MANAGING THE RISK FROM RADIOACTIVE MATERIALS IN GAS DRILLING WASTEWATER

POLICY OPTIONS FOR PENNSYLVANIA

MASTERS OF PUBLIC POLICY CANDIDATE
FRANK BATTEN SCHOOL OF LEADERSHIP AND PUBLIC POLICY

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Key Terms and Acronyms

Conventional Drilling - Industry term referring to traditional oil and gas wells

CWT - Centralized Water Treatment, privately owned and operated water treatment facility

EPA - U.S. Environmental Protection Agency, federal agency

Flowback - All liquid that returns to the surface through an oil or gas well

Horizontal Drilling - Industry innovation allowing multi-directional drilling to reach previously unreachable pockets of resources

Hydraulic Fracturing - Industry innovation that uses high pressure injections of water into the ground to break up rock formations to extract the contained fuel resources

NORM - Naturally Occurring Radioactive Materials

PADEP - Pennsylvania Department of Environmental Protection, state agency

POTW - Publicly owned treatment works, aka municipal water treatment facility

Produced Water - water found inside of rock formations that returns to the surface as flowback

RCRA - Resource Conservation and Recovery Act of 1976, federal law

TENORM - Technologically Enhanced Naturally Occurring Radioactive Materials

Unconventional Drilling - Industry term referring to oil and gas wells drilled using hydraulic fracturing and/or horizontal drilling techniques.

Executive Summary

Oil and gas production in the U.S. has benefited from technological innovations such as hydraulic fracturing and horizontal drilling that allows access to previously inaccessible mineral resources. Along with these benefits are significant externalities and concerns for public health and environmental quality. One relatively unexplored concern particular to the state of Pennsylvania is the radium content of wastewater from drilling operations. So-called Technologically Enhanced Naturally Occurring Radioactive Materials are co-produced by the drilling process and put workers, the environment, and public health at risk when TENORM move from wastewater to contaminate soil, roadways, and, most importantly, water resources. Given the tremendous volumes of drilling wastewater, TENORM can create a significant waste management challenge for policy makers and local planners.

A divisive political debate around a variety issues related to hydraulic fracturing makes movement on TENORM regulation difficult at the federal level. In the absence of stronger EPA protections, this report identifies 4 possible courses of action that can be taken at the Pennsylvania state level to reduce the risk of TENORM exposure from oil and gas drilling operations:

1. Maintain a status-quo minimal regulatory framework
2. Update standards to require industry best practices for storage and treatment
3. Mandated monitoring for TENORM at treatment facilities and new wells
4. Increase permits for decentralized water treatment systems

Each of these policy options was evaluated based on four criteria: their estimated effectiveness in reducing TENORM exposure risk; their expected costs, either to the state or as industry burden; their sustainability in terms of political and public support; their administrative feasibility.

Wastewater management from the oil and gas industry is exceptionally complex, and there is no single solution for all circumstances. For Pennsylvania, the most significant and pressing short-term issue is a dearth of reliable and accurate data reporting total TENORM risk and specific regions where TENORM risk may be elevated. Given the state’s budget limitations, the most effective short-term solution would address these data gaps first. It will be my recommendation that policy makers focus on a program that mandates monitoring for TENORM at multiple points of the wastewater management cycle.

Introduction and Problem Statement

For the past 15 years, advances in drilling technology have allowed the oil and gas industry to capitalize on significant shale resources that were previously not economically viable. Natural gas produced through this new technology accounts for over 67% of all natural gas[1] drilled in the U.S. today (Perrin and Cook 2016). This *shale revolution* saw the expanded production of dry shale gas from less than 5 billion cubic feet per day in 2007 to around 50 billion cubic feet per day in 2017[2]. Twenty percent of this total production comes from Pennsylvania, where much of the Marcellus Shale is located[3]. (U.S. Energy Information Administration 2018). Most of Pennsylvania's natural gas comes from unconventional wells, using techniques like hydraulic fracturing and horizontal drilling to fracture rock formations and access pockets of natural gas deep underground.

The increased production certainly provides benefits to society: the price of natural gas has steadily declined for Americans and the overall price of energy has been cut in half since 2007 (U.S. Energy Information Administration 2016). Booms have created high paying jobs in many rural communities, and the Congressional Budget Office estimated that increased shale production will be responsible for a 0.8 percent increase in federal tax revenue in 2020 (CBO 2014), which is about $35 billion–roughly the combined budgets for the Environmental Protection Agency (EPA) and Department of Energy (Raimi 2017, pg 163). Fracking advocates also tend to highlight benefits like reduced greenhouse gas emissions from natural gas[4] and decreasing the U.S.'s dependence on foreign energy sources (Raimi 2017).

Despite these potential benefits, the rapid expansion of drilling operations in Pennsylvania and across the U.S, has been closely scrutinized by scientists and environmental groups. Both conventional and unconventional drilling operations produce enormous amounts of wastewater that is known to contain dangerous[5] substances like benzene, toluene, and xylene (Elliot et al 2017). Drillers add these chemicals to the drilling fluid as part of the fracking process, and this fluid returns to the surface as wastewater. Much attention has been given to the hazardous chemicals in fracking wastewater, and while the patchwork of regulations is not without loopholes, the EPA and the Pennsylvania Department of Environmental Protection (PDEP) have begun to restrict disposal options for fracking wastewater specifically to protect surface and groundwater resources from these contaminants.

The current regulatory efforts fall short in managing the risk of a different contaminant, one that drillers do not add during the process: naturally occurring radioactive materials, or

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[1] See Appendix Figure 1 - "Marketed Natural Gas production in the United States"
[2] See Appendix Figure 2 - "Monthly dry shale gas production"
[3] See Appendix Figure 3 - "Map of Marcellus Shale and Permitted Wells"
[4] Vs other fossil fuels like oil and coal
[5] Toxic and often carcinogenic, posing dangers to humans and plant/animal life exposed to the waste

NORM. The drilling process disrupts rock formations, releasing NORM into the wastewater that flows back to the surface. Pennsylvania geology is somewhat unique and has particularly high levels of NORM, most notably radium^{226} , radium^{228,} and lead^{210}. The public may be more familiar with the radon gas found in many Appalachian basements, but unlike radon gas, the release of NORM into fracking wastewater can be challenging to manage because the drilling process concentrates the NORM, creating *Technologically Enhanced* NORM, or TENORM. In these higher concentrations or through prolonged exposure, radiation can cause serious damage to human health[6] and contaminated habitats.

This report will present several government and independent studies that have consistently indicated potentially dangerous levels of radiation in wastewater from Pennsylvania oil and gas operations, and that current treatment, reuse, and disposal methods continue to expose the environment to the elevated radiation from TENORM. These studies have linked this TENORM exposure directly to the oil and gas industry in Pennsylvania, sampling from sites where wastes have been released into the environment either intentionally as treated discharge into rivers, or unintentionally though spills from the storage or transportation of the wastewater.

Waste from oil and gas operations are currently regulated under the Resource Conservation and Recovery Act (RCRA), classified as *non hazardous* waste. In an overview of federal waste management policies, environmental economist Hilary Sigman suggested that the motivation for the lower classification was "probably more political than environmental" (Sigman, p219, 200). A recent lawsuit against the EPA has forced a review of this classification and may result in rules changes, but such changes are uncertain and not required. Regardless, the rule change process will take several years, and until then, stricter protections will be left to individual states. Pennsylvania has some restrictions on oil and gas wastewater management, but these restrictions are not consistent for conventional and unconventional operations and do not require monitoring or prevention for TENORM.

This issue is more complicated than a traditional waste management policy problem. Some might view TENORM risk management as a standard negative production externalities problem, giving policy makers a number of tools for correcting the market failure. The most efficient market-based solutions like pollution taxes, abatement subsidies, or cap-and-trade systems minimize the costs of dealing with this externality, but are inappropriate solutions in this case because of the severe damage that can be caused by hotspots of concentrated pollution, which all market-based solutions are unable to prevent[7]. And, the wastewater produced is not technically pollution–it's waste–but would become pollution once the environment has been exposed to the waste. Producing less waste is more difficult to incentivize because of

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[6] Radium 226 & 228 have their own damaging effects on human health explained later, and both decay down to radon, which is the second leading cause of lung cancer in Americans, behind smoking (Casey et al, 2015)

[7] See Tietenberg (1995), for a discussion on market based solutions and hotspot concerns

engineering limitations, so the challenge is incentivizing less environmental exposure from the waste, which is done through optimizing waste management practices. Though a solution like having the EPA classify the waste as *hazardous* and setting standards accordingly may seem straightforward, any policy change would have to pass through significant political barriers that have made regulations for many other parts of the oil and gas industry exceptionally difficult to enact.

In the absence of adequate federal regulation, this report aims to identify and analyze the state of Pennsylvania's policy options for addressing the risks of NORM/TENORM exposure. Oil and gas exploration, both conventional and unconventional, produces significant quantities of wastewater containing a variety of harmful substances, and the management practices for these wastes are inconsistently regulated by the state of Pennsylvania, leaving most of the waste management decisions to the industry itself. **Current policy does not currently account for the hazards from TENORM contained in exploration wastewater, and the oil and gas industry uses a patchwork of management solutions that leave too many vulnerabilities in a system meant to protect drinking water resources and critical habitats.**

The purpose of this policy project is to make a specific recommendation for local regulators to better manage this externality. To do this, I will begin with a thorough background in the science of TENORM, Pennsylvania geology, the drilling practices that bring TENORM into the wastewater, the various types of wastes produced that may include TENORM, current pathways for that waste, and an assessment of the primary holes and vulnerabilities are for environmental exposure to TENORM from oil and gas wastewater. I will then present a review of current literature of best practices for managing TENORM exposure, including surveys of other states on the Marcellus Shale that have similar geology. Following this review, I will introduce three specific options for Pennsylvania policy makers and evaluate those options against several criteria, including a cost-effectiveness analysis.

Note that this report is limited in a few important ways. First, the focus will be specifically for managing the wastewater from oil and gas operations; while TENORM exposure is thought to be most significant from wastewater, it can also enter the environment through solid waste like drill cuttings, treatment facility sludge, and other waste that typically ends up in local landfills, and this report will leave those pathways largely unexplored. Policy makers should not assume that the scope of this current project fully covers the necessary management practices for TENORM from oil and gas operations. Secondly, as mentioned before, fracking wastewater contains a slew of particularly nasty substances, TENORM among them, and the focus here will be specifically to address only the gap in TENORM risk management. Lastly, while significant and peer reviewed studies will be relied on for this policy analysis, an original data analysis will not be included because much of the pertinent data is not publically available.

