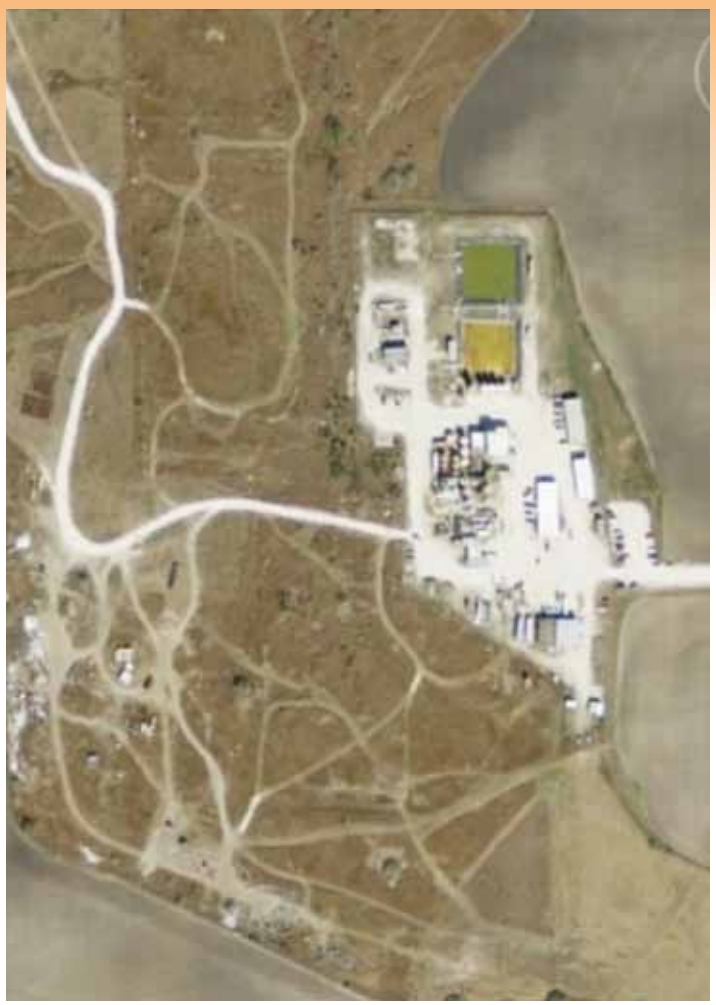
Nuclear Fuel's Dirty Beginnings

Environmental Damage and Public Health Risks From Uranium Mining in the American West

March 2012



Authors

Geoffrey H. Fettus

Matthew G. McKinzie

Natural Resources Defense Council

NRDC

THE EARTH'S BEST DEFENSE

EXECUTIVE SUMMARY

Uranium mining anywhere poses significant environmental, economic, and social risks. In the high plains, Rocky Mountains, and intermountain West, however, where water resources are already scarce, it is inevitable that water-intensive uranium extraction poses significant risks to the region's environmental and public health. Nonetheless, domestic and international mining companies are showing renewed interest in recovering uranium that lies beneath the iconic landscapes and fragile ecosystems of the American West. Projections of a U.S. and global "nuclear renaissance" have sparked forecasts of a uranium supply shortfall and rising uranium prices, spurred by the prospect of significant public subsidies for new nuclear power generation, and ultimately prompting a flood of uranium mining claims and applications for exploration permits in water-limited states such as Colorado and Utah. The vast majority of proposed uranium mines are "in-situ leach" (ISL) solution mines, which typically use large well-fields of hundreds of wells, diesel-powered pumps, and huge volumes of groundwater to dissolve the uranium from the ore bearing rock and bring it to the surface.

