium-226 (Ra-226), and radium-228 (Ra-228), among other daughter products in the decay chain.

We measure the concentration of radioactivity in units known as a picocurie (pCi). For example, all soil is naturally radioactive and, on average across the United States, contains U-238, Ra-226, Ra-228, Th-230, and Th-232 in concentrations of about 1 pCi per gram of soil (pCi/g). These concentrations vary significantly depending on where you live in the United States. In the area where the Blue Ridge Landfill is located, concentrations of these materials are higher than the rest of the country due to the natural geology of the site. Concentrations of radionuclides in waste materials were determined by reviewing landfill gate tickets and radiation measurement data provided by each waste generator, summarized below.

The average natural background radioactivity in Blue Ridge Landfill soils is higher than averages across the US due to the natural geology of the site.

Radionuclide	Average concentration in waste materials deposited at the BRLF (pCi/g) ^a	Average natural background radioactivity in BRLF soils (pCi/g) ^b	Average natural background radioactivity values for US soils (pCi/g) ^c
U-238	13.3	^d	0.95
Ra-226	163	5.6	1.1
Ra-228	60.8	1.3	1.0 ^e
Th-230	169	4.6	~1.0 ^f
Th-232	89.1	1.4	0.95

^a Based on radiation measurement data provided by each generator

^b Based on soil sampling at landfill performed by Chase Environmental and the State of KY on March 4, 2016

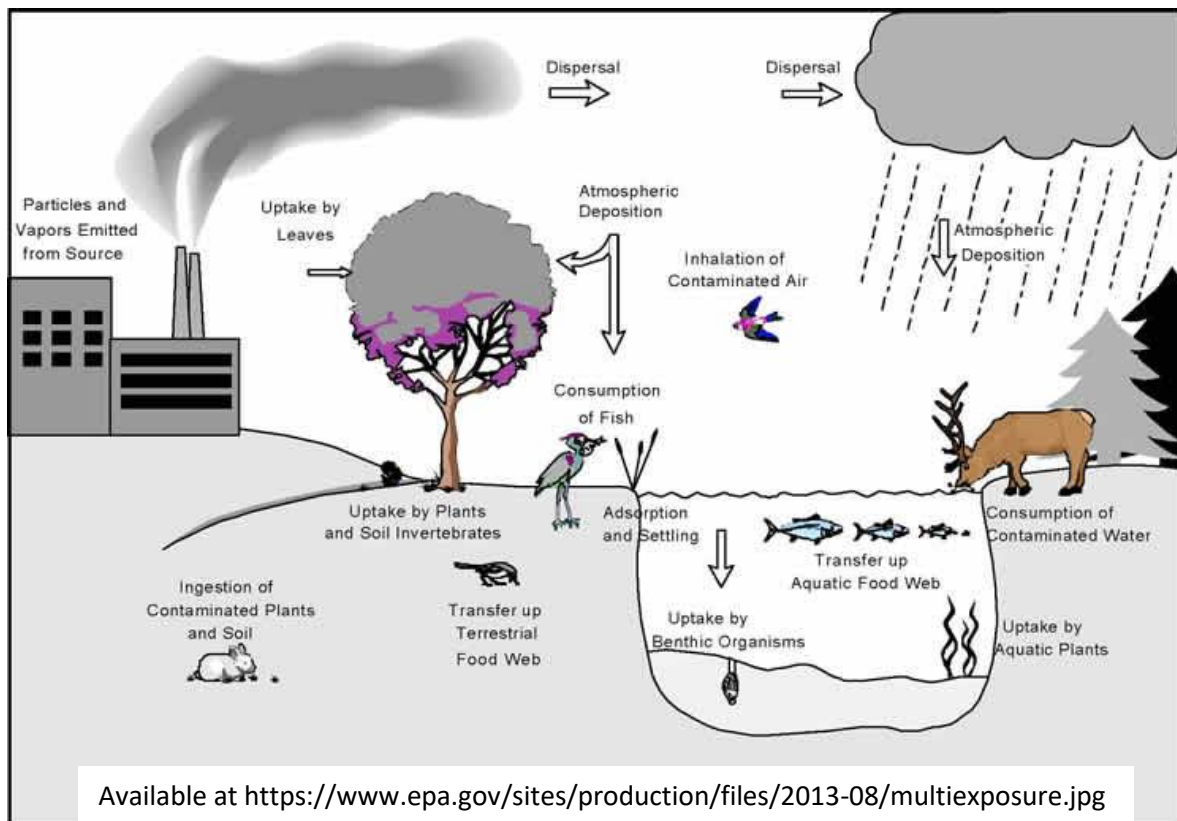
^c Pennsylvania Department of Environmental Protection TENORM Study Report (2015)

