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2021, pp. 195-202. https://doi.org/10.56577/FFC-71.195

in:

Geology of the Mount Taylor area, Frey, Bonnie A.; Kelley, Shari A.; Zeigler, Kate E.; McLemore, Virginia T.; Goff, Fraser; Ulmer-Scholle, Dana S., New Mexico Geological Society 71st Annual Fall Field Conference Guidebook, 310 p. https://doi.org/10.56577/FFC-71

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THE ENVIRONMENTAL LEGACY OF URANIUM MINING AND MILLING IN NEW MEXICO

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Abstract—Between 1951 and 1989, the Grants mining district of northwestern New Mexico produced more uranium than any other district in the United States. Almost 250 mines were located in New Mexico, consisting of both open pit and underground mines. Open pit mines, especially the large Jackpile–Paguate Mine on the eastern flank of Mt. Taylor, left a large area of open pits and exposed strata that remains largely unremediated. The Jackpile–Paguate Mine is now a Superfund site. Underground mines had a large impact on regional aquifers, but groundwater levels have largely recovered after closure. Eight mills were built to process uranium ore at one time or another in the state using either the acid leach (seven mills) or alkaline leach process. The Bokum Mill was built but never operated. Tailings were disposed as a slurry in unlined tailings piles. Tailings wastewater was of very poor quality characterized by either low pH (acid leach mills) or high pH (alkaline leach mill), high total dissolved solids, and high concentrations of metals and radionuclides. Most mills were located in remote locations and present little threat to health or the environment, but the Homestake Mill near Milan, NM was declared a Superfund site in 1983 and remediation is continuing. Though no mining or milling has occurred for over 20 years, it is important to understand the legacy of uranium production to develop effective remediation strategies and minimize risks to health and the environment if production resumes in the future.

INTRODUCTION

Uranium was discovered in 1789 by the German chemist Martin Heinrich Klaproth in the mineral pitchblende, which contains a mixture of uraninite ($UO_{2(s)}$) and smaller amounts of schoepite ($U_3O_{8(s)}$; LANL, 2013). Originally, it had limited use as a coloring agent in glass and ceramic glazes. Nuclear fission, the splitting of a heavy atom into two smaller atoms by bombarding it with neutrons, was discovered in December 1938 by Germans Otto Hahn and his assistant Fritz Strassmann, and a theoretical understanding of the process was proposed a month later by Lise Meitner and her nephew Otto Robert Frisch (Rhodes, 1986). The enormous amount of energy released by fission reactions was immediately recognized along with its potential as a source of power and as the basis for a powerful weapon. This led to the Manhattan Project, which began in 1942. Less than six years after the discovery of fission, an entirely new industry involving the production of nuclear power and the manufacturing of nuclear weapons was created.

Much of the research on the bomb, as well as its construction, was done in Los Alamos, New Mexico. Most of the uranium used for the Manhattan Project came from the Shinkolobwe mine in the Belgian Congo (now the Democratic Republic of the Congo), an incredibly rich pitchblende deposit containing up to 65% U_3O_8 (Nichols, 1987), although a small fraction came from tailings from vanadium mills in Colorado and Utah (Hewlett and Anderson, 1990). Therefore, it is ironic that shortly after the war, world class uranium deposits were discovered less than 150 miles from Los Alamos.

In less than seven years, the demand for uranium grew explosively, and U.S. production went from near zero in 1950 to 35 million lbs/yr of uranium concentrate (represented as U_3O_8) by 1956 (EIA, 2019). Uranium mining occurred at numerous locations throughout the country, especially in the western states (EIA, 2018). The DOE (2014a) identified 4225 mines that produced uranium for U.S. defense programs. Of these, 247 mines were located in New Mexico and produced 47% of total ore mined domestically. Sixty-five mines were on Navajo lands located in the Grants mining district (also often referred to as the Grants mineral district or the Grants uranium district; EPA et al., 2007). McLemore et al. (2013) described the major uranium ore deposits in the Grants district, including their locations and estimated reserves. Thomson (in press) provides a broader discussion of environmental contamination from uranium mining and milling in the western U.S. and its relevance to health impacts. It includes a summary of waste stabilization and remediation technologies.