This development is cause for concern, given that during earlier uranium mining booms—spurred by construction of tens of thousands of nuclear weapons and more than a hundred nuclear power plants during the Cold War—uranium mining and milling practices were not regulated in any meaningful way. In fact, it was not until the late 1970s and early 1980s that Congress, the Nuclear Regulatory Commission (NRC) and the Environmental Protection Agency (EPA), finally instituted a legal and regulatory framework to address the environmental and public health impacts of uranium milling. That effort, however, resulted in a splintered patchwork of controls that has remained largely ineffective. Furthermore, the federal government has *never* regulated conventional mining (i.e., underground and open pit) since exempting production of uranium ore from licensing in the Atomic Energy Act of 1961. Consequently, uranium extraction in the American West has left behind a tainted legacy of serious damage to the environment and human health. Many of the communities affected by uranium recovery have been disproportionately low-income or minority populations, representative of an all too common pattern of environmental and economic injustice with respect to resource extraction.

The question examined in this report is whether current controls on both conventional hard-rock mining and milling, and alternative solution-mining techniques for uranium recovery, are sufficient to prevent a new round of harms to the natural resources and communities of this region, which is already being heavily exploited for the extraction of oil, natural gas, coal, coal-bed methane, and now shale-gas. The combined impacts of uranium mining alongside these extraction techniques in the American West have remained

unexamined and unaddressed at the state and federal level. In response, this report will also examine the cumulative impacts, where the long-term impairment of freshwater aquifers is a major concern, compounded by population growth, prolonged dry weather conditions, and severe competition for water resources.

IN-SITU LEACH URANIUM MINING

Since ISL technology was first used in the early 1960s, the uranium mining industry has touted the process as noninvasive and environmentally friendly.[1] Preliminary analysis of publically available information—commissioned by Natural Resources Defense Council (NRDC)—however, indicates that:

1) Comprehensive federal analysis of ISL environmental impacts is lacking
2) ISL uranium mining entails an increased risk of radioactive and heavy metal contamination to land, air, and most significantly, underground water systems (aquifers)

Our research and analysis reveal that despite a clear legal obligation under the National Environmental Policy Act (NEPA) to analyze the long-term cumulative effects of sacrificing aquifers to uranium mining and other forms of resource extraction, the NRC and its sister federal agencies, such as the Department of the Interior's Bureau of Land Management (BLM), have failed to study these cumulative impacts. Moreover, there is a distinct unwillingness or lack of resources on the part of the federal regulators to collect and analyze what data do exist, despite relevant legal requirements and a clear obligation not to repeat the mistakes of the past. Hence, information on original groundwater quality and potential future uses is insufficient, or simply absent, from any wider regulatory understanding of the American West's future need.

Consequently, federal decision-makers such as the NRC, and other federal and state agencies engaged in licensing, permitting, and leasing the use of lands and groundwater, lack a comprehensive understanding of the cumulative and connected environmental impacts of federal actions to facilitate and regulate the vast array of extractive industries that are sapping the sustainability of groundwater and other critical natural resources in the American West.

This lack of understanding has led to uranium extraction projects that cause irreparable environmental devastation. NRDC's research reveals that 62 out of the 100 current and prospective ISL mining sites fall within western counties for which "high" or "extreme" risks of water sustainability are predicted by mid-century (see Table 4 and Figure 19). At these sites, the groundwater chemistry has been or could be contaminated to the point that the aquifer is degraded and lost to other beneficial uses over a long term. Unfortunately, hope for remediation of the groundwater at these sites is minimal, as previous efforts to restore water to pre-mining quality have proven to be expensive, with the process lasting

Credit TK

Figure 1: Radiation hazard sign at Crow Butte in-situ leach mining facility in Nebraska. S*ource:* Owe Aku, Lakota Media Project, February 2010.

longer than originally scheduled and yet still failing, especially for contaminants such as uranium or radium, both of which have well-documented adverse human health effects.

The neglect of uranium mining impacts by federal research and analysis can be attributed to the flawed framework responsible for regulating resource extraction. The NRC and the EPA share jurisdiction for ISL mining regulation, with the NRC serving as the primary licensing body, applying environmental standards for uranium recovery set by the EPA. These regulatory standards are both faulty and outdated. Federal and state regulations for *uranium milling*—or hard rock uranium recovery—have not been updated for more than two decades and do not match today's scientific understanding of the impact that radiation and heavy metals have on the environment and public health.