^d No background value for U-238 at Blue Ridge was available

^e National Research Council Evaluation of Guidelines for Exposures to TENORM (1999)

^f Based on parent U-238 value

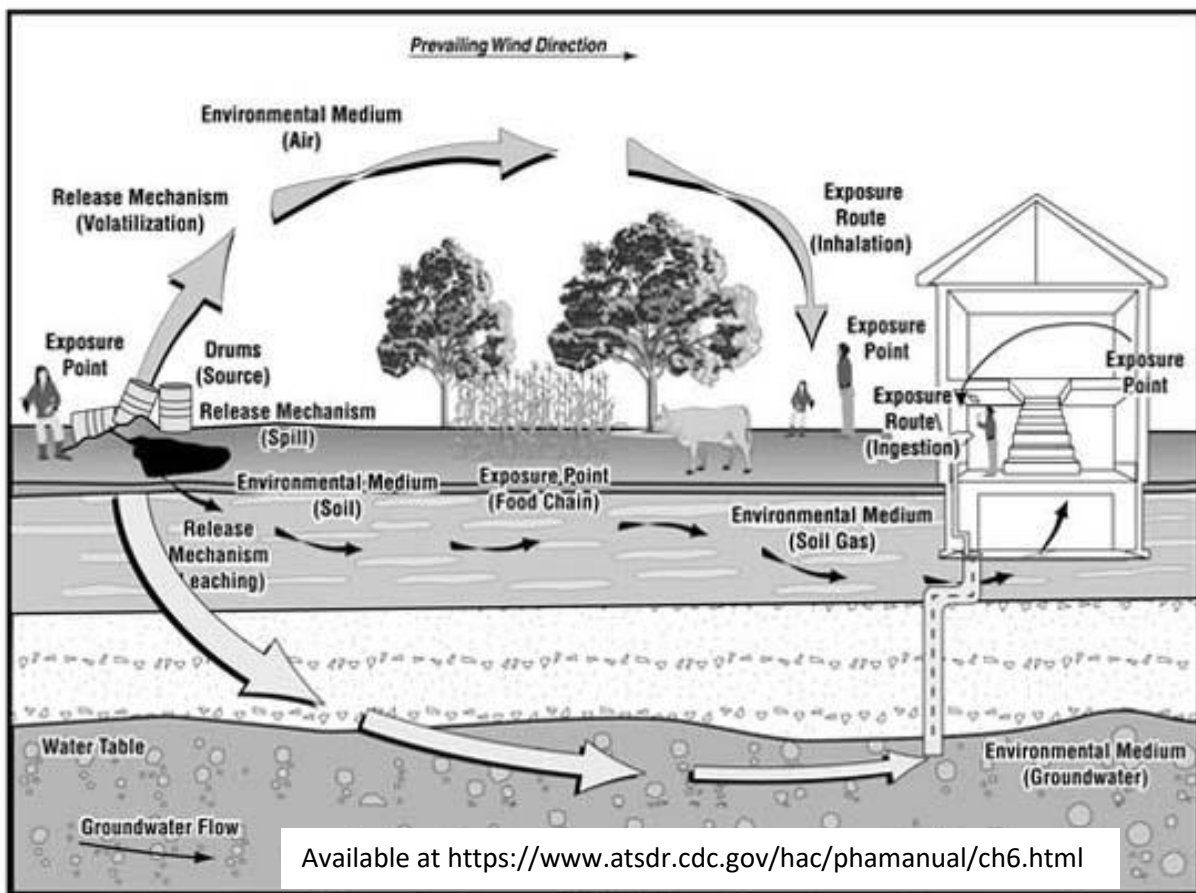
Once we know the source, we need to understand how the radioactive material is transported through the environment including different media such as air, water, or vegetation. Scientists have studied this transport for many years and the figure below shows a variety of environmental transport mechanisms, not all of which are relevant to the evaluation of dose for the Blue Ridge Landfill.