Understanding the problem: radiation, drilling, and produced wastewater

To best understand and apply management solutions, policy makers should be aware of the overall drilling process and how radioactive materials are introduced into drilling by-products. It is also important to put radiation exposure into perspective. Life on earth is exposed to radiation from many different sources, and there is no practical or reasonable way to eliminate this exposure. Instead, I will present the best scientific understand of the type of radiation exposure involved and the health and legal limits of exposure. With this in mind, I will provide a brief overview of the drilling process and how NORM/TENORM enter the various waste products. Focusing on the wastewater, I will present numerous studies that demonstrate elevated radiation levels directly tied to drilling activities.

Turning toward management solutions for this problem, I will then provide an overview of current disposal practices and government regulations, highlighting the key vulnerabilities in the overall system. This section will also compare policy options from other Marcellus Shale states.

RADIATION: SCOPE, MEASUREMENT, AND THE HEALTH AND LEGAL LIMITS

Radiation, at least within the scope of this policy discussion, is the product of unstable isotopes of elements like thorium and uranium moving towards a more stable atomic configuration. In this process of decay, the unstable radioisotopes release ionizing radiation energy in the form of sub-atomic particles (World Nuclear Association 2012). Depending on where the atom is in a decay series, this energy can be categorized as alpha, beta, or gamma radiation, each with very different effects for life that it contacts. Alpha radiation contains large particles unable to penetrate human skin, but can be very harmful if internalized, as it would be if found in drinking water. Beta radiation contains smaller particles that can penetrate skin and cause skin burns, but are still most harmful when internalized like alpha particles (EPA 2018). Gamma radiation has the greatest penetrating power, similar to that of standard x-rays (World Nuclear Association 2012). Pennsylvania geology contains radioisotopes at many different stages of decay[8], but our current understanding is that the primary NORM that can be brought to the surface through oil and gas drilling are radium^{226} , radium^{228,} and lead^{210} which emit alpha, beta, and beta radiation, respectively (World Nuclear Association 2016).

Radiation is measured in a few different ways, primarily because alpha radiation can have a much greater impact on biology than beta radiation in the same dose. The normalized unit is sievert (Sv), sometimes represented in the smaller units of millisievert (1000 mSv = 1Sv) or microsievert (1000 μSv = 1 mSv). The sievert is used to measure a dose of exposure to humans. Most experts express exposure limits in terms of either a total annual accumulation or a single

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[8] See appendix figure 4 for the decay series and half life chart for Thorium and Uranium

large dose, both in sieverts. Because the types of radiation differ, it is difficult to report or limit total exposure in situations where the exposure comes from different sources.

The National Council on Radiation Protection and Measurements estimates that the average American is exposed to about 6.2 mSv annually, about half of which comes from background sources of NORM and the other half from man-made sources, particularly medical exposure (NCRP 2009). For industries that emit radiation, EPA permits require that such an industry not expose the general public to more than 1 mSv annually. For workers in those industries, the EPA limits their annual exposure to 50 mSv. An annual dose of 100 mSv is enough to increase risk of cancer, but much larger single dose exposure is necessary to see actual radiation poisoning, typically in the range of 2-8 Sv[9].

Other measurement units indicate the quantity of radioactive material present in sample. The international standard is the becquerel (Bq) often given in terms of Bq/l for water concentrations or Bq/kg for solid concentrations. Some U.S. agencies like the EPA use the picoCurie (pCi/L) for standards related to drinking water. Because different sources of radiation have different effects, these limits are often split. The most important limit for this discussion is the EPA's combined radium^{226} and radium^{228,}limit of 5 pCi/l of drinking water, equivalent to 0.185 Bq/l (EPA Radionuclides Rule). Similarly, the EPA restricts soil concentrations of radium to 5 pCi/g for the top 15cm of soil.

The public may be at risk from TENORM through a few different pathways. Drinking water sources may be exposed to TENROM contaminated water, and if not properly treated or diluted, will lead to increased radiation exposure for consumers. Most of the population's drinking water comes from public treatment facilities that are required to maintain the EPA's 5 pCi/l limit, but households that use private wells would still be at risk if their source groundwater was exposed contaminated wastewater. According to 2015 American Housing Survey data, an estimated 985,000 Pennsylvania residents use a well as their primary source of drinking water (U.S. Census Bureau 2015). Workers may also be exposed to TENROM through interaction with wastewater during transportation or disposal, or by working to clean up spills or leftover solid waste products. Aside from human exposure, it is important to note that TENORM contamination may also cause damage to affected habitats and endanger the animals that depend on those habitats.

TENORM EXPOSURE PATHWAYS THROUGH PA OIL & GAS DRILLING

As explained by the EPA, hydraulic fracturing is an industrial practice that forces fluids in large quantities into underground rock formations at a pressure that causes the rock to *fracture*. Known as well stimulation, this process begins with an injection of liquids to break open the rock, then

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[9] See appendix figure 5 for a list of common sources of exposure and their average dose

of proppants like sand to fill the open fractures, and finally the return of the liquid "flowback" to the wellhead along with any gas that was released by the fractured rock (EPA 2016).

The flowback will also include *produced water*, which is any additional water within the broken rock formations that can now travel back to the surface through the drilling line. Produced water released from fractured shale is a “remnant of ancient seawater” (Brown 2014), and can have very high salt content; in most cases, higher concentrations of salt in shale brine indicate higher radioactivity (Rowan, Engle, Kirby, & Kraemer 2011). Over millions of years inside the shale rock, the salt water interacts with the uranium in the rock and mobilizes the radioisotopes (Haluszcak, Rose, and Kump 2012). Untreated, this water has been measured at up to 18,000 pCi/L of radium^{226} according to a U.S. Geological Survey report on radium in produced water from the Marcellus shale (Rowan et al 2011). Produced water in Pennsylvania is particularly salty, and therefore has particularly high measured radium levels compared to other natural gas shales; the Marcellus median radium content is about 2,460 pCi/L compared to about 734 pCi/l in all other measured shales in the U.S. (Rowan et al 2011).

Hydraulic fracturing is not especially new, but advances in horizontal drilling have made fracturing feasible for much of the previously inaccessible Marcellus shale. Gas wells that are drilled with these techniques are classified as unconventional wells; traditional oil and gas wells that are not hydraulically fractured are classified as conventional wells. This distinction is important because specific regulations often do not apply to both types of wells. Conventional gas wells also have the potential to tap into rock formations with salty produced water, and studies show that radioactivity levels of produced water are similar in the Marcellus region for conventional and unconventional gas wells if conventional wells are breaking into Paleozoic rock formations (Haluszck, Rose, and Kump 2012). Researchers have been able to trace NORM samples back to conventionally drilled wells, and have determined that “in many cases, the chemistry of effluents from unconventional and conventional wells is indistinguishable” (Vengosh et al 2015).

In many states, the practice of hydraulic fracturing presents a danger to local water systems because of the enormous amount of water that is sent *down* the well to break up rock formations. Even with reuse, typically only about 10-25% of the water used in fracking makes its way back to the surface as flowback (Hammer & VanBriesen 2012), so water usage becomes a concern in more arid drilling regions like California and Texas. With Pennsylvania’s more abundant water supply, the primary concern is with managing the wastewater post drilling. Though each drilling situation has different requirements and produces different flowback, a typical well drilled on the Marcellus shale will result in .42-2.52 million gallons of wastewater each time the well is fracked (Hammer & VanBriesen 2012). To put this in perspective, compare this to the .66 million gallons of water in an Olympic swimming pool; fracking a single Pennsylvania gas well can produce almost 4 Olympic swimming pools worth of extremely radioactive wastewater.

According to the Pennsylvania Department of Environmental Protection's 2016 annual report[10] on the state's oil and gas industry, 1,321 permits for new unconventional wells were issued in 2016 (PADEP 2016). If following the observed averages, these wells will have produced a total of 554.82-3328.92 million gallons of radioactive wastewater in 2016 alone.

Once the flowback, which includes the salty produced water, returns to the surface, there are several pathways for dealing with the waste. In many parts of the country, the most popular strategy involves drilling a deep hole and sending the wastewater to what is known as a Class II injection well. Much of the controversy around fracking involves the use of these injection wells and their potential to hasten the arrival of earthquakes (Raimi 2017). Class II injection wells are not a suitable option in most of Pennsylvania because of the state's unique geology (Abdalla et al 2011), so only a very small number of these injection wells exist. Instead, drilling operators typically store the wastewater on-site in engineered pond-like impoundments or enclosed tanks, and then either reuse the water to fracture new wells or send it private water treatment facilities for treatment and discharge into waterways (Shih, Swiedler, & Krupnick 2016). Increasingly, the industry has moved toward reuse[11] as the primary pathway for fracking wastewater in Pennsylvania (Shih, Swiedler, & Krupnick 2016). A small portion of the water is trucked out of state to places where injection wells are possible, primarily Ohio and West Virginia.

An analysis of the potential risk pathways indicated exposure risks from transportation related spills, leaks in the protective casing inside of a well, and spills from on-site storage, but most significantly from disposal (Rozell and Reaven 2012). These researchers noted that wastewater disposal risk models presented large epistemic uncertainty because data gaps for how effective private wastewater treatment facilities are at removing contaminants in the water before discharge, but still estimate the risk of exposure to contaminated drilling wastewater was, in the best-case scenario, 200m^3 of total spilled water per well, and up to 13,500m^3 in the worst case scenario (Rozell and Reaven 2012). Given the number of wells on the Marcellus shale, the researchers liken the volume of contaminated water that could be exposed to the environment to "several hours flow of the Hudson River or a few thousand Olympic-sized swimming pools" (Rozell and Reaven, p1391, 2012).

A recent EPA final report on the impacts of hydraulic fracturing also indicated the most significant risk of environmental exposure from fracking wastewater exists when the wastewater is discharged to surface water resources without proper treatment or when untreated wastewater spills during storage or transport (EPA 2016). Spills of this kind of wastewater are challenging to clean up because of the extremely high density of solid materials in the water, which allows the spilled water to move quickly through to groundwater, which tends to not move as quickly.