LEGACY EFFECTS OF URANIUM MINING

Early production of uranium ore in New Mexico came from small surface mines, while underground mining became more prevalent as companies chased ever deeper ore bodies. However, Anaconda moved about 400 million tons of ore, subore, rock, waste material, and overburden between 1952 and 1982 at the Jackpile–Paguate open pit mine complex on the Laguna Pueblo near the southeastern flank of Mt. Taylor (EPA, 2020a). The mine produced about 25 million tons of ore. The complex covered almost 7900 acres and was 625 ft deep at its deepest point. A 1982 photo of one of the pits at this mine is presented in Figure 1. Note the presence of a small pit lake.

Underground uranium mines had minor surface impact and typically consisted of a building for the mine hoist and changing facilities, a pad for waste rock and low grade ore storage, and ponds for treating mine water. Figure 2 is a photo of an underground mine that shows these features. While most large

FIGURE 1. Air photo of one of the pits of the Jackpile mine showing a small pit lake at the bottom (photo by author, 1982).

FIGURE 2. Air photo of the Kerr-McGee Section 36 mine (photo by author, 1981).

mines (ore production >100,000 tons) have been remediated, remediation of many small mines has not been addressed or the mine status is unknown (DOE, 2014a). Remediation generally consisted of blocking mine openings to prevent access and, at some sites, regrading waste rock piles to limit erosion and airborne dust transport. Potential long-term environmental impacts are unknown.

While the surface impact of underground mining was minor, the impact on groundwater resources was substantial as ever deeper mines became located below regional aquifers. These mines required pumping large volumes of water, up to 3,000 gal/min, to keep the mines dewatered. Lyford et al. (1980) estimated that the total amount of mine dewatering was 10,000 acre-ft/yr (12x10^6 m^3/yr) in 1979, and predicted regional groundwater declines of 1,000 ft or more by 2000 in the Grants district. Mine closure following collapse of the industry in the 1980s prevented this occurrence, and aquifer drawdowns have largely recovered.

No open pit or underground uranium mining is currently practiced in the United States. All domestic uranium mining is produced from *in-situ* recovery (ISR) mines (see Thomson and Heggen, 1983 for a summary of ISR technology) located in Wyoming (four mines) and Nebraska (one mine; EIA, 2019). Several small scale and pilot ISR uranium mining projects were conducted in New Mexico between 1970 and 1980 with limited success (McLemore et al., 2016). One of the most notable projects was a large field scale pilot test of ISR technology that was done near Crownpoint, NM (Vogt et al., 1984). The Crownpoint project consisted of a series of injection and extraction wells located on 100-ft centers, each drilled to a depth of about 2,000 ft. An oxidizing solution of $NaHCO_3$ was circulated through the ore body to oxidize and extract uranium, which was then recovered by ion exchange (IX) at the surface. The pilot mine test began in 1979 and concluded in 1980, and was followed by six years of intermittent aquifer restoration efforts, which demonstrated that groundwater quality could be restored to below groundwater standards (Hydro Resources, Inc., 1997).

The principal contaminants in wastewater from underground mines were sediments, uranium and radium. The industry developed a very simple treatment process, illustrated in Figure 3 (Thomson and Heggen, 1983). Solids were removed in settling ponds. Uranium was removed by IX. Finally, barium chloride ($BaCl_2$) was added to precipitate radium as a Ba-Ra-SO_4 co-precipitate, which was also removed by settling. An example of a mine water treatment system is shown in Figure 2. In this system, mine water passed through two settling ponds to remove suspended solids, then into an IX facility to recover uranium (the building near the left margin of Fig. 2). Barium chloride ($BaCl_2$) was added at this point and the Ba-Ra-SO_4 co-precipitate settled in the third pond. Treated water then flowed through a polishing wetland and into a dry arroyo. IX recovery of uranium was profitable, and the Phillips/United Nuclear Corporation and Kerr McGee Mills continued to recover uranium from mine water from closed mines until 1982 (DOE, 2018) and 2002 (McLemore and Chenoweth, 2017), respectively.