It is difficult to measure the movement of radioactive materials through the environment directly. Therefore, we use mathematical models that have been developed and validated over many decades of research. These models allow us to estimate concentrations of radioactive materials in different environmental media at a location where an individual may come in contact with them.

Humans come into contact with radiation by breathing it in, ingesting it in contaminated food or water, or absorbing it through the skin.

Exposure describes how a person may come into contact with a radionuclide. The figure below shows a variety of potential human exposure pathways, not all of which apply to this assessment. We take into account the pathways a person can be exposed, including breathing, ingesting drinking water, and radiation that is external to the body but can penetrate skin and expose internal organs (e.g., gamma rays). In addition, we use high-sided assumptions to ensure that doses are not underestimated. A scenario of exposure is a characterization of a person and the different ways they might be exposed. For example, at the Blue Ridge Landfill, we have looked at multiple scenarios to address potential current exposure related to hypothetical landfill workers, students and teachers in the middle and high school, and office workers at the landfill as well as potential future exposures for students and teachers and a hypothetical resident living at the current school location. Radiation dose into the future was determined by running a groundwater model out to over 100,000 years.



Once we know a person's exposure, we can estimate the dose by using dose coefficients. Dose coefficients define the dose a person receives for a given concentration of radioactive material and have been tabulated based on decades of research. They vary depending on a number of factors, including the radioactive material, the method of exposure (inhalation/ingestion), and the chemical form of the radionuclide.

To summarize, we started with a quantity of material, moved it through the environment, and determined how the public might come into contact with that material so that now we can determine a person's radiation dose. Once the dose has been determined, we can estimate risk. Risk in this context means the increased chance of getting cancer above the rate normally expected in the population at large.

Is there uncertainty in these calculations?

There is always some uncertainty in estimating dose and risk to people exposed to radioactive materials in the environment and we have ways to address it. Some methods are more complicated than others. One of the most straightforward approaches to addressing uncertainty and to be sure we do not underestimate dose and risk is to make assumptions in our calculations that result in a dose that is deliberately high. To do this, we selected concentrations of radioactive materials in TENORM, release and transport model parameters, and exposure assumptions to provide an overestimate of actual radiation dose a person would receive both during disposal and in the future. For example, if the concentration in the waste was not reported by the waste generator for one of the waste loads then the waste was assumed to be the same as the load with the highest reported concentrations from that generator even if the waste description suggested otherwise. The exposure assumptions were also designed to overestimate the dose that anyone actually might have received by assuming that the wind was always blowing towards a person, and for a landfill worker assuming that they were standing next to every load of waste as it was disposed and breathing the dust that may have been generated. For the workers, students, and teachers closest to the disposal operation that might have been exposed, the calculations assumed a high breathing rate so that this exposure pathway was not underestimated. When considering potential doses in the future, no credit was taken for the landfill liner. Based on all these points we are sure that the calculated doses are larger than any actual doses that were received, or that will occur in the future. Even with these assumptions, the resulting dose and risk to people is extremely small compared to other sources of radiation exposure in our environment.

Is there a way to prove the calculations are correct?

Validation of the calculations uses independent measurement data to confirm that predicted doses were consistent with expectations. In the case of the TENORM buried at the Blue Ridge Landfill, the increased radiation exposures to the public are too small to be able to separate from background radiation levels experienced every day. If there is any excess radiation in the environment from the burial of this TENORM, it is not distinguishable from the natural radiation in the environment.

What are the regulations associated with the disposal of fracking waste?