Furthermore, this regulatory framework was designed to address conventional uranium milling—not unconventional techniques, such as ISL mining, likely to comprise the majority of new uranium recovery sites in the next decade. Regulations promulgated in the late 1970s and 1980s did not contemplate ISL mining and its associated harms, and the legal framework that currently governs ISL mining is wholly inadequate to the task of protecting scarce western groundwater resources. This regulatory negligence must be rectified if the nation is to avoid future risks to the public health and environment. Simply updating regulations for conventional milling would solve only part of the problem the nation faces going forward into a new round of domestic uranium mining and milling.

Both the EPA and the NRC should move swiftly to update the relevant environmental protections for uranium recovery. The sooner improved standards can be put into effect, the sooner public health and the environment will be protected. The EPA, to its credit, has commenced a revision of its health and environmental protection standards for uranium and thorium mill tailings.[2] Apparently content with the status-quo until the EPA issues new standards, the NRC has yet to

move forward with reforming its own regulations. In fact, for several years the NRC has declined to publish a draft groundwater protection rule for ISL facilities. As of now, the EPA still has not issued even a draft set of more protective regulations.[3] Immediately after the EPA issues its draft rulemaking, the NRC should commence work on its own ISL rulemaking proceeding that conforms to the EPA's proposed standards. Until that time, NRDC supports a moratorium on the review and granting of any new ISL uranium mining licenses.

Moreover, the NRC should defer action on any new application for a uranium recovery license until there is federal adoption of key elements of Colorado's 2008 Land and Water Stewardship Act, which requires substantially more stringent protections than currently exist. Also, the White House Council on Environmental Quality (CEQ) should undertake a full inter-agency review of the cumulative and connected impacts of all current federal programs and proposed agency actions to facilitate and regulate extraction of mineral and fossil-energy resources in the arid West, including, but not limited to, the NRC's program to license new uranium recovery operations. The CEQ review should address:

- Long and short-term environmental impacts on critical natural resources, such as groundwater, air-quality, animal habitat, and vegetation, along with reasonable alternatives that might better protect these resources. The environmental review effort should include participation across federal agencies.
- Impacts on national parks and other protected areas where U.S. uranium mining has been concentrated, in the vicinity of the four corners region.
- The reasonable alternative of continuing primary reliance on the global uranium market, which for more than two decades has proven to be a dependable and economical source of uranium for US reactors.
- Reasonable alternatives for meeting the national purpose and need for these resources—including uranium—by identifying technology alternatives that are less environmentally destructive or can substitute partially or entirely for the proposed natural resources extraction.
- Economic and social impacts before U.S. states and communities are asked to accept a significant risk of impairment to their scarce groundwater resources in return for fleeting economic gains.

In addition, states should take the initiative by enacting stronger environmental, public health, and taxpayer protections that address the harms of uranium recovery. Whether an *agreement state*—one that has assumed NRC's regulatory authority over uranium recovery—or one that has separate authority to regulate conventional uranium mining—states should pass strong laws that seek to limit the environmental harms inflicted by uranium recovery and protect the economic interests of the state by requiring that uranium mining companies post adequate cleanup bonds.[4] Optimistically, in the face of federal inaction, some states are already implementing stricter regulations and enforcement around uranium recovery. For example:

- Colorado has passed the first protective state law that directly addresses the environmental impacts of both conventional and ISL mining methods
- South Dakota has rejected, for the second time, a new ISL mine's Underground Injection Control Permit application due to inadequate and conflicting information
- Wyoming commenced more vigorous enforcement and levied fines against an ISL operator for falling far behind in implementing groundwater restoration obligations as stated in its mining permits
- The Navajo nation enacted a ban on any type of uranium mining and processing on Navajo territory until past harms have been remediated

RECOMMENDATIONS

In sum, it is critical to avoid repeating past regulatory negligence when licensing new uranium mills and mines. There are still some 4,000 abandoned uranium mines scattered across the landscape of the West, and decades after the closure of operations, a significant number remain to be cleaned up.[5] A full accounting of the costs and the path forward has only just started after decades of neglect. The costs of what cleanup has been done—a price-tag that is certainly in the hundreds of millions of dollars—has been borne in large part by taxpayers rather than the mining companies and downstream customers of the uranium products.