Unquestionably the biggest impact of underground uranium mining on human health was due to radon inhalation (Brugge and Buchner, 2011). The radon isotope radon-222 is an intermediate product in the decay chain of uranium-238 and decays by alpha emission with a half-life of 3.8 d. Because it is an inert gas, radon is non-reactive. However, radon and its daughter products can be adsorbed onto particles of smoke and dust that are subsequently trapped in the lungs where high energy alpha decay particles damage lung tissues. This greatly increases the risk of cancer and other pulmonary diseases. The Centers for Disease Control and Prevention (CDC, 2017) summarized the health risks of underground uranium mining and reported a six-fold increase in lung cancer for white miners and a threefold increase for non-white miners. The difference in risk was explained by a lower incidence of smoking among non-white miners, especially Navajos. The high incidence of cancer in underground miners led the Navajo Nation to pass the Diné Natural Resources Protection Act in 2005 that banned uranium mining on the reservation (Navajo Nation Council, 2005).

LEGACY EFFECTS OF URANIUM MILLING

Eight mills were built to process uranium ore in New Mexico (EPA, 2011), however, the Bokum Mill near Marquez, NM, never operated. Milling consisted of grinding the ore to fine particles, leaching the ore with an acid or base solution, and then extracting the dissolved uranium from solution using either solvent extraction or IX. A generic process flow diagram is presented in Figure 4. All of the New Mexico uranium mills used the acid-leach process except the United Nuclear–Homestake Partners Mill near Milan, NM, which was an alkaline leach mill. The barren tailings were piped as a slurry to a nearby tailings pile, which was retained behind a dam or berm constructed with sand from the tailings. The quality of water in the tailings slurry was poor with very high concentrations of total dissolved solids, uranium, radionuclides, and other constituents (Table 1).

None of the tailings piles constructed before 1980 were lined, hence, infiltration of contaminants into underlying

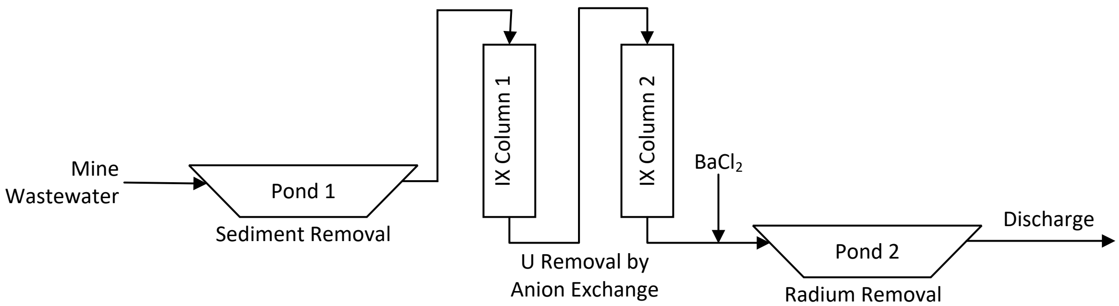

FIGURE 3. Diagram of typical mine water treatment process used by New Mexico uranium mines.