There are no uniform national regulations or guidelines for management of TENORM waste. Management of these materials falls under a variety of regulatory authorities, including the Environmental Protection Agency, the Nuclear Regulatory Commission, and the authority of individual states. This makes interpretation of results and determination of acceptable levels of dose and risk difficult. Some examples of annual dose limits provided by the Nuclear Regulatory Commission are shown in the table below.

Category	Annual Regulatory Limit (mrem)
Member of the public	100
Radiation worker	5000
Pregnant female radiation worker	500

What levels of dose are we seeing from our calculations?

The maximum reasonable radiation dose received during the disposals of the TENORM materials is 4.7 mrem.

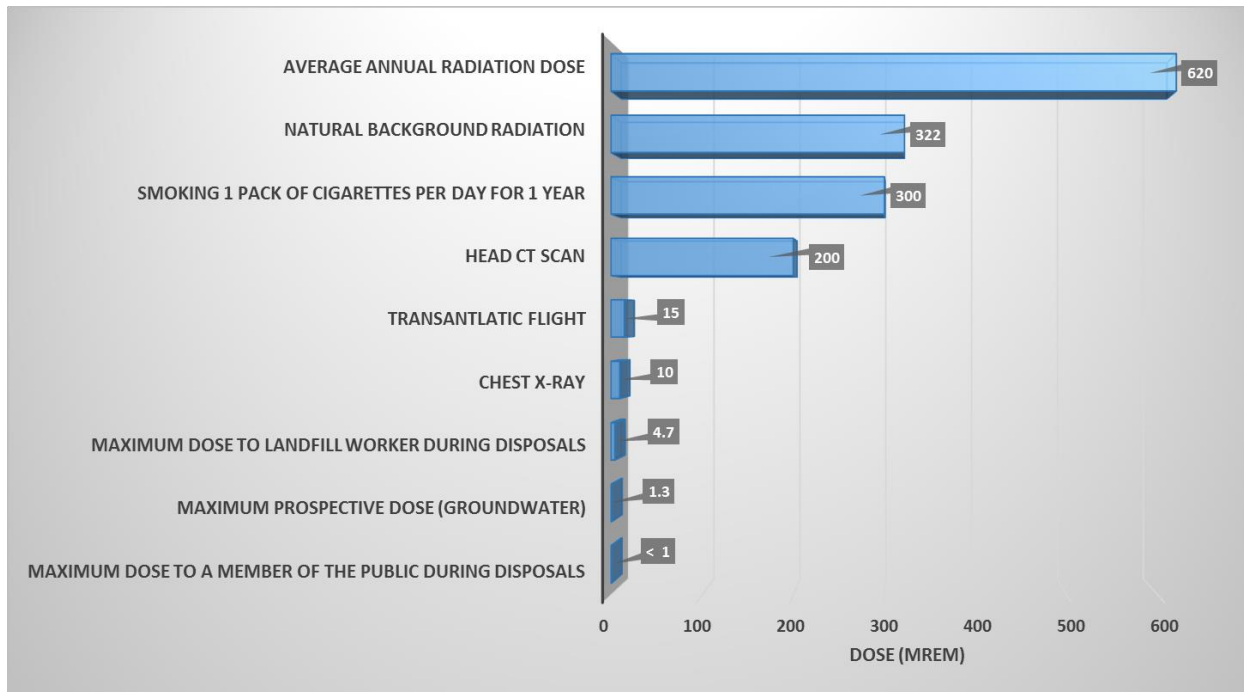
From our calculations, the maximum dose to a landfill worker present during all 92 disposals is 4.7 mrem. The maximum dose to a person at the office or school is significantly less than 1 mrem. The groundwater assessment demonstrated that the maximum predicted dose to a member of the public in the far future is 1.3 mrem in a year. None of these exposures exceed regulatory standards in the present day, nor are they predicted to in the future.

What do these doses mean in comparison to radiation exposures people normally receive?

Everyone is exposed to radiation on a daily basis from both natural and man-made sources. According to the National Council on Radiological Protection (NCRP), the average annual radiation dose per person in the US from all sources is about 620 mrem (6.2 mSv; NCRP 2006). Most (about 52% or 322 mrem) of this dose comes from natural background radiation sources. Other contributors to annual radiation dose are medical procedures, such as x-rays or CT scans. A single chest x-ray gives about 10 mrem, a single head CT about 200 mrem. The figure below puts the radiation doses to landfill workers and the public into perspective.