The relevant federal and state agencies must update the existing regulatory structure for both conventional and unconventional uranium recovery to reflect the best available scientific data and analysis of the environmental impact and long-term public health risks. The EPA is moving forward on this front, and the NRC should join the EPA in a collaborative effort to protect the environment from the impacts of renewed and possibly greatly expanded uranium recovery in areas with scarce and even diminishing groundwater resources. In parallel with this effort, the CEQ should initiate a broad NEPA review of the cumulative and connected environmental impacts of all current and proposed Federal programs that facilitate or regulate the extraction of fossil-energy and mineral resources in the American West, including uranium recovery operations regulated by the NRC. For the interim, further licensing of uranium recovery operations should be deferred until fully protective environmental standards and an effective system of regulatory enforcement are in place.

I. URANIUM MINING IN THE UNITED STATES: A HISTORICAL AND LEGAL OVERVIEW

To gain a greater perspective of how and why future uranium mining projects pose a threat to environmental and public health, it is important to have the historical context of uranium mining in the western United States.

Most U.S. mining activity has been susceptible to boom-and-bust cycles. Uranium is no exception. The first boom came in the late 1950s to fuel the nation's nuclear weapons stockpile; production of uranium oxide soared from 5.56 million pounds in 1955 to 35.28 million pounds in 1960. Another boom in the late 1970s, corresponding to the rapid initial build-out of nuclear power plants, brought production to a record 43.70 million pounds in 1980. Each of these booms was followed by plummeting uranium prices and left a landscape of thousands of abandoned mines sprinkled across the western United States.[11] Figure 2 provides details on historical U.S. uranium production; it also illustrates the increase in production from in-situ leach (ISL) operations in the past decade, relative to conventional mining operations.

The launch of the nation's effort to make an atom bomb—the Manhattan Project—during World War II triggered