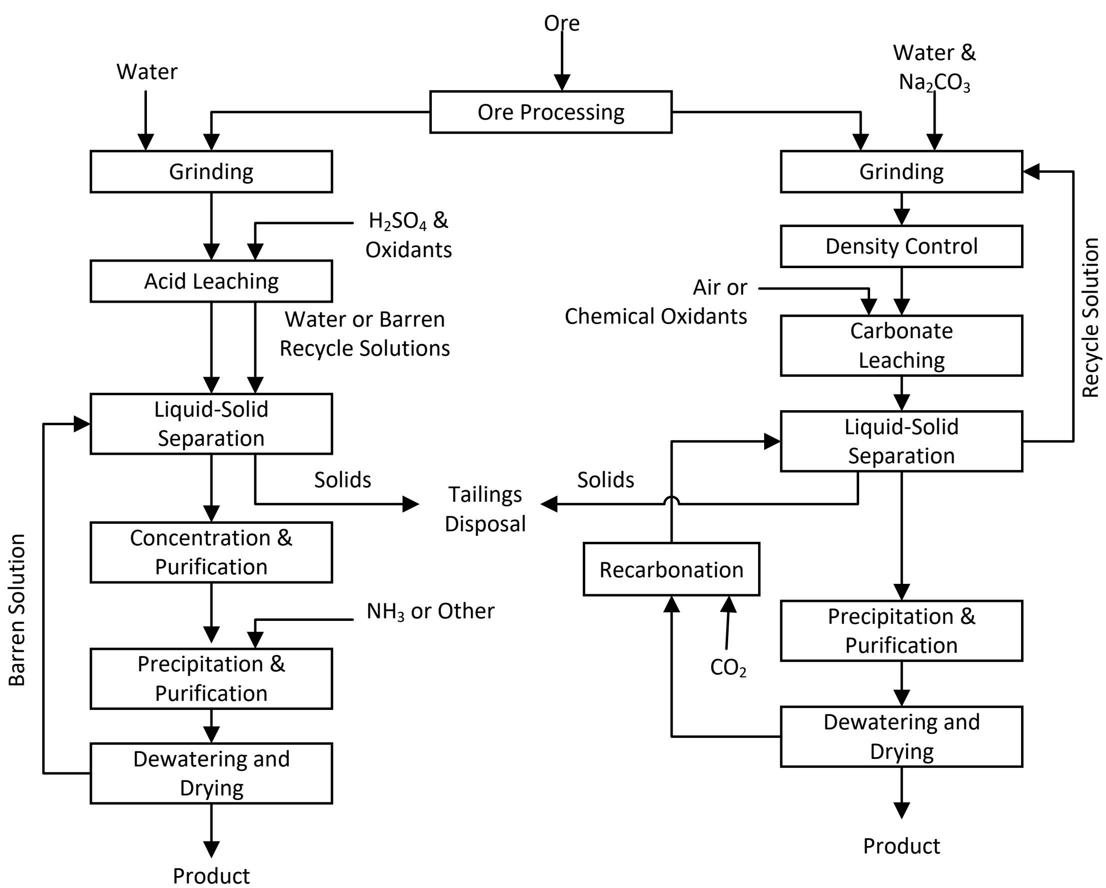

FIGURE 4. General process diagram of the acid-leach and alkaline-leach processes for milling uranium ore (adapted from Merritt, 1971).

TABLE 1. Water quality data from acid-leach and alkaline-leach uranium mines in New Mexico (Thomson et al., 1982). All concentrations in mg/L except as noted.

	Four Acid Leach Mills (average of 14 samples)			*One Alkaline Leach Mill (average of five samples)*		
Constituent	*Minimum*	*Median*	*Maximum*	*Minimum*	*Median*	*Maximum*
Arsenic	0.18	1.3	5.6	2.1	5.0	7.2
Nitrate (as N)	3.3	400	3960	1.1	16	335
Molybdenum	0.2	0.9	29.5	72	98	105
Selenium	0.006	0.21	6.97	22.1	29.5	51.2
Sulfate	300	29,700	56,000	550	8400	16,700
Uranium	1.1	15	69	4.2	53	70
Vanadium	39	74	107	1.2	14	16
pH (pH units)	0.3	1.05	2.15	9.9	10.1	10.3
Ra-226 (pCi/L)	15	70	1800	56	58	90
Gross a Rad. (pCi/L)	3200	38,000	73,000	3400	6700	10,000