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[10] See appendix figure 6 for PADEP's new well permit trends for the past 8 years

[11] See appendix figure 7 for PA fracking wastewater pathways 2008-2015

The mixing with slower groundwater results in a localized build up of contamination, so the "impacts from produced water spills can last for years" (EPA 2016).

To summarize, there is a strong understanding of how TENORM is brought to the surface through oil and gas drilling wastewater, and of how contaminated that wastewater is. Additionally, there are accurate estimates of how much wastewater is produced, and what is currently done with most of it. Spills pose the greatest risk to the environment, which can happen during on site storage or during transport to injection wells or treatment facilities. Though many spills of varying sizes have been documented, the EPA report admits that "because of the significant data gaps and uncertainties in the available data, it was not possible to fully characterize the severity of impacts, nor was it possible to calculate or estimate the national frequency of impacts on drinking water resources" (EPA 2016). Environmental exposure to TENORM contaminated wastewater has the potential to cause serious harm, but we are not actually sure how often or where exposure has occurred. This is the heart of the why policymakers have struggled to enact consistent policies to safeguard the public from this risk. Fracking on the Marcellus shale has only been in practice for about 8 years; industry is moving faster than government can monitor and track the potential risks from industry innovation.

CURRENT FEDERAL AND STATE REGULATIONS

Wastes from hydraulic fracturing operations have been given key exemptions from federal waste management rules. The Resource Conservation and Recovery Act of 1976 (RCRA) requires the EPA to regulate both hazardous and nonhazardous wastes, and was intended primarily to protect groundwater and surface water from the harmful byproducts of industrial activities (Sigman 2000). By Congressional act, wastes produced by the oil and gas industry are exempt from RCRA all together, and fracking wastes specifically have been designated as non-hazardous wastes by the EPA (Warner and Shapiro 2013). Additionally, 2005's Energy Policy Act included the notorious *Halliburton Loophole* that "precluded the federal government from regulating fracking under major environmental laws" (Warner and Shapiro 2013 p6), including the Hazardous Materials Transportation Act (HMTA) and Safe Drinking Water Act (SDWA), when concerning the transportation and underground injection of wastewater.

These exemptions are unusual for environmental regulation; most other regulatory structures begin with well defined federal rules and the EPA enforcing those rules. Instead, it seems that Congress and the EPA have removed themselves completely from regulating fracking, which some federalism scholars argue was deliberate venue shopping to ensure that regulations were made at the state level, where there are "fewer resources available for research, enforcement, and interstate coordination" (Warner and Shapiro 2013 p2).

Private and municipal wastewater treatment facilities are regulated under the Clean Water Act, which do not allow for wastewater to be dumped directly into surface water sources; it must be treated first. CWA sets standards for a variety of contaminants in treated water and wastewater sent from oil and gas operations must be treated to those standards before discharge into streams. The CWA sets limits for NORM and TENORM at 5 pCi/l for public treatment facilities that treat drinking water sent directly for public consumption, but does not limit TENORM/NORM for discharge into general surface waters (Hammer and VanBriesen 2012). Note that in Pennsylvania, a PADEP rule in 2011 required that no fracking wastewater could be sent to public water treatment facilities, so policy recommendations moving forward need only apply to private facilities, often referred to as centralized water treatment (CWT) facilities.

The EPA is currently reviewing its rules regarding hydraulic fracturing under RCRA, as was ordered by a judge following a 2016 lawsuit from a variety of environmental organizations. Changes to their rules are not required, and announcements would not be expected until 2021. Changes to the federal regulation of hydraulic fracturing wastes are not expected to occur any earlier than this. There are no federal regulatory limits for exposure to radiation or TENORM generally, though radium and other radioactive materials are covered by the SDWA which requires public water treatment plants to ensure a maximum of 5 pCi/l (Geltman and LeClair 2018).

The state of Pennsylvania has assumed the primary responsibilities for regulating the oil and gas industry within its borders. The state has taken steps to help prevent exposure to some of the chemicals used in hydraulic fracturing, primarily by requiring disclosure of the chemicals used in the drilling process, but of course these disclosures do little to inform the public on NORM/TENORM concentrations of flowback (Rozell and Reaven 2012). While some actions have been taken to stop the treatment of wastewater at public utilities that are ill equipped to handle the industrial waste, the PA DEP does not have specific requirements for the safe handling of TENORM contaminated wastewater. A 2016 final rulemaking[12] updated state regulations for unconventional gas drilling, banning the use of temporary open storage pits, though more permanent open air impoundment ponds are still in use. The new rules do not specify TENORM limits or practices, but they do require operators have some form of TENORM management and monitoring plan on file with the state. Additionally, reporting on drilling activity, chemicals used, and other practices is now required monthly through PADEP's website; note that the gathered data are *self-reported* by industry and the PADEP notes through a disclaimer that these reports are not verified by the state. There are rules that require radiation monitoring at solid-waste landfills (Geltman and Leclair 2018). A 2013 report from the PADEP looked at TENORM exposure, primarily to oil and gas workers and the immediate communities,

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[12] 25 PA. Code CHS. 78 and 78a, Environmental Protection Performance Standards at Oil and Gas Well Sites

and concluded that no further actions were required to limit risk, but that the risk from spills and transportation was still significant (PADEP 2015b).

SURVEYING NEIGHBORING STATE POLICIES

Pennsylvania shares the Marcellus shale with New York, Ohio, and West Virginia primarily, who have taken on the policy problem differently.

New York has placed tighter restrictions on the oil and gas industry, including a state-wide ban on hydraulic fracturing (Geltman and LeClair 2018), but NORM and TENORM risks persist through the state's 24,000 conventional wells, and exposure would also be possible through any fracking wastes that are brought into the state from Pennsylvania.

Ohio has perhaps the strongest requirements for TENORM of the Marcellus shale producing states; NORM and TENORM are clearly defined, the standard 5 pCi/g applies to both relevant radium isotopes, landfill disposal limits are in place, and monitoring mechanisms are in place so that treatment facilities and disposal sites cannot accept waste until TENORM content is known (Geltman and LeClair 2018).

West Virginia is estimated to have roughly 100,000 oil and gas wells, and restricts TENORM waste to 5 pCi/g for solid waste (Geltman and LeClair 2018). These guidelines are meant to apply to landfill waste, and do not apply to wastewater.

INDUSTRY BEST PRACTICES AND OTHER REGULATORY EFFORTS

It should be clear by now that neither federal nor state level regulators are taking strong action on TENORM exposure from oil and gas operations. This does not mean that radioactive waste is going untreated into rivers and groundwater. Without a consistent or comprehensive regulatory framework, the oil and gas industry is disposing wastewater through a few different pathways based on operational cost effectiveness and generally known industry best practices. Additionally, numerous environmental groups have provided recommendations to lawmakers for a set of best waste management practices, some of which have been voluntarily adopted by drillers.

The Natural Resources Defense Council has studied hydraulic fracturing extensively, and has released guidance for policymakers and industry leaders to best manage wastewater (Hammer and VanBriesen 2012). Their report thoroughly examines the entire scope of waste management options for both solid and liquid waste. Based on their survey of the greatest vulnerabilities, their primary recommendations related to TENORM in wastewater management include adding TENORM/NORM within a stricter set of contaminant limits for discharge to public waterways;

monitoring and identifying the waterways most affected by wastewater pollution and working to reduce discharge to those bodies; classifying shale gas wastewater as hazardous regardless of the RCRA exemption; prohibition of open storage pits; and require closed storage tanks have secondary containment barriers to contain spills (Hammer and VanBriesen 2012). These best practice recommendations are intended to reduce environmental exposure and help regulators more quickly identify areas of environmental contamination.

Other research has identified open-air impoundment storage tanks as a primary source of risk, and found that larger and more frequent spills occurred with open pit storage than with closed tanks (Kuwayama et al 2017). They note that closed tanks can also fail, and recommend better monitoring and data collection on both storage methods before deciding to ban either outright. They indicate that most spills occur due to liner malfunction or over filling of the storage device (Kuwayama et al 2017). These researchers advocate for a searchable database of spill data–such a database would require increased monitoring of storage limits and more timely reporting of incidents. Additionally, analysts have recommended that all pits and storage tanks have mandatory secondary containment mechanisms (Kiparsky and Hein 2013).

Monitoring methods are complicated as well because not all testing devices or methods account for the total content of all potential NORM/TENORM sources. One study analyzed the EPA's recommended testing procedure for radiation levels in drinking water and found that the particular chemistry of Marcellus shale-produced water masked the true radiation content of their samples; the standard EPA wet chemical test "recovered as little as 1%" of the radium^{226} in their samples (Nelson et al 2014). PADEP determined that TENORM levels were not high enough to warrant a change in policy, and Nelson et al's study suggests that this determination may be based on an underestimation of TENORM content. The political debate around fracking in general complicates the feasibility of more standard regulations, and law researches have advocated for increased transparency and reporting as a way to more clearly identify high-risk situations, including spills and chemical composition (Kiparsky and Hein 2013).

Using these industry best practices and cost analyses, some scholars have begun to produce models that aim to optimize the mix of waste management strategies given set resources, distances to treatment facilities, transportations costs, and risks of environmental damages (Shih, Swiedler & Krupnick 2016). Their model is impressive in its incorporation of multiple perspectives and priorities, and though it is untested, it may begin to provide analysis of the current wastewater management cycle through future applications. It may not be immediately applicable for Pennsylvania policy makers, but it is promising work that will help identify the most cost-effective solutions that also protect environmental interests.

Currently, this model has identified an expected tendency for industry waste management based on a company's most cost-efficient option. In Pennsylvania, for most well sites, this means storage on site, light treatment, and reuse in future fracking (Shih, Swiedler, & Krupnick 2016). These practices are not entirely out of line with the NRDC’s base recommendations for onsite treatment and reuse. Current industry practices are dictated by cost, and some of that calculation includes the cost of spill cleanup and legal action when the waste is mismanaged.

Despite following these industry best practices, environmental exposure to elevated TENORM has occurred. A recent independent study tested for NORM/TENORM presence in stream rock beds near private treatment effluent discharge sites and found consistent samples showing total radium at 90-25,000 Bq/Kg (Lauer, Warner, & Vengosh 2018). Notably, their samples came from CWT’s dedicated to *conventional* wastewater treatment, which suggests that in Pennsylvania, policies that only apply to unconventional wastewater will not eliminate the risk of TENORM exposure.