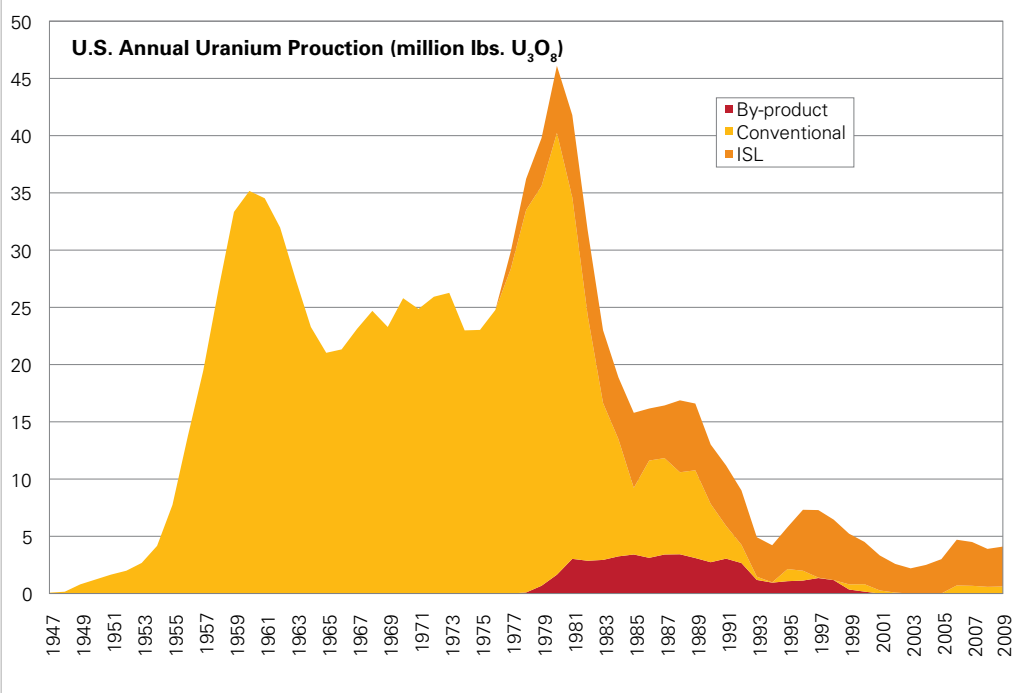


Figure 2: Historical U.S. uranium production after World War II. *Sources:* U.S. Department of Energy/ Energy Information Administration, eia.doe.gov/cneaf/nuclear/dupr/usummary.html; Uranium Energy Corporation, uraniumenergy.com/uranium/usup/.

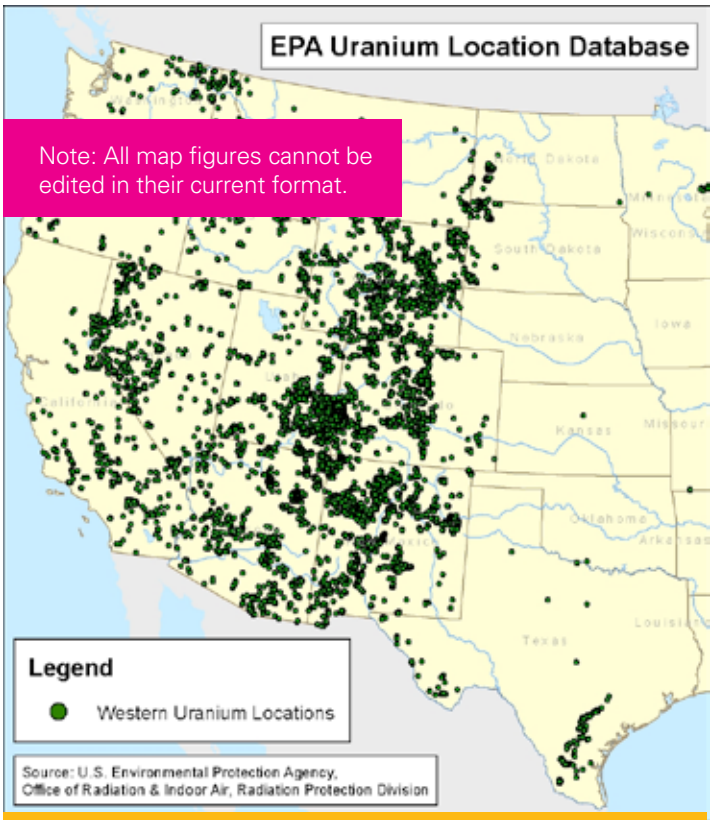


Figure 3: The EPA's Uranium Location Database (ULD) contains records for approximately 15,000 uranium mines in the United States, 4,000 of which had documented production between the 1940s and 1990s. Mine location information was collected by the EPA from federal, state, and tribal agency sources. The majority of mines having uranium as the primary commodity are located in Colorado, Utah, Wyoming, New Mexico, and Arizona, typically on federal or tribal lands.