groundwater occurred. Because most of the mills were at remote locations, threats to human health were negligible. However, the Anaconda Bluewater and United Nuclear–Homestake Partners Mills were located close to subdivisions near Milan, NM, and caused regional groundwater contamination that impacted domestic wells. In 1985, Homestake paid to connect residents to the Milan public water system to provide them with safe drinking water. Groundwater near the Homestake and Anaconda Bluewater tailings piles contains elevated concentrations of uranium, selenium and other constituents from natural sources. In addition, the hydraulic gradient in this area is very flat and has changed as a result of pumping from the aquifers by domestic, agricultural and industrial users, infiltration from the tailings piles, infiltration from San Mateo Creek, and groundwater remediation activities. Thus, determination of groundwater hydrology and background water quality is one of the objectives of EPA's current field investigations (EPA, 2016).

Generally, the objective of groundwater remediation programs is to clean the water to meet groundwater standards, not necessarily to drinking water standards or background water quality conditions. At mill sites, the standards are established by the Nuclear Regulatory Commission (NRC), while state groundwater standards apply outside of the property boundary. Alternative abatement standards (AAS) may be established if cleanup to NRC or state standards is not feasible by the maximum use of commercially accepted abatement technology (NMAC 20.6.2.4103). Alternative abatement standards have been established for groundwater quality beneath a number of sites, including the Anaconda Bluewater Mill, the L-Bar disposal site, the Ambrosia Lake disposal site, and the Rio Algom Mill, and an application for AAS has been made for the Homestake Mill site (EPA, 2015).

Other uranium mill tailings sites in New Mexico have been remediated by consolidating wastes from near the site into a single pile and covering them with an engineered cap. The principal objectives of stabilizing the piles include: 1) isolate and stabilize the tailings to prevents their mobilization by wind or erosion, 2) prevent rain and snow melt from seeping through the pile and contaminating underlying groundwater, and 3) prevent radon gas from diffusing up through the cover to the atmosphere.

REGULATORY PROGRAMS DEALING WITH LEGACY URANIUM PRODUCTION

There are three major federal programs that provide regulatory authority over legacy wastes from U production, including a program administered by DOE under the Uranium Mill Tailings Radiation Control Act (UMTRCA), and a program administered by the EPA for remediation of sites under the Comprehensive Environmental Response, Compensation and Liability Control Act (CERCLA), also known as Superfund. Finally, a large financial settlement with successors of a former uranium mining and milling company, referred to as the Tronox settlement, has provided funds for investigation and remediation of sites on and near the Navajo Nation. These are discussed below.

UMTRCA

UMTRCA was passed in 1978 and gave DOE responsibility to ensure safe disposal, stabilization, and long-term monitoring of tailings from uranium milling (DOE, 2014b). Two categories of sites were identified: Title I sites that were inactive when the legislation was passed and Title II sites that were still active or had corporate owners still active in uranium production. DOE assumed responsibility for the Title I sites, and the site owners were given responsibility for waste stabilization and closure of the Title II sites. Twenty four sites across the country were identified as Title I sites, though the list was later reduced to 22 sites. Two Title I sites were in NM, one in Shiprock and another in Ambrosia Lake. Once a site has been closed, title to the property is transferred to the DOE, which provides long-term custody, monitoring, and care under its Legacy Management Program (DOE, 2020). Table 2 gives the location and summary information about uranium mill tailings piles in New Mexico. Note that three of the tailings piles have not

TABLE 2. Summary of uranium mill tailings piles in New Mexico.

Site Name	Company	Title I or II*	Years Operated	Year Closed	Mass of Tailings (M tons)	Reference
Ambrosia Lake	Phillips Petroleum/United Nuclear Corp.	I	1958-1963	1995	2.5	DOE, 2020
Bluewater, NM Disposal Site	Anaconda Copper/ARCO	II	1953-1982	1995	24	DOE, 2020
Homestake	United Nuclear/Homestake Partners	N/A	1958-1990	-	22	NRC,2018a
L-Bar Mill	SOHIO	II	1977-1981	2000	2.1	DOE, 2020
Rio Algom	Kerr McGee/Quivara/Rio Algom	N/A	1958-2002	-	33	NRC, 2018b
Shiprock	Kerr McGee/Vanadium Corporation of America	I	1954-1963	1985	2.5	DOE, 2020
Church Rock	United Nuclear Corp.	N/A	1977-1982	-	3.5	NRC, 2019

*N/A are sites not currently in DOE Legacy Management program.

been completely closed, and therefore their titles have not been transferred to DOE for ownership and long-term management.