Evaluation Criteria

In comparing the different policy alternatives, I will evaluate based on the following criteria:

ESTIMATED EFFECTIVENESS IN REDUCING EXPOSURE RISK

As defined, the policy problem in Pennsylvania is a high risk of exposure to TENROM from drilling wastewater, primarily to individuals with private water wells or to environments near water storage or effluent discharge sites. Policies to address this problem must provide a reasonable pathway to risk reduction. The best policy options should effectively address the management of current environmental exposure while also attempting to lower the potential of future exposures.

This criterion will assess each policy option's ability to address the risks of TENORM exposure. A score will be assigned along a simple *low, medium, or high* scale that estimates how well the program reduces environmental and public health exposure to TENORM from drilling wastewater. A *high* score will indicate that the program provides obvious, relatively immediate, and widely distributed risk reductions for Pennsylvania residents and general habitats. A *low* score will indicate that the program may offer risk reductions, but those reductions are not clear or ensured. A *medium* score will meet somewhere in between with clear explanation for where the reductions are and are not ensured.

Evaluating the current risk level is difficult because of significant gaps in data, so reducing that risk may include filling relevant data gaps, closing administrative loopholes, or ensuring best waste management practices. Risk reductions are also difficult to ensure across the entire population, so this criterion will also attempt to identify where the risks are reduced, to which populations, and how those reductions are measured.

COSTS FOR INDUSTRY OR PENNSYLVANIA

This criterion will discuss the cost of relative risk reductions identified by the first criterion. The anticipated costs for each policy option will be identified and compared with anticipated outcomes. All costs will be estimated over the life of program, with future discounting as appropriate.

Each program is likely to have some unique costs, but generally each policy option will be evaluated in terms of upfront implementation costs, annual maintenance costs, and any associated facility or personnel costs. Any assumptions or valuation plugins will be specified when used.

This analysis will make no judgments as to who should bear the associated costs, but it will attempt to at least identify which parties will be most greatly affected by additional costs, with the major distinction being between industry or the state of Pennsylvania. Because total costs may be wildly different or difficult to accurately calculate, and effectiveness is not measured uniformly across policy options, comparing the total costs of the programs will not be particularly useful. After a discussion of each program's expected costs, I will assign a *high, moderate,* or *low* score for this criterion; *low* costs will be considered ideal, with *high* costs being less than ideal. Generally. a lower cost for greater risk reductions will be preferred and discussed in terms of trade-offs.

SUSTAINABILITY

TENORM exposure is an extremely long-term problem, and solutions implemented now need to be building toward a sustainable plan to address the risk. Political feasibility and issues of equity are at the heart of this criterion: are the proposed programs likely to face resistance from industry or political leaders? Additionally, do the proposals use current and emerging technology and best practices appropriately? Keeping up with energy innovation is particularly difficult for regulators, and any plan to reduce TENORM exposure risk must address these challenges.

Sustainability will be scored with simple *high, medium, low* ranking. Programs that can be quickly removed or become obsolete with potential EPA regulations will be scored less favorably. Programs that, for reasons of political feasibility or public support, are easier to sustain will be scored more favorably. Administrative feasibility will be more completely evaluated independently, so challenges associated with implementation and maintenance will not be considered under this criterion unless they relate directly to political or public support.

ADMINISTRATIVE FEASIBILITY

Implementation will need to consider the state's limited resources, including manpower. This criterion will attempt to evaluate how easily and quickly those programs can be implemented and maintained through their expected life.

Administrative feasibility will evaluate the complexity of each proposal and make determinations related to how likely that complexity will contribute to overall program effectiveness. These determinations will be made with considerations for current state resources, manpower, and the interaction between affected agencies and industry. The implementation and timeline for expected benefits will also be considered here, including the potential need for a phased roll out.

This criterion will be scored as *high, medium, or low*, with high scores going to options that use available resources efficiently, have minimal complications related to implementation, and have relatively easy program maintenance. Lower ratings will be given to programs that have significant implementation, timeline, or maintenance complications that may slow or reduce the intended impact of the program.

Evaluation of Policy Alternatives

ALTERNATIVE 1: MAINTAIN STATUS QUO

The current regulatory structure does very little to ensure environmental and public health protection from exposure to TENORM from oil and gas drilling wastewater. While there are some basic restrictions on a firm's wastewater management options, the industry is currently determining their waste management practices by minimizing the cost of treatment and disposal. At this time, the lowest cost option for most drilling sites is to store wastewater to be reused in future drilling. Some sites are able to transport wastewater to centralized treatment for discharge into public waterways or transport it to an injection well either inside or outside the state of Pennsylvania.

Transport and storage methods carry the potential for spillage, and treatment facilities are not required to fully monitor and control for TENORM reduction in all circumstances. Additionally, proper monitoring is not in place, so timely awareness of environmental exposure to TENORM contamination will continue to be difficult. The costs of maintaining the status quo will be heavily discounted as TENORM contamination lasts for many years (thousands in some cases) and can cause health effects that take years to develop in humans. Additionally, current risk of environmental exposure is likely increase as new wells are drilled, which is at a rate of about 1,000-3,500 each year.

Estimated Effectiveness in Reducing exposure risk

Estimating the current exposure risk is difficult because of previously stated gaps in data and minimal attention given to the NORM/TENORM content of wastewater by the state. The problem is that, despite these data gaps, a significant risk is reasonably assumed and without data tracking, that risk is very difficult to mitigate. Current industry practices for waste management may change based on internal costs and innovation, but maintaining the status quo would do nothing to ensure improvements in these practices. For this criterion, maintaining the status quo is graded as *low*.

Costs for Industry or Pennsylvania

Maintaining the status quo would not require additional program costs for the state or regulatory costs for industry; it is assumed that drilling operators are already minimizing their costs through current waste management practices. However, operators may not be fully considering damage remediation within their cost functions. In a case well-known to industry insiders, ExxonMobil Corp and a contractor that helped them de-scale TENORM contaminants from a pipeline were held liable for $168 million in damages to the Louisiana landowner whose farmland was damaged (Rysavy 2008). In Pennsylvania, the drilling firm Range Resources paid $4.15 million in fines to the state because of soil and groundwater contamination from improper on-site wastewater storage that led to localized leaks (Hopey 2014); a smaller leak from another

Pennsylvania producer, WPX Energy Appalachia, contaminated well drinking water for 5 nearby families and paid $1.2 million in fines to the state (Hopey 2017). As demonstrated, environmental exposure can occur through different pathways, and the volume of exposure can significantly alter the associated clean up costs or government fines. With this in mind, it may be difficult for firms to accurately calculate and plan for potential liabilities from industrial accidents. No reasonable accurate accounting of total such costs can be made because of these vast uncertainties and gaps in data.

Sustainability

Maintaining the status quo is the easiest option politically, as it requires no additional action on the part of law or policy makers. Hydraulic fracturing policy is difficult for policy makers because of the uncertainty around associated environmental damages and the known short term economic benefits such as lower energy prices and local development. Federal regulators are currently considering options to increase or maintain standards for oil and gas wastewater management; though unlikely to change significantly in the near term, it is possible that new federal rules may require changes to the status quo. Additionally, public support for stricter regulations grows as reports of environmental or health hazards are introduced into the debate. For this criterion, maintaining the status quo is graded as *medium*.

Administrative Feasibility

Maintaining the status quo would not require additional programmatic support from state or local agencies. The state should consider the reasonable possibility that maintaining the status quo will lead to increased environmental damages that, in the case of TENORM, are particularly difficult and expensive to clean up, as described previously. The work required for such efforts can fall on PADEP or local authorities, and any claims filed against firms relating to damages may also involve costs to local or state court systems. For this criterion, maintaining the status quo is graded as *medium*.

ALTERNATIVE 2: ALIGN STATE REGULATIONS WITH BEST PRACTICES

Though many current industry practices aim to properly manage the wastewater, such advances are not required and are therefore subject to change if lower cost disposal methods become available. There is still room for improvement in bringing Pennsylvania drillers up to industry best practices. For example, in the two cases of on-site storage spills cited before, the drilling companies were fined $4.15 million and $1.2 million dollars *and* were required to upgrade their storage practices to stronger standards than are required by the state normally (Hopey 2014). Pennsylvania lawmakers recently updated the rules for the oil and gas industry in 2016, but these rules did set specific standards for TENORM management.

These regulatory updates should include a minimum standard for onsite storage: storage tanks will have secondary containment systems and permanent impoundments will have increased liner quality standards; both of these practices have been shown to minimize the risk of spills from on-site storage.

Current rules do not require operators treat stored water to reduce TENORM content for water being reused in drilling operations. Treating specifically for TENORM reduction would lower the associated risk of spills or leaks from these impoundments while waiting to be reused in future drilling processes. Reuse of wastewater should be encouraged, and adding treatment requirements to wastewater prior to reuse may have an unintended effect of reducing the volume of reused wastewater. Tighter regulations may provide incentives for reuse of 80% of flowback while also requiring TENORM treatment; such incentives may include tax benefits or subsidies for private treatment.

Estimated Effectiveness in Reducing exposure risk

If enacted fully and implementation concerns are overcome, this policy option should significantly reduce TENORM exposure risk by ensuring waste management practices that approach the best of what is currently possible given economic and technological capacity. Given that injection wells are not widely suitable in Pennsylvania, reuse and treatment are the best options for reducing the concentrations of TENORM in wastewater prior to release into the environment. Tightening standards for onsite storage should also marginally decrease the risk from spills associated with imperfect storage practices.

This option, once in place, should have the greatest effects in the short term. Long term, though, the option may be limited by the applicability of reuse as a waste management option for an industry that will eventually decline in the state. Reuse is only viable if there is a demand for fracking liquid equal to or greater than the amount of wastewater needing to be reused. New well permits have steadily declined; if this trend continues, reuse in hydraulic fracturing operations will not be possible for all wastewater. Given these limitations, and the expected political and administrative barriers discussed below, the expected high gains in risk reduction should perhaps be tempered. For this criterion, increased treatment and storage standards is graded as *medium.*

Costs for Industry or Pennsylvania

TENORM treatment requirements will involve the most significant costs for this policy option. According to a comprehensive survey of oil and gas waste management cost methods, the treatment of highly saline produced water ranged from roughly \$6-\$17[13] per barrel of contaminated water (Puder and Veil 2006). With treatment, TENORM is typically separated from the water and condensed into sludge or solid waste that must be disposed of, at an estimated

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[13] The original 2006 report specifies \$5-\$15, my numbers have been adjusted for inflation.

cost of $19-$170[14] per ton of waste if disposed of in a TENORM-accepting landfill site (Puder and Veil 2006). Accurate estimates for per-ton solid waste generated from barrel of treated wastewater are difficult at large scale because of the variance in TENORM content being removed from the water; costs for the solid waste disposal portion of this program will not be calculated, but should be kept in mind.