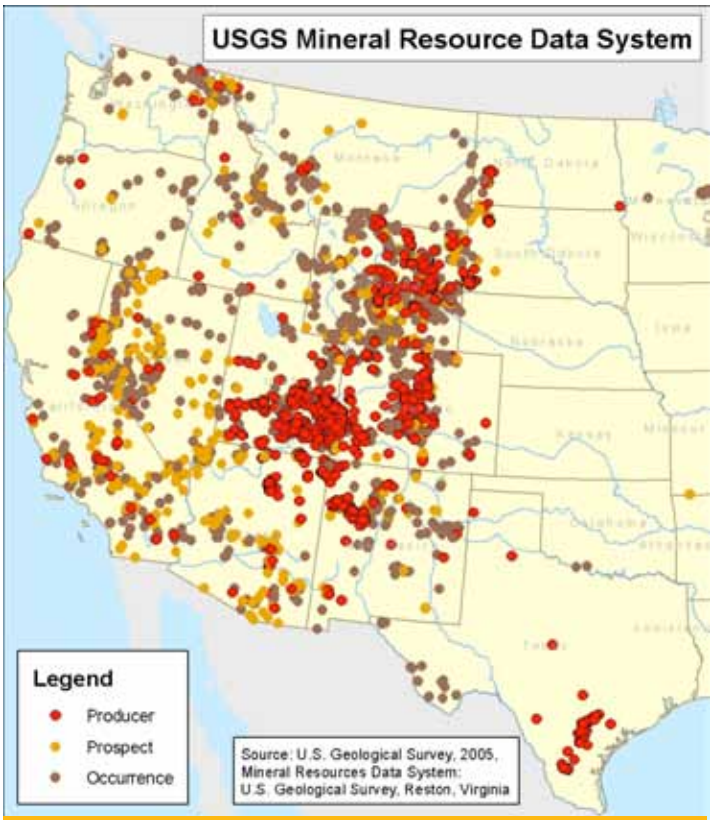


Figure 4: Uranium production sites (past and present), occurrences, and prospects in the western United States, from the USGS Mineral Resources Data System. A uranium occurrence is a locality where uranium has been found. A prospect is an occurrence that has been developed, for example by subsurface drilling, to determine the extent of mineralization.

high demand for uranium as a critical material for nuclear weapons. This spurred the creation of a U.S. government procurement program that actively supported uranium exploration until 1970, primarily in the Four Corners region of the American Southwest, an area comprising Colorado, Utah, Arizona, and New Mexico.[12,13] Significant production continued until the mid-1980s, when demand declined and uranium-producing facilities began to close.[14] Figures 3 and 4 show the geographical distribution of uranium in the United States using EPA and U.S. Geological Survey (USGS) data, respectively.

A BRIEF HISTORY OF CONVENTIONAL URANIUM MINING REGULATION

Most uranium mining and milling sites were operated and managed under a minimal public health and safety regulatory regime that had only recently been implemented. The Nuclear Regulatory Commission (NRC) regulates all commercial entities, operations, and facilities that work with anything "nuclear," including uranium, otherwise referred to (along with the element thorium) as "source material" under the foundational law, the Atomic Energy Act of 1954 (AEA).[15] They are called source materials because when subjected to further processing or neutron bombardment in a reactor, they are the source for "fissile materials" (plutonium and U^{233}, respectively) suitable for use in either nuclear explosives or nuclear reactors. Uranium that is highly enriched in the isotope U^{235} can support an explosive chain reaction when rapidly assembled in sufficient mass, while natural uranium and uranium enriched at levels under 20 percent U^{235} are usable in power reactors. The NRC has regulatory jurisdiction over these source materials when their concentration in mined ores equals or exceeds 0.05 percent by weight.

The AEA requires that a person or company obtain an NRC license to transfer or receive in interstate commerce any source material "after removal from its place in nature."[16] The NRC understood this particular section of the law (Section 62 of the Act) as precluding jurisdiction over conventional uranium mining but as establishing its jurisdiction over the milling of uranium. The AEA left the thousands of conventional uranium mines that dot the western landscape essentially unregulated for decades. The ongoing cleanup of those mines (from tiny underground operations to large open-pit surface mines) is a direct consequence of this lack of regulation.[17] This somewhat counterintuitive state of affairs dates back 50 years and means that the NRC regulates facilities that concentrate, extract, chemically

process, isotopically enrich, or fabricate uranium, but not the conventional mines that remove the uranium ores that are the source of feed materials for such facilities. However, ISL mines recover uranium from the underground ore body in a manner that is somewhat analogous to the way aboveground uranium mills concentrate uranium from crushed ores. Therefore, the NRC legally regards ISL mines (i.e., well fields and associated processing operations) as "uranium recovery" facilities over which it has regulatory jurisdiction.