Superfund

The second federal program that continues to play an important role in mine waste and mill tailings management is the Superfund program. Three sites in New Mexico are being addressed by the Superfund program: the Homestake Mill site near Milan and the United Nuclear Church Rock site which were both listed in 1983, and the Jackpile–Paguate Uranium Mine on the Laguna Pueblo which was listed in 2013 (EPA, 2016).

The Homestake tailings pile was declared a Superfund site in 1983 primarily due to concerns about radon emanation from the pile. However, the pile, like other tailings piles in New Mexico, was unlined, which resulted in extensive contamination of shallow groundwater principally by nitrate, selenium, and uranium (Weaver and Hoffman, 2019). A small failure of the tailings dam occurred in 1977, but no off-site release of contaminants occurred (IAEA, 2004). Cleaning up groundwater to background water quality has been the principal focus of remediation activities at this site in recent decades. Remediation consists of pumping contaminated groundwater to a treatment plant where it is treated by IX and reverse osmosis (RO), then reinjected down-gradient from the plume to force the flow of contaminated groundwater flow back towards the collection wells. Waste brine from the RO process is disposed of in evaporation ponds. Figure 5 taken in 1981 shows the proximity of the Homestake tailings pile to residences and the large amount of water present on top of the pile. A photo of the site taken in 2020 (Fig. 6) shows the partly stabilized pile and the RO concentrate evaporation ponds, which use fountains to spray water into the air to increase the rate of evaporation.

The Jackpile–Paguate Mine site was mined from 1952 to 1982. The health concerns at the site include exposure to airborne dust and radionuclides and contaminated surface water. Partial reclamation of the mine was conducted between 1982 and 1994 and mainly consisted of stabilization of waste-rock piles. However, continuing concerns about health risks to nearby residents led to the site being declared a Superfund site

FIGURE 5. Photograph of the Homestake uranium mill tailings pile in 1981.

FIGURE 6. Photograph of the Homestake uranium mill tailings pile in 2020.

in 2013 (EPA, 2020a). Current work at the site is limited to air monitoring and planning for future remediation.

The United Nuclear Corporation opened a uranium mine near the Church Rock Chapter of the Navajo Nation, 17 miles northeast of Gallup, NM in 1968. The company subsequently built an acid leach mill that operated from 1977 to 1982. Tailings were disposed in a pond created by a dam built using the sand fraction of the tailings. On the morning of July 16, 1979, the tailings dam failed and released a slurry containing 1,100 short tons of mill tailings and 94 million gallons of very acidic water (pH ~1.2) to the Puerco River (also known as Rio Puerco; Brugge et al., 2007; U.S. House of Representatives, 1979). The Puerco River flows south and west through the town of Gallup and then westward onto the Navajo Nation. Contaminated water flowed approximately 80 miles down the dry river bed, but did not reach any perennial streams. The region is sparsely populated and though the river is not a source of potable supply, it is used by grazing animals.

An analysis of the failure suggested that differential settling within the dam occurred prior to failure, which resulted in formation of cracks (Nelson and Kane, 1980). Sand was placed next to the dam to form a sand "beach," which was expected to fill these cracks. However, the water level in the pile rose above the top of the sand beach and saturated the sand of the tailings pile dam, which decreased its strength and caused instability with subsequent failure. The very low pH of the tailings fluid was likely a contributing factor, as it caused dispersal of clays and other materials in the dam, further decreasing soil strength.