The amount of wastewater generated annually varies, but PADEP estimates that the average total Pennsylvania unconventional drilling wastewater from 2013-2015 was 39 million bbl. Currently, about 65% of wastewater is being reused, equivalent to about 25.35 million bbl. The treatment cost for current volume of reused water, then, would be $152.1-$430.95 million annually. A program goal of incentivizing increased reuse of wastewater up to 80% would require a total treatment cost of $187.2-$530.4 for 31.2 million bbl treated, an increase of $35.1-$99.45 million. The treatment cost for all operators would range from $234-$663 million annually for 100% treatment.

Treatment would also require transportation costs. Under current rules, untreated water destined to be reused is stored onsite and/or transported to new drilling sites. Researchers have developed an operator transportation cost model that estimates a single truck with 30m^3 volume capacity, roughly 250 barrels, will cost about $100 per mile[15] (Marufuzzaman, Ekşioğlu, and Hernandez 2015). If no wastewater was currently being transported and this policy option suddenly required transportation, operators could expect a state-wide cost of $10.14 million per mile for the roughly 101,400 full trucks needed to transport 65% of average annual wastewater. Puder and Veil estimate that operators will not use trucks to transport wastewater more than 75 miles away if other disposal options are possible (2006). With this in mind, transport costs might be estimated at $10.14-$760.5 million in total annually, assuming at least one mile of transportation. In reality, though, transportation costs are already being covered by operators regardless of treatment, so it is unclear how much of this total transport cost estimate would increase with treatment standards prior to reuse.

These treatment and transportation costs are not insignificant, combining for a low estimate of $162.24-$912.6 million annually and a high estimate of $441.1-$1,191.45 million annually to treat and transport the current level of 65% of reused wastewater. As an annuity with 7% discounting, this equates to a lifetime cost of $2,317-$17,021 million. Any treatment and transportation costs at present are borne by operators; given PADEP's operating budget of about $150 million, any increases in total social costs are likely to remain funded privately. For this criterion, increased treatment and storage standards are graded as *high.*

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[14] $15-$135, adjusted

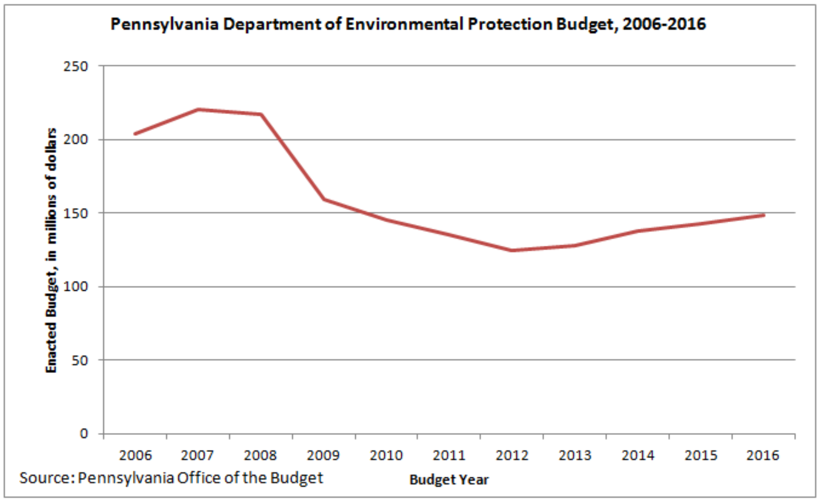
[15] In fixed costs, assuming a full 30m^3 load(250 barrels)

Sustainability

Even if a best-case scenario increased costs by only 25%, these proposed standards would still impose over $100 million in annual compliance costs on to operators. New standards would require PADEP formally propose them for a public commenting period. For the most recent update of standards, the process from proposal to enactment took about 2 years and did not place a significant burden on operators because the strictest updates were banning temporary storage pits, a practice that wasn't largely used anymore in Pennsylvania. These new standards would impose a much higher burden, and should expect to face resistance from industry leaders and stakeholders. If the new rules managed to pass through public commenting, industry lobbyists would very likely target elected officials who would support removal of the new standards. With TENORM being a largely unquantified public risk, it will be extremely difficult to sustain strict and expensive treatment requirements until those risks are better understood. For sustainability, this policy option is graded as *low*.

Administrative Feasibility

Tightening various TENORM standards would do little to address the problem without proper monitoring and enforcement from PADEP. However, under current standards, PADEP inspectors are failing to meet the current needs of state water inspection across the board. EPA has recently warned PADEP that the state is not meeting requirements for timely inspections and follow up for reported violations; by EPA's estimation, PADEP lacks the personnel and budget to meet current federal requirements for monitoring and enforcement (Cusick 2017). PADEP's budget has decreased over 40% in the past decade, with a resulting loss of 25% of its workforce (Cusick 2017). With this situation in mind, adding oversight and enforcement duties to PADEP offices and workers would likely not result in immediate intended program effectiveness.



Source: Pennsylvania Office of the Budget

The implementation timeline is likely to increase because of the required public comments process as well, and generally at least one year is given to operators to become compliant with new rules. For this criterion, increased treatment and storage standards are graded as *low*.

ALTERNATIVE 3: MANDATED MONITORING OF TENORM LEVELS

There are different methods for testing for radium levels in wastewater, and Pennsylvania's unique geology requires different methods from standard practice in other parts of the country. It is critical that industry self reporting of TENORM levels and PADEP auditors are using monitoring techniques appropriate for the unique chemistry of Pennsylvania's produced water. As researchers have shown, the standard EPA approved test for radium detection in drinking water detected only 1% of radium in Marcellus samples; instead of these standard methods, monitoring should be done only with Nondestructive high-purity germanium (HPGe) gamma spectroscopy (Nelson et al 2014). Movement on TENORM policy in Pennsylvania has been slow because there are significant data gaps demonstrating the problem in real time. Better monitoring practices could be used to fill the holes in the current data, which will help policymakers at the PADEP make more informed determinations about TENORM exposure rules. If part of the problem is a lack of action based on a misunderstanding of the severity of TENORM risk, then more comprehensive monitoring and data collection will seek to correct this misunderstanding.

An improved monitoring framework would also help identify priority areas. TENORM measuring and reporting would be required before and after treatment, and also near discharge sites. This will allow a more informed evaluation of treatment quality, and also more quickly identify public water sources that might be at most risk for contamination. The state of Pennsylvania already requires similar monitoring practices at solid waste sites like landfills, so alternative 3 is about extending this practice to provide more comprehensive monitoring to both solid and liquid waste.

Improved testing will also aid in the instance of reported spills. If the TENORM content of spilled water is more accurately measured, PADEP will be better able to respond to and begin cleaning operations sooner.

Estimated Effectiveness in Reducing Exposure Risk

Increased monitoring does not directly lower the TENORM content in wastewater, but increasing public understanding of TENORM content in oil and gas wastewater will aid regulators in identifying habitats and watersheds where the greatest risks exist, and take more targeted action. Such targeted actions may involve requiring remediation at the expense of the operator responsible for a spill or improper discharge. A better understanding of the TENORM risk should also inform better policy around worker safety for those who are involved in oil and gas operations as well as workers charged with transporting, treating, and disposing of associated wastes. Notably, monitoring at CWT facilities would allow keeping tabs on both conventional and unconventional wastewater. PADEP's current assessment is that the risk from TENORM is too low to require further state actions, but better monitoring is expected to provide PADEP with the data needed to make a more accurate assessment. For this criterion, monitoring protocols will be graded as *medium.*

Costs for Industry or Pennsylvania

In 2000, the EPA considered new standards for public drinking water treatment facilities to monitor for and treat drinking water specifically for NORM content. A preliminary cost-effectiveness analysis for these proposed standards reveals useful insight into the expected costs associated with monitoring programs specific to measuring radium content (Industrial Economics Incorporated 2000). The analysis determined the expected cost for adding accurate and complete radium testing on top of other testing protocols. Since current operators are already monitoring and reporting other chemical contents of their wastewater, the increased costs for adding TENORM monitoring should be reasonably comparable.

In their analysis, adjusted for inflation, the increased radium monitoring requirements would cost $38-$532 annually per site (Industrial Economics Incorporated 2000). According to a 2011 resource from PADEP detailing the private water treatment facilities that are or will be accepting oil and gas wastewater, fifty-seven facilities would be impacted by this TENORM monitoring requirement. Thus, adding a TENORM monitoring requirement at private treatment facilities that process unconventional wastewater can be expected to cost operators $2,166-$30,324 annually. Calculated as an infinite annuity, this cost is valued at $30,943-$433,200 with a 7% discount rate. If this burden were spread evenly among the nearly 80 drilling firms operating in Pennsylvania, the cost would be around $5,000 lifetime per operator. This average is for perspective only, as it would be far more appropriate to calculate individual firm burdens based on wastewater volume, which is outside of the scope of this report.

For monitoring water coming directly out of newly drilled well, on-site testing may be more appropriate. According to a state of Maryland report, direct testing for radium isotopes is estimated to cost between $120-$220 for one-time samples from the general public, say if a homeowner wanted to test their well water (Maryland Department of the Environment 2000). There were 1321 new unconventional wells drilled in 2016 (PADEP 2016), so for a high estimate, assume an increase to 1500 new wells next year. Testing water directly at these new wells would cost $158,520-$290,620 annually for 100% coverage. As an annuity with 7% discounting, this cost would be about $2.3-4.2 million. These costs are calculated as a high estimate; private firms are likely to be able to secure a better rate for bulk testing than the general public.

While these costs appear quite low at first glance, remember that they are strictly for monitoring TENORM content in wastewater at different points of the waste management cycle. If TENORM is detected at unsuitably high levels, treatment or disposal procedures would not be included in the calculated costs. The costs for monitoring pay for information: more accurate data that ideally leads to better future policy decisions. For this criterion, monitoring protocols have been rated as *low*.