The AEA's limiting of the NRC's jurisdiction to stages of uranium processing that occur after ores are removed from their place in nature left several regulatory gaps that remained unaddressed, except in the most piecemeal fashion. Over time, conventional uranium mining operations were gradually regulated under various laws, including the Safe Drinking Water Act (SDWA), the Clean Water Act (CWA), the Clean Air Act (CAA), and state mining laws, and thus came under the purview of the EPA and delegated state authorities. But even then, problems of application persist that are beyond the scope of this report.

The CWA, to take one example, covers only those radioactive discharges that *do not* fall into the "source, by-product, and special nuclear material" category.[18] Uranium is a source material. Radon or other radionuclides that exist in a tailings pile are a by-product material. And while there are now SDWA limitations that can be enforced, the extent to which a citizen or state can use tools like the CWA to address the harms of conventional uranium mining remains complicated and expensive.

In 1946, when Congress passed the AEA and created the Atomic Energy Commission (AEC), it made the federal government the sole purchasing agent for domestically produced uranium.[19] The AEC set fixed prices for uranium and, in an effort to spur the nascent nuclear industry and its domestic suppliers, provided incentives such as roads and buying stations.[20] With a focus almost entirely on production and growth, the AEC allowed the uranium mining industry to operate without serious environmental or public health supervision. Uranium prospectors would file claims for potential sites and usually adjacent areas. Ownership of these claims was (and still is) regulated according to the 1872 Mining Law and is enforced by the U.S. Department of the Interior (DOI).

In open-pit mining, one or more pits are excavated to expose the uranium deposit. In the 1950s these pits tended to be small, covering a few acres. More recently, open-pit mines have covered hundreds to thousands of acres; the Jackpile Mine on Laguna Pueblo in New Mexico consumed about 3,000 acres. The overburden (that is, the unwanted material overlying the uranium deposit) is moved to a nearby mine-waste area, and dikes and ditches are often constructed around these waste piles to collect precipitation runoff and divert it to sedimentation ponds. The piles and associated sediment-laden ponds contain radioactive residues and other hazardous materials.[21] Waste piles, low-grade ore piles, and mine-water settling ponds also typify surface facilities at large underground mining complexes. Oxidation of mine wastes in both cases releases soluble hexavalent (+6) uranium, radionuclides, and heavy metals to surrounding soils and surface water courses.

Mill tailings—waste created from the extraction of uranium concentrate, or yellowcake (U_3O_8), from mineralized ores—contain all of the radiological and heavy metal contaminants indigenous to the ore, plus the acids or strong bases and organic compounds used to leach the uranium from the rock. Mill tailings are fine-grained sands that retain 99 percent of the ore's original radioactivity.[22] At some closed mills, efforts to stabilize tailings piles were ineffective or simply negligent, and tailings material was subsequently spread by wind and water erosion to adjacent lands and communities. All 52 inactive and active uranium mill tailings piles, most of which were created before federal regulations were adopted in the early 1980s, are unlined and the source of extensive localized groundwater contamination. The removal and use of mill tailings as construction material also resulted in extensive local surface contamination.[23]

The environmental and public health damage from decades of essentially unregulated conventional uranium milling precipitated the Uranium Mill Tailings Remediation Control Act (UMTRCA) of 1978 (Public Law 95-604).[24] UMTRCA Title I established authority for the Uranium Mill Tailings Remedial Action (UMTRA) Project, in which Congress directed the Department of Energy (DOE) to clean up 22 radioactively and chemically contaminated uranium mill tailings sites (all pre-1978) and the nearby areas into which contamination had spread. UMTRCA Title II gave the NRC authority to regulate "active" uranium milling and tailings disposal at 26 uranium mills licensed in 1978. As stated previously, regulations adopted by the NRC in the 1980s for control of conventional mill tailings during and after operations are still applied by NRC to ISL/ISR operations today.