The maximum radiation dose received in this scenario is 4.7 mrem, which increases an individual's risk of cancer by 0.0002% or 2 persons in a population of one million.

While not every member of the public uses tobacco products, this is a large source of radiation dose to those who do. The dose comes from the natural radioactivity in tobacco, especially polonium-210 and lead-210. These emit alpha particles that create a significant dose to the lungs. There have been numerous studies of the levels of radioactivity in tobacco smoke and the resulting dose from smoking about one pack of cigarettes a day for a year. The estimated dose to the lungs ranges between 300 mrem per year up to over 3,000 mrem per year.



What do the doses mean in terms of the risk to people?

Based on detailed epidemiological studies of radiation exposure and cancer, we can estimate the risk once we have calculated a dose using what is called a risk coefficient. We don't fully understand the relationship between dose and risk of cancer at extremely low doses but for radiation protection purposes and to be prudent, we assume any small amount of exposure and dose will produce a proportionately small increase in risk. To make an estimate of risk we use a risk coefficient recommended by the International Commission on Radiological Protection of about 0.00005% per mrem or 5 persons in a population of 10 million receiving a dose of one millirem. Therefore, in the case of the Blue Ridge Landfill exposures, the additional risks as shown in the table below are small compared to the 40% risk we already have in life from all sources.

Exposure scenario	Dose (mrem)	Risk above baseline value of 40% (%)
Landfill worker during disposals	4.7	0.0002
Member of the public during disposals	< 1	< 0.00005
Maximum prospective dose	1.3	0.00006

Why does a dose assessment take so long to complete?

Performing a detailed dose assessment is a complex task that requires detailed knowledge of the source, transport pathways, and potential exposure scenarios, coupled with appropriate dose coefficients. The dose assessment for the Blue Ridge Landfill required obtaining information from multiple sources, including load and generator specific data, which were used to compute the weighted average concentration used as the basis for the source term, and environmental sample analysis results from various contractors and the State of Kentucky. We had to receive these data in order to base our

assessment on factual information. Additionally, there are no established models for calculating doses from TENORM waste disposal in a municipal landfill. Thus, models from other disciplines, namely emissions from construction and aggregate operations and low-level radioactive waste disposal operations were adapted to this specific assessment. Above all, we wanted to be sure our work was thorough, transparent, and following the basic principles of science.

Qualifications and Experience of Risk Assessment Corporation

Risk Assessment Corporation (RAC) was founded by Dr. John E. Till in 1977 (www.racteam.com). Dr. Till has concentrated his 40-year career on radiological and chemical environmental risk assessment, while leading a team of independent scientists. Radiological risk assessment is a multidisciplinary science, requiring individuals with a number of different skills to work together as an integrated team. RAC team members bring together technical skills and problem-solving experiences from a wide variety of disciplines, including dose and risk assessment, onsite and offsite monitoring, data evaluation, process engineering, environmental transport modeling, database development and use, geographic information systems integrated with databases and assessment models, radiation biology, and interactive public involvement.

RAC team members have been integral members of and advisors to nationally and internationally recognized organizations including the National Academy of Sciences, the National Council on Radiation Protection and Measurements, the International Commission on Radiological Protection, the Atomic Energy Agency, the Environmental Protection Agency Science Advisory Board, and the United Nations Scientific Committee on the Effects of Atomic Radiation among others.

Examples of RAC's work include reconstructing doses and risks to the public from radioactive materials released from the Fernald Feed Materials Production Center during its 38 years of operation near Fernald, Ohio, and reconstructing historical public exposures from the former Rocky Flats Nuclear Weapons Plant near Denver, Colorado that operated from 1952 – 1989. Later, RAC also worked with the Radionuclide Soil Action Level Oversight Panel to develop recommendations for soil cleanup at the former Rocky Flats Site. The panel consisted of a mix of technical specialists and individuals with no technical experience drawn from public interest groups, local governments, and the general public.