Sustainability

Evaluating this alternative on sustainability presents an interesting dilemma. The proposal is for a fairly low-cost monitoring enforcement program that better alerts waste managers and regulators to elevated levels of an uncertain-but-particularly-dangerous contaminant; near-universal support is reasonable to assume. As was demonstrated in the cost evaluation for policy option 2, treatment of wastewater with elevated TENORM content is expected to be extraordinarily expensive; it may be just as reasonable to assume industry concern that monitoring would lead to treatment burdens, and this concern would be deepened if industry insiders were aware of the magnitude of current underreporting of TENORM concentrations in wastewater. Still, a reasonable monitoring program that puts very little burden on the private sector for significant public gains should have the political support needed to stay afloat for the foreseeable future. For this criterion, sustainability has been rated as *high.*

Administrative Feasibility

PADEP would need to collect and store reports from operators monitoring for TENORM. Luckily, the state already requires monthly reporting on a variety of other drilling activities from operators, so most of the administrative burden would fall on operators in completing the monitoring reports and submitting them through PADEP's online reporting system. It is assumed that this reporting system is automated to some degree in terms of PADEP's collection of data; if true, then there should be minimal increased burden for adding TENORM monitoring to PADEP offices. This is ideal, considering the previously discussed cuts to PADEP's operating budget and personnel. The proposal is not particularly complex, and there are less than 100 treatment facilities to keep track of for this monitoring, and even fewer operators that would be submitting reports. While the treatment facilities and operators would likely need time to implement the monitoring program at their sites, a full rollout is reasonable to assume within a standard timeline. For this criterion, monitoring has been rated as *high*.

ALTERNATIVE 4: DECENTRALIZED WATER TREATMENT SYSTEMS

Permit requests for building new CWT facilities have increased over the past two years. Treating water on-site or closer to the drilling site reduces transportation costs to the industry and lowers the risk from spilling. With closer options for treatment, the need for extended on-site storage or reuse of untreated wastewater will be reduced. At present, most treated water is done at a number of large facilities throughout the state; lawmakers could choose to issue more permits or fund a subsidy for the building of smaller, more decentralized treatment facilities. Smaller treatment facilities would process less waste overall and be close enough to reduce some of the risks involved in transportation and storage.

Estimated Effectiveness in Reducing exposure risk

A more decentralized system would locate treatment facilities much closer to drilling sites, reducing travel time and likely some of the spills associated with extended transport. Transportation from drilling site to CWT for treatment and disposal was identified as pathway for potential spill and environmental exposure, but it is a relatively minor risk when compared with the risk from onsite storage and improperly treated discharge. Though these risk reductions would be welcome, they are not quite at the scale needed. For this criterion, subsidized CWT's are rated as *low*.

Costs for Industry or Pennsylvania

For this evaluation, a comparison of centralized vs. decentralized municipal water treatment facilities was sourced for primary relative costs. Though this cost-effectiveness analysis is evaluating a slightly different situation, the relative costs are still useful.

Table 1 - Economies of Scale for 3 Types of Water Treatment Systems

Capacity	**Unit Construction Cost**	**Unit O&M Cost**
10,000 gal/day - onsite	$70 per gpd of capacity	$13 per gpd of average flow
100,000 gal/day - satellite	$35 per gpd of capacity	$5 per gpd of average flow
1,000,000 gal/day - CWT	$17 per gpd of capacity	$2 per gpd of average flow

Source: Barnstable County Wastewater Cost Task Force (2000)

In their comparison of costs for different wastewater treatment systems, the Barnstable County Wastewater Cost Task force identified significant economies of scale for building and operating water treatment facilities at the larger CWT size relative to decentralized satellite facilities or onsite treatment. Note that these costs appear lower than cost estimates determined for wastewater treatment in policy option 2; this is because the Barnstable County estimates are for facilities that treat municipal level waste, and not the more expensive industrial waste with TENORM removal needed. The identified economies of scale do indicate, however, that moving from a CWT system to a decentralized system would likely come at significant increase in overall treatment costs. On the other side, building decentralized treatment facilities closer to drilling sites will certainly reduce travel costs, which were estimated at $100 per mile, per full truck. Though reductions are certain, the magnitude of these expected reductions is uncertain without a thorough geospatial analysis of proposed building sites and projected future well sites. For this criterion, decentralized water treatment subsidies are rated as *moderate* cost.

Sustainability

Once a new system is built, it is very costly, and therefore difficult, to change course. A program that incentivized the building of new water treatment facilities closer to drilling sites would be sustainable as long as the burden was not shifted to the state; increased permitting allowances or a small subsidy would likely survive through the completion of systems in areas where private operators deemed it cost effective to build more treatment sites. This program is likely to garner support from operators as it is meant to incentive them to build facilities that may help lower their transportation costs. For sustainability, decentralized water treatment facilities is rated as *high*.

Administrative Feasibility

The primary administrative responsibilities fall on permitting offices that must evaluate proposals for new treatment facilities. Incentivizing more of these facilities through minor subsidies or other mechanisms would increase the volume of these proposals, which may already be tough for state agencies to process. With PADEP's budget limitations, adding more applications would not necessarily mean increasing staffing to deal with those applications was possible. The permitting and building process is costly in terms of time regardless, so the main concern with administrative feasibility is that a full scale roll out may not be reasonable; with this policy option, expect to need significant phase-in time. For administrative feasibility, decentralized treatment facilities are graded as *medium*.

Outcomes Matrix

Options	Risk Reduction	Cost	Sustainability	Administrative Feasibility
1: Maintain Status Quo	**Low**	**N/a**	**Medium**	**Medium**
2: Align State Regulations with Identified Best Practices	**Medium**	**High**	**Low**	**Low**
3: Alternative 3: Mandated Monitoring of TENORM levels	**Medium**	**Low**	**High**	**High**
4: Decentralized Water Treatment Systems	**Low**	**Moderate**	**High**	**Medium**

Recommendation: Mandated Monitoring of TENORM levels

PADEP should mandate monitoring for TENORM content for all wastewater at multiple points in the waste management cycle, including pre-entry to treatment and discharge facilities and on-site for new wells and long term storage in impoundments.

It is difficult to manage potential TENORM risk with the current data gaps that prevent full understanding of that risk. PADEP's reporting indicated that TENORM risk exposure was quite low and that further action was not needed. As demonstrated, there is evidence that this determination may have been understated or made based on improperly tested wastewater samples. In the short term, the biggest TENORM related problem for the state of Pennsylvania is that the state doesn't have a reliable understanding of the magnitude of TENORM risk exposure pathways, and one way to improve on this dimension is to increase the size and quality of the data set.

At present, operators are required to have some form of TENORM management plan on file with PADEP, but monitoring for specific levels is not required or even indicated. My recommendation would not set a specific limit for TENORM content in wastewater, but it would help policy makers identify the areas of high need when reporting is done accurately. As such, it would allow regulators to focused on the highest marginal benefit gains by targeting the water resources, localities, and habitats that would be most affected by TENORM exposure to well operations that test particularly high. Other options may have reduced TENORM exposure risk, but would have done so at significantly higher cost in terms of burden to producers and also through political and administrative feasibility. In the short term, setting up a monitoring mandate for operators provides the easiest pathway to the biggest immediate gains.

Implementation Considerations

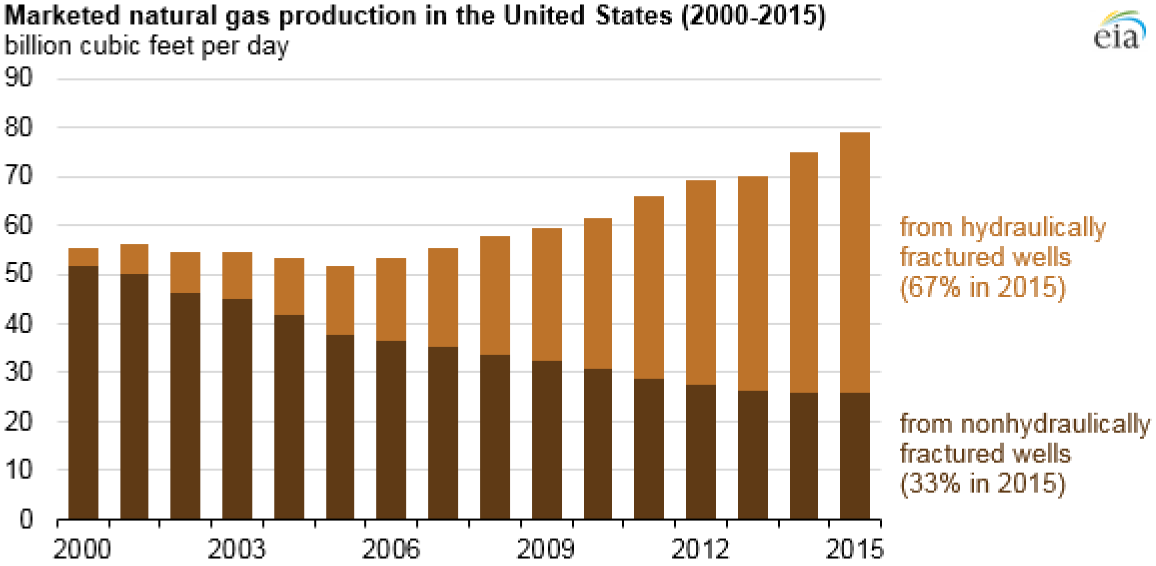
The most significant consideration with a monitoring mandate is that the type of testing for wastewater samples is restricted to Nondestructive high-purity germanium (HPGe) gamma spectroscopy. HPGe testing is one of many common and EPA-approved testing methods, but is still a somewhat new technology. The somewhat unique chemistry of produced water from the Marcellus Shale obstructs other traditional testing methods, and HPGe has been shown to be the most accurate testing technique under these circumstances.

Operators should already be familiar with similar monitoring and reporting requirements for other parts of their operation, so compliance should not provide significant burden to the private sector. Enforcement and perhaps even auditing may be necessary tools for PADEP during the initial rollout to ensure that operators are using the correct monitoring techniques and reporting test results accurately.