The milling sites alone have cost the federal government (and thus the taxpayer) billions of dollars in cleanup costs.[25] And while cleanup programs have been ongoing for decades, a handful of sites have been addressed only within the last few years. The EPA's *Technologically Enhanced Naturally Occurring Radioactive Materials* (TENORM) report estimated $2.27 billion in cleanup costs just for the uranium mills (i.e., not including the legacy costs of cleaning up and stanching the flow of contamination from conventional mine sites).[26] At locations in Wyoming, Nebraska, and New Mexico where the NRC is overseeing the cleanup of mills or ISL sites, estimates exist for approximately half the sites and add up to more than $80 million.[27] At other sites where NRC Agreement States, such as Texas, Colorado, and Utah have direct oversight authority over cleanup, estimated costs or completion dates have not yet been determined.

Turning to conventional mines, the EPA estimates the average cost of closure at nearly $14 million per mine. When the costs for the Midnite Mine in Washington and the Northeast Church Rock Mine in New Mexico are added, the average cost will probably increase substantially. The EPA has identified more than 520 abandoned uranium mines on Navajo land alone, with the cleanup cost likely to reach into the hundreds of millions of dollars.[28]

PROSPECTS FOR NEW MINES: CONVENTIONAL AND IN-SITU LEACH

For the past 20 years, the production of uranium in the United States has been relatively low, but the historic boom-and-bust cycle has shown signs of a possible recurrence.[29] In 2007 the Environmental Working Group used information collected by the Bureau of Land Management (BLM) and found that in just four states (Colorado, New Mexico, Utah, and Wyoming), uranium claims had surged from an estimated 4,300 staked in fiscal year 2004 to more than 32,000 in fiscal year 2006.[30]

NRDC ascribes much of this recent speculative claim activity to an anticipated uranium supply shortfall and a short-term spike in the price of uranium that has since largely receded. Because uranium is not traded on a commodity exchange that records the executed prices of all transactions, uranium prices are negotiated directly between individual buyers and sellers, and the terms of many transactions remain confidential. Two uranium market consulting firms track these transactions and regularly publish "indicative" prices for both long-term uranium supply contracts and short-term single delivery sales on the spot market, which typically accounts for less than 15 percent of total uranium sales.

In the decade from 2000 to 2010, prices for uranium ballooned and then dropped again. Rising demand beginning in 2003 prompted a modest increase in production in the United States. And while the World Nuclear Association (WNA) in 2007 reported that market forces were bringing new uranium projects into production, the timetables of planned uranium projects often change with fluctuations in uranium's price. In the summer of 2007, the immediate cash purchase price, or spot price, briefly rose to an historic high of $137 per pound of uranium oxide (U_3O_8) , but then fell by more than two-thirds by May 2010, when it fell to just above $40 per pound.[31]

Figure 5 shows the weighted (by size of transaction) average annual spot prices and multiannual (long-term negotiated contract) prices for U_3O_8 since 1980 for nuclear utilities in the European Union, where a long-term data set for both spot market transactions and long-term contract prices is publicly available. The figure shows that long-term contract prices, reflecting the vast bulk of all uranium sales by weight, fluctuate within a much narrower range than do spot prices.

Figure 6, compiled from multiple sources by the International Panel on Fissile Materials (IPFM), shows the average constant-dollar price paid per kilogram of uranium by U.S. reactor operators over nearly 40 years.[32]

The chart reveals no secular trend toward permanently higher prices for uranium, suggesting that U.S. uranium mining areas with economically marginal deposits of low-grade ore will remain vulnerable to short-term swings in the uranium market. As of August 1, 2011, the spot price indicator for uranium (U_3O_8) was approximately $52.25 per pound ($115.20 per kilogram).[33]

While the sharp run-up in uranium prices of 2007 and 2008 has largely receded, the future extent of growth in uranium demand and mine output remains unclear. A significant fraction of the existing U.S. demand was met in the past decade from Russia's surplus weapons uranium stockpile. But with this arrangement scheduled to end in 2013, and with demand likely to grow in Asia as nuclear power expands in