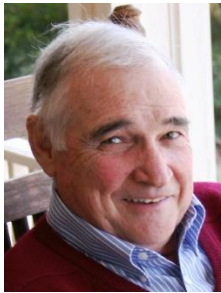
Apart from these and other dose reconstruction projects, RAC has been involved in a wide variety of other projects associated with the occurrence of radionuclides and chemicals in the environment and potential human exposures. For example, in 1997, RAC was asked by the Department of Justice to perform a series of technical audits of Los Alamos National Laboratory (LANL) for compliance with the Clean Air Act, 40 CFR 61, subpart H. The project was initiated by a lawsuit filed by Concerned Citizens for Nuclear Safety (CCNS) against the U.S. Department of Energy and the former director of Los Alamos National Laboratory. Settlement of the suit required that the audits be performed by an organization agreed to by all parties, and RAC was chosen as the independent auditor. The audit process was a success and led to significant improvements in the compliance program at LANL.

RAC has also offered scientific courses for many years, developing and presenting courses designed to enhance the general knowledge of the audience on such topics as risk assessment, pathway analysis, risk-based decisions for corrective action, risk communication, and other areas of specific or general interest. RAC is currently contracted by the U.S. Nuclear Regulatory Commission (NRC) to present up to five one-week training courses on risk assessment to NRC staff. RAC presented the first course to NRC staff in April 2015, and the contract runs through 2019.

In addition, RAC has developed the RACER® system over the last 10 years. RACER is an innovative method that converts environmental data directly to human health risk to facilitate and enhance decision making and communication about risks from chemicals and radionuclides in the environment. RACER integrates

scientific approaches with data management expertise, informed by years of experience in dose and risk assessment. The result is an approach geared toward turning data into knowledge that can be effectively communicated to a diverse audience, starting with clear objectives and using integrated processes and flexible design to make technically sound decisions. This is accomplished through the implementation of customer-specific processes and tools with a focus on stakeholder interaction and sustainability.

Biographical Summaries of RAC Staff



[John E. Till, Ph.D., President, Risk Assessment Corporation](#)

John is a graduate of the U.S. Naval Academy. He served in the U.S. Navy Nuclear Submarine Program and retired a Rear Admiral in the U.S. Naval Reserve in 1999. Dr. Till was selected to present the 37th Lauriston S. Taylor Lecture at the annual meeting of the National Council on Radiation Protection and Measurements in March, 2013. He is also the 1995 recipient of the E.O. Lawrence Award from the Department of Energy in the field of Environmental Science and Technology for his work in public involvement and research in dose reconstruction. Dr. Till is the 1995 recipient of the E.O. Lawrence Award from the Department of Energy in the field of Environmental Science and Technology for his work in public involvement and research in dose reconstruction.

In 1977 he formed Risk Assessment Corporation (RAC), and he has been the leader of historical dose reconstruction studies at five key facilities within the Department of Energy weapons complex. He has also led independent studies focusing on exposure of atomic veterans, derivation of soil action levels at Rocky Flats, the impact of the Cerro Grande fire at Los Alamos National Laboratory, and developing the RACER (Risk Analysis, Communication, Evaluation and Reduction) process for decision makers who need immediate access to environmental data for estimating human health risk and communicating information to the public. Dr. Till's scientific achievements include numerous open literature publications and books that stress new approaches to transport and fate mechanisms in environmental and risk analysis. His most recent book, *Radiological Risk Assessment and Environmental Analysis* was published in 2008 by Oxford University Press. Recent scientific responsibilities include membership on the International Commission on Radiological Protection (ICRP), and chairman of the National Academy of Sciences Committee to Review the Dose Reconstruction Program of the Defense Threat Nuclear Agency.