Van Metre and Gray (1992) reported that the total amount of U (1,500 kg) and gross-alpha radioactivity (46 Ci) released by the spill was small fraction of the cumulative amounts of U and gross-alpha radioactivity released by mine dewatering between 1960 and 1979 of 560,00 kg and 230 Ci, respectively. They concluded that most of the U was immobilized on alluvial sediments and therefore migration through groundwater was limited.

The failure of the tailings dam was a public relations disaster for the U.S. uranium industry as it brought national attention to its poor waste management practices and the potential risks associated with these wastes. Remediation activities under the Superfund program consist of consolidating and stabilizing the mine and mill wastes and cleaning up groundwater in the alluvium and upper portions of the Cretaceous Gallup Sandstone (EPA, 2020b).

Estimates of up to 16.4 million lbs of U_3O_8 in undeveloped uranium ore remain near the Church Rock site (McLemore et al., 2013).

Tronox Settlement

For almost three decades, there has been little federal attention paid to the environmental legacy of uranium development in the Grants mining district; however, a large source of funds became available beginning in 2015, due to a legal settlement with successors to Kerr McGee. Tronox was a chemical company that mainly produced titanium dioxide. It was divested from Kerr-McGee in 2006, which among other things, ceded all of Kerr-McGee's uranium properties to Tronox. Kerr-McGee was subsequently purchased by Anadarko Petroleum Corporation, also in 2006. In 2009, Tronox filed for bankruptcy and also filed suit against Kerr-McGee, Anadarko and others claiming that the uranium properties were transferred without revealing the environmental liabilities that were associated with them. Based on the magnitude of the environmental damages, the U.S. intervened in the case to recover environmental response costs. The case was settled in 2015 with Anadarko agreeing to pay $5.15 billion to fund remediation activities at 17 sites, the "largest recovery relating to governmental environmental claims and liabilities" (EPA, 2016). The Tronox settlement provided approximately $1 billion for remediation of U mining and milling problems on and near the Navajo Nation.

Funds from the Tronox settlement are being used to address approximately 101 mines on and near Navajo lands. A map of the mines on and near the Navajo Nation, that also identifies those mines that will be remediated with funds from the Tronox settlement, is presented in Figure 7. Abandoned mines near Mt. Taylor are referred to by EPA as the Eastern Abandoned Uranium Mine (AUM) Region that extends westward from the community of San Mateo, NM to Church Rock, NM.