TENORM risk is likely to not be a topic at most family dinner tables, and it is important that any increased public attention from setting a new priority for TENORM monitoring be met with educational tools and transparency. TENORM has the potential to cause serious harm, but is a much lower risk than exposure from refined uranium products used in nuclear energy; TENORM exposure should not be misunderstood as being equivalent to exposure from nuclear reactor accidents or weapon detonations. Public policy should aim to mediate public concerns while also committing to a better understanding of the scope of the risk. NORM, after all, are *naturally occurring*, and somewhat inevitable parts of life on Earth. With a better understanding of the total exposure risk, TENORM can be managed effectively with current technology and resources.

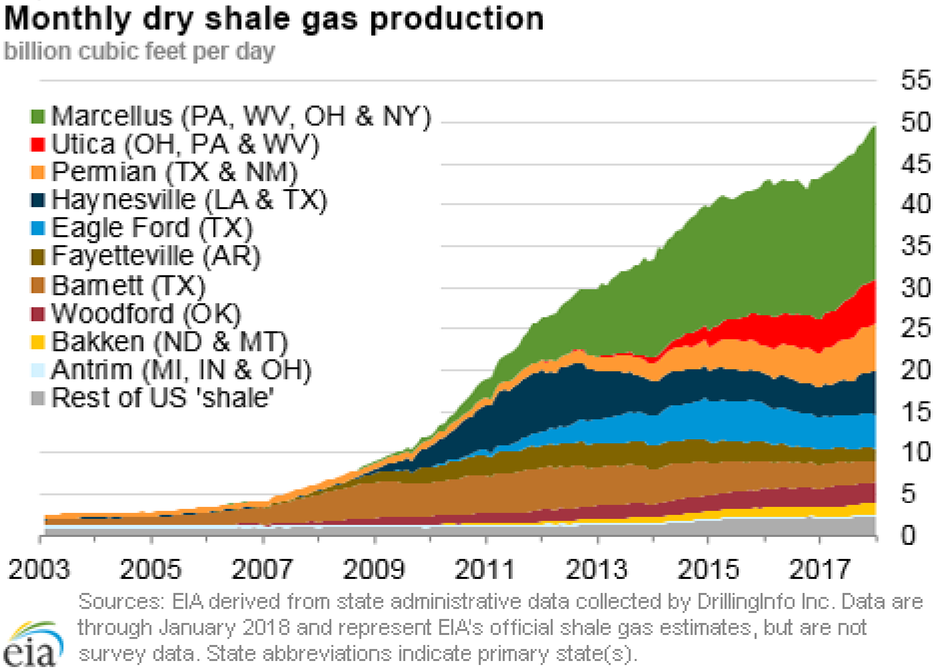
Appendix - Tables and Figures

Figure 1:



source: Energy Information Agency

Figure 2:



Sources: EIA derived from state administrative data collected by DrillingInfo Inc. Data are through January 2018 and represent EIA's official shale gas estimates, but are not survey data. State abbreviations indicate primary state(s).

Figure 3:
Map of the Marcellus Shale with Permitted Wells

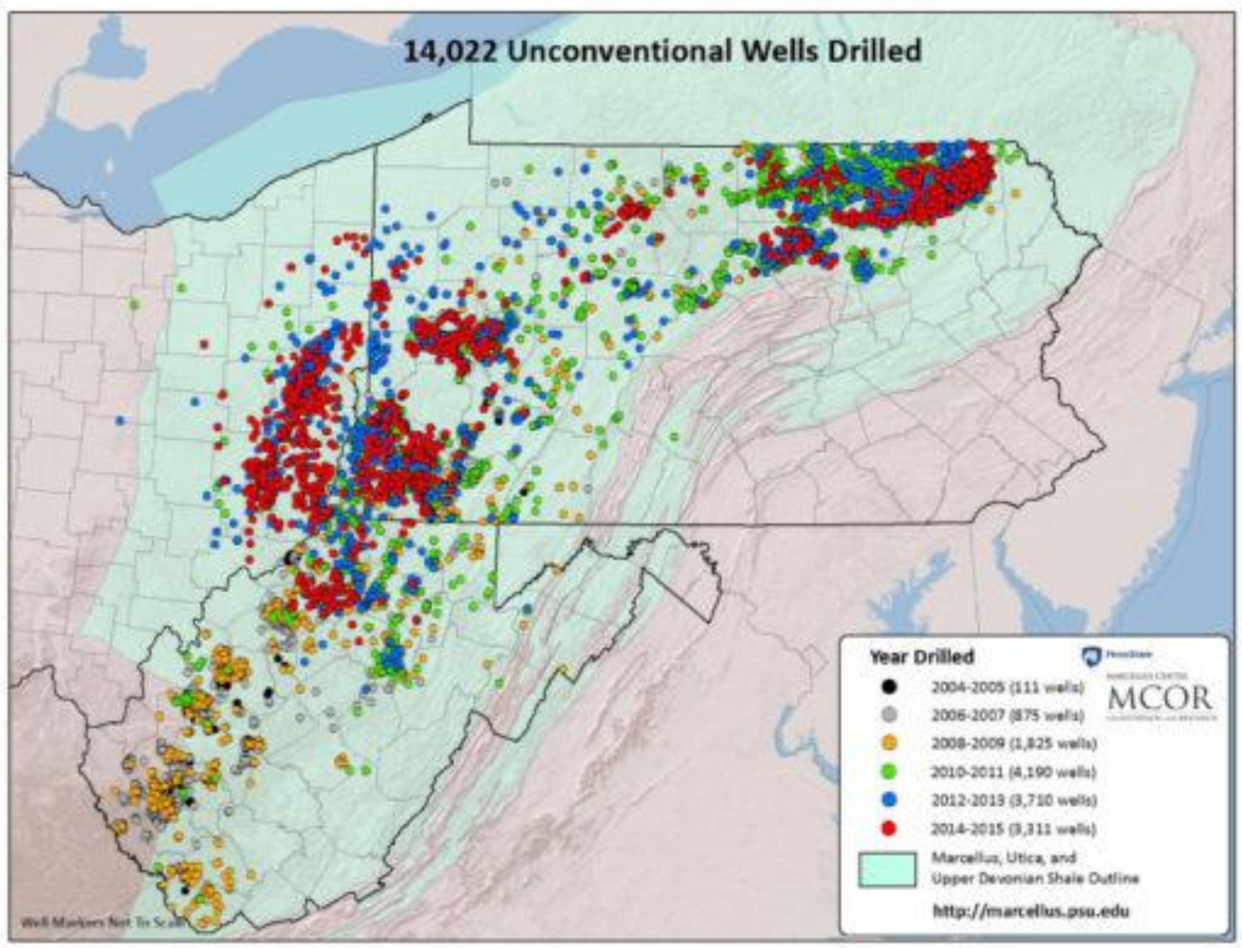
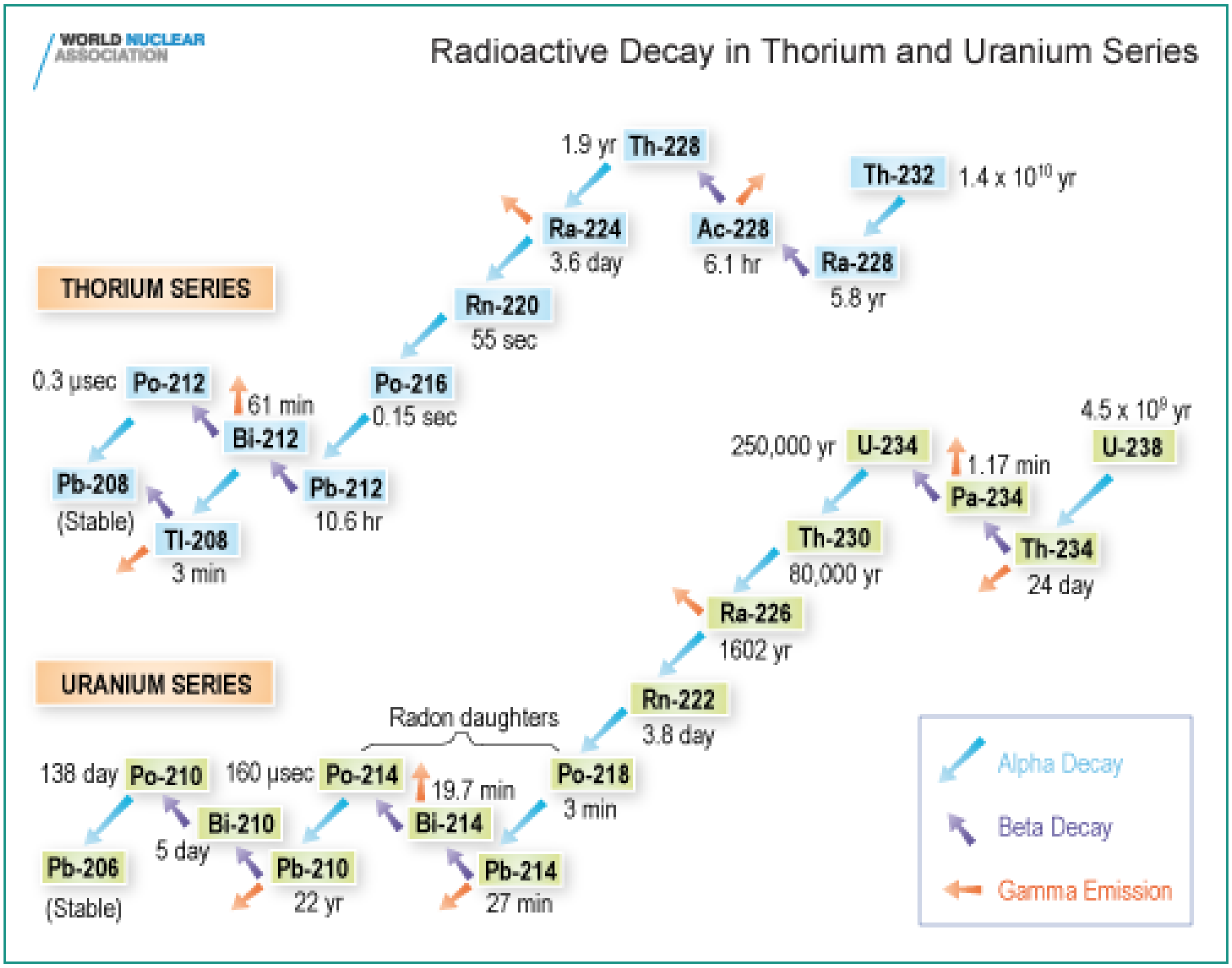
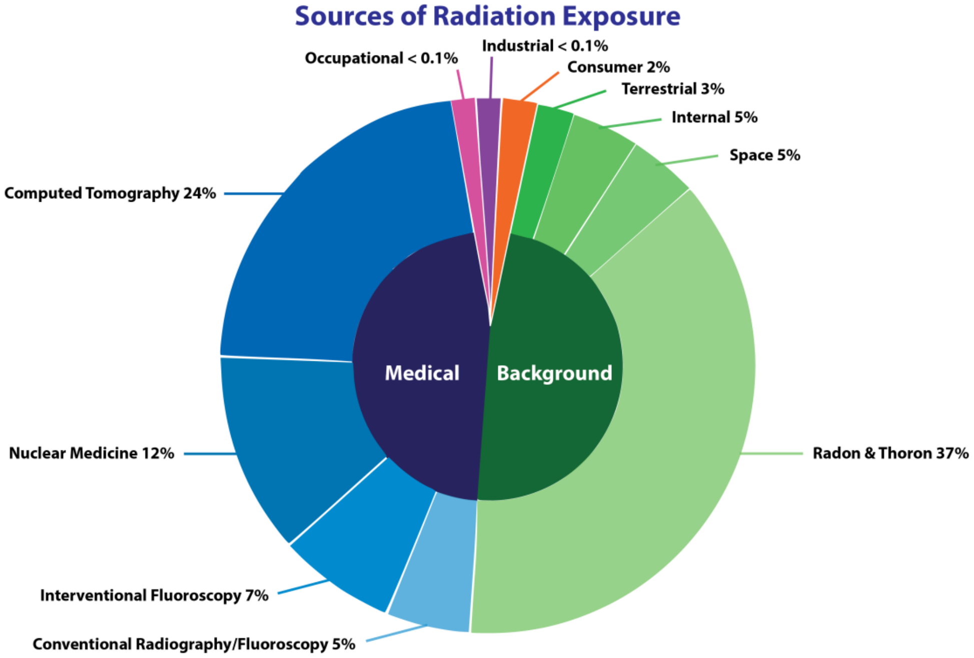