[Helen A. Grogan, Ph.D., President, Cascade Scientific, Inc.](#)

Helen has more than 25 years of experience in radioecology, dose reconstruction, and the assessment of radioactive and non-radioactive hazardous wastes. Dr. Grogan first worked in Switzerland at the Paul Scherrer Institute where she was responsible for the biosphere modeling aspects of the safety assessment of both high-level waste and low/intermediate-level waste repositories. She assisted in development of the International Features, Events and Processes (FEP) Database for the Nuclear Energy Agency, Organization for Economic Cooperation and Development, in France that is used internationally in the performance assessment of radioactive waste disposal systems. One of her interests is the validation of computer models developed to predict the fate and transport of radionuclides in the environment, and she authored a chapter on this topic in the book she co-edited with Dr. John Till, *Radiological Risk Assessment and Environmental Analysis* (Oxford University Press 2008). She has served on committees for the International Atomic Energy Agency, National Academy of Sciences, the

Environmental Protection Agency and the National Council on Radiation Protection and Measurements. She is a council member of the National Council for Radiation Protection and Measurements, and has served as a member of the U.S. Delegation to the United Nations Scientific Committee on the Effects of Atomic Radiation since 2014. As a principal researcher for RAC, she manages the technical aspects of the team's projects.



[Emily A. Caffrey, Ph.D., President, Radian Scientific, LLC](#)

Emily graduated in 2016 with her Ph.D. in Radiation Health Physics. Her research included environmental dose assessment and computational dosimetry methods. She is interested in statistical uncertainty analysis, data interpretation, risk assessment, and source term development. She has excellent analytical skills and is adept at presenting information to a wide range of audiences.



[Thomas E. Johnson, Ph.D., CHP, TMANR, Inc.](#)

Tom received his Ph.D. from Purdue University in 1997. He is a Certified Health Physicist (CHP) and also certified by the National Registry of Radiation Protection Technologists (NRRPT). His research areas include in-situ uranium mining and radiological risk associated with by-products of industrial technologies such as fracking. He has published extensively in the open scientific literature specializing in the transport and fate of radionuclides in the environment. Current work also involves the long term impacts of the Fukushima accident and implications to people who were displaced due to radioactive contamination.



[H. Justin Mohler, M.S., Bridger Scientific, Inc.](#)

Justin has more than 15 years of experience in various aspects of environmental health physics, including environmental sampling and measurement, tabular and spatial data management and interpretation, environmental transport, exposure and risk assessment, and communication and presentation of technical information. Mr. Mohler has extensive experience with database design and management, using and maintaining relational databases for several projects. Mr. Mohler specializes in managing and analyzing large and diverse sets of environmental monitoring data, with a focus on their use for regulatory compliance, dose and risk calculations, and model calibration and validation.



[James R. Rocco, B.S., Sage Risk Solutions LLC](#)

Jim has more than 30 years of experience in environmental risk management, risk-based decision making, environmental compliance, and corrective action. He is a Principal in Sage Risk Solutions LLC (Sage), a consulting firm specializing in environmental risk management for commercial, industrial and Brownfields properties, and he began working with RAC in 2001. Prior to his involvement in Sage and RAC, he was employed by BP Exploration & Oil Inc. in engineering and management positions related to construction, maintenance, health and safety, environmental compliance, and corrective action. Mr. Rocco's experience and expertise includes human health risk evaluation, community and stakeholder communication and interaction, and database and

geographic information system (GIS) development and implementation. He has a broad range of experience in the management, communication, and resolution of environmental risks and in the design, specification, and development of processes, software applications, and GIS applications to support decision making and the accessibility, presentation, and dissemination of information. He is a co-author of the chapter on Site Conceptual Exposure Models in Till and Grogan, *Radiological Risk Assessment and Environmental Analysis* (Oxford University Press 2008).



[Arthur S. Rood, M.S., K-Spar, Inc.](#)

Art has more than 25 years of experience in multimedia assessment of contaminants in the environment. His broad range of experience includes data collection and analysis, instrumentation, multimedia contaminant transport modeling, and dose and risk assessment. He has developed models used in environmental assessments including the COMIDA food chain model, and GWSCREEN and MCM groundwater and vadose zone assessment models for Low-Level waste performance assessment. He also has extensive experience in atmospheric transport and has taught Environmental Modeling for the University of Idaho. He co-authored the chapter Terrestrial Food Chain Pathways: Concepts and Models in the textbook, *Radiological Risk Assessment and Environmental Analysis* (Oxford University Press 2008).