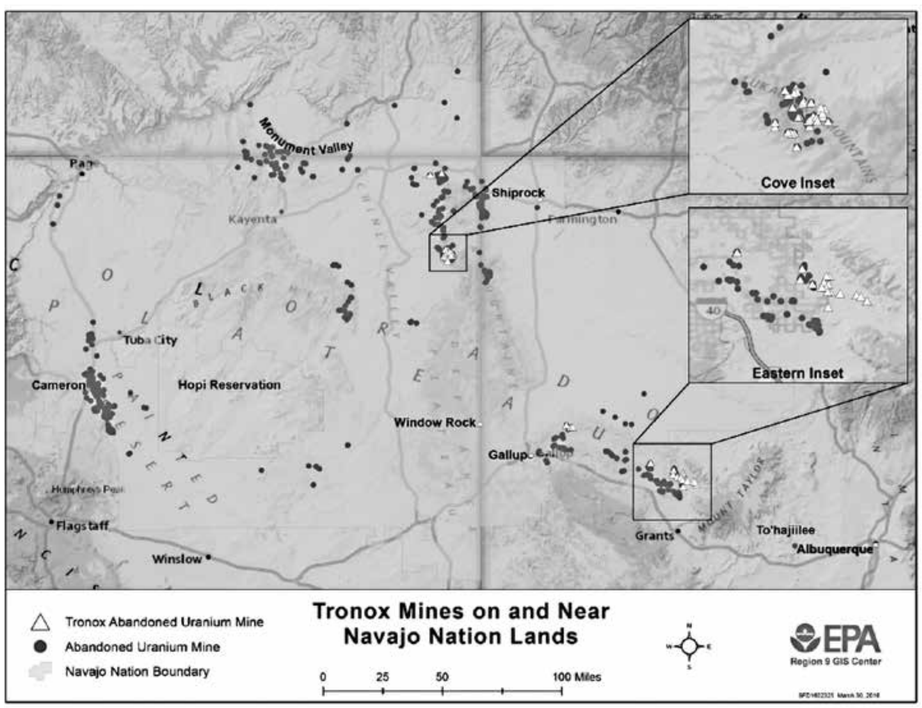

FIGURE 7. Map of uranium mines on and near the Navajo Nation and identification of those which will be remediated with funds from the Tronox settlement (EPA, 2019).

About 15 of these mines will be remediated with Tronox funds (EPA, 2019). As part of the investigation, EPA and the state of New Mexico have used Tronox funds to describe the nature and extent of groundwater contamination in the San Mateo Creek watershed from near Milan, NM up to its headwaters near San Mateo, NM.

Other Federal, State, and Tribal Agencies Involvement in Remediation of Legacy Impacts from Uranium Mining and Milling

Most activities to address legacy impacts from uranium development in the Grants mining district are being led by either the DOE, which is mainly focused on mill sites, and the EPA, which has responsibility for remediation of Superfund sites and abandoned mines. Other agencies with significant responsibility for addressing legacy issues include (EPA, 2011; EPA, 2016):

- U.S. Bureau of Land Management – Identify and cleanup abandoned mines on BLM property. Participate in permitting of proposed mines on BLM property.
- U.S. Forest Service – Identify and cleanup abandoned mines on USFS property. Participate in permitting of proposed mines on USFS property.
- NM Environment Department – Protect ground and surface water supplies by participating in field investigations and establishing appropriate water quality standards.
- NM Energy, Minerals and Natural Resources Department – Maintain a database of mine sites, oversee mine closure and reclamation of mines. Permits new mines.
- NM Department of Health – Conduct public health surveillance to assess exposure to uranium
- Pueblo Governments – Participate in public outreach, field investigations and remediation activities.
- Navajo Nation – Because of its size and the large number of abandoned mines and mills present, the Navajo Nation has its own Abandoned Mine Lands Department that conducts its own investigations and reclamation in collaboration with EPA Region IX and the DOE (Navajo AML Department, 2020).

CONCLUSIONS

Since the discovery of major uranium reserves in New Mexico after 1950, uranium production has played a major role in the economy and culture of New Mexico. In 1979, there were 38 producing mines supplying ore to six operating mills, and the industry employed 7,000 people (SJBRUS, 1980). In 2020, the only activity is associated with remediation of legacy sites, along with minor exploration and permitting for possible future development.

However, New Mexico is estimated to have 179 million lbs of U_3O_8 at \$50/lb, second in total reserves only to Wyoming, and additional resources are available (McLemore and Chenoweth, 2017). A number of mine projects have been proposed (McLemore et al., 2013). Three notable projects in the advanced permitting stage are the Roca Honda underground mine (near Jesus Mesa on the northwest flank of Mt. Taylor), and two projects under development by Laramide Resources (an underground mine near Church Rock, NM and an *in-situ* recovery (ISR) mine near Crownpoint, NM; Laramide Resources, 2020).

Whether uranium production resumes in New Mexico is uncertain. Nevertheless, it is vital that the environmental impacts of past uranium development be recognized and understood to address mistakes from the past and allow careful development with appropriate protections of human health and the environment should uranium development occur in the future.

ACKNOWLEDGMENTS

The comments and suggestions of two reviewers, Dr. Virginia McLemore of the NM Bureau of Geology and Mineral Resources, and Anchor Holm, P.E., of the NM State Land Office, greatly improved the accuracy and quality of this paper. The paper also benefitted from critical comments and suggestions provided by the editors, Bonnie Frey and Dr. Dana Ulmer-Scholle. Their assistance is gratefully acknowledged.

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