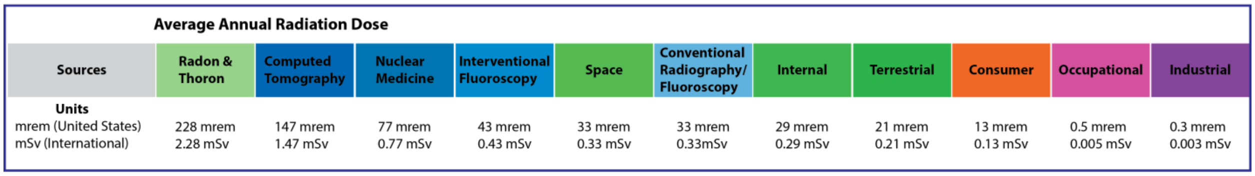
Figure 4:
Radioactive Decay in Thorium and Uranium Series



Source: World Nuclear Association

Figure 5:
Common Sources of Radiation Exposure and their Amounts

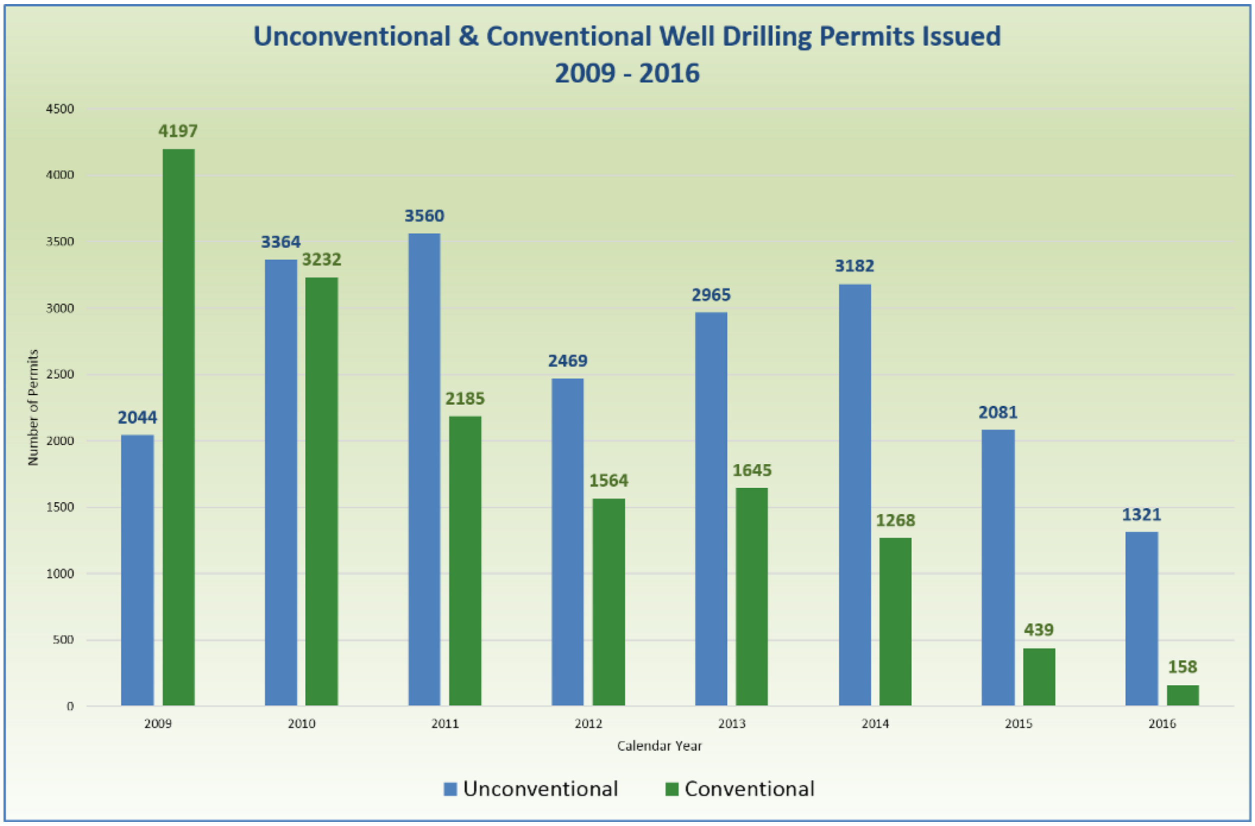

Sources of Radiation Exposure


Average Annual Radiation Dose

Sources	Radon & Thoron	Computed Tomography	Nuclear Medicine	Interventional Fluoroscopy	Space	Conventional Radiography/ Fluoroscopy	Internal	Terrestrial	Consumer	Occupational	Industrial
Units mrem (United States) mSv (International)	228 mrem 2.28 mSv	147 mrem 1.47 mSv	77 mrem 0.77 mSv	43 mrem 0.43 mSv	33 mrem 0.33 mSv	33 mrem 0.33mSv	29 mrem 0.29 mSv	21 mrem 0.21 mSv	13 mrem 0.13 mSv	0.5 mrem 0.005 mSv	0.3 mrem 0.003 mSv

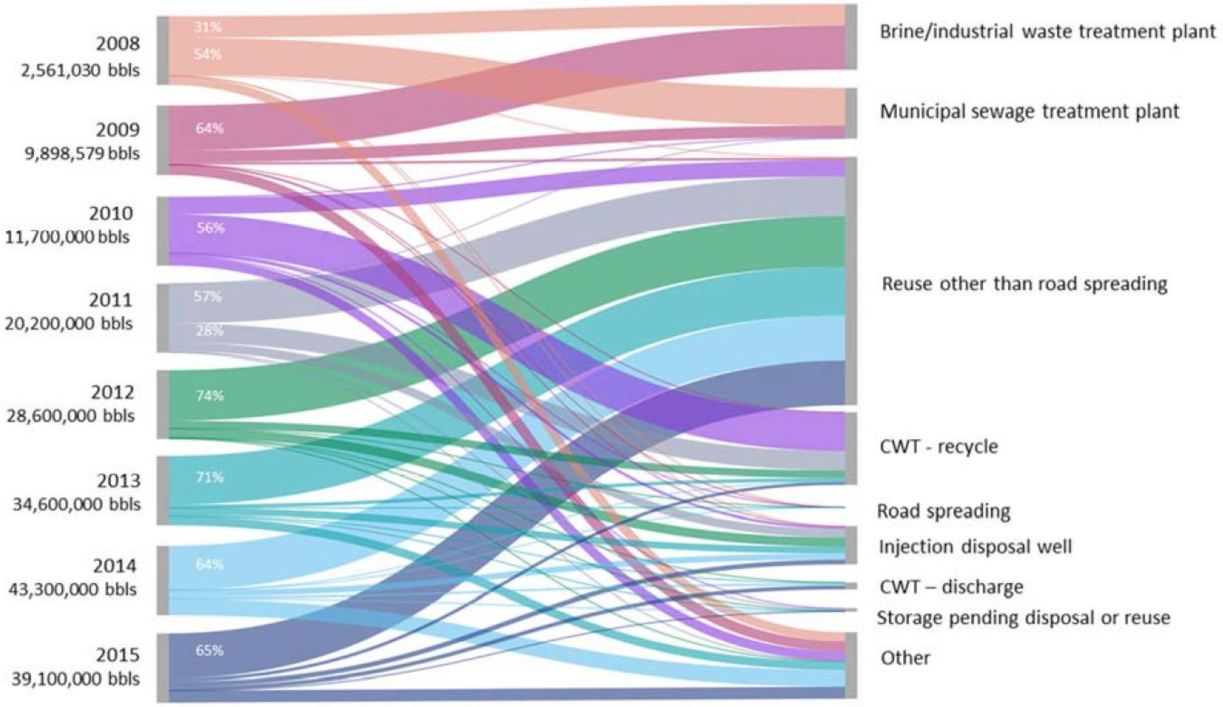
(Source: National Council on Radiation Protection & Measurements, Report No. 160)

Figure 6:
Unconventional & Conventional Well Drilling Permits Issued (in PA), 2009-2016



Source: PADEP 2016 Annual Oil and Gas Report

Figure 7:
Wastewater Generation and Management Options in Pennsylvania, Unconventional Gas Wells



Source: Shih, Sweidler & Krupnick 2016; PADEP Data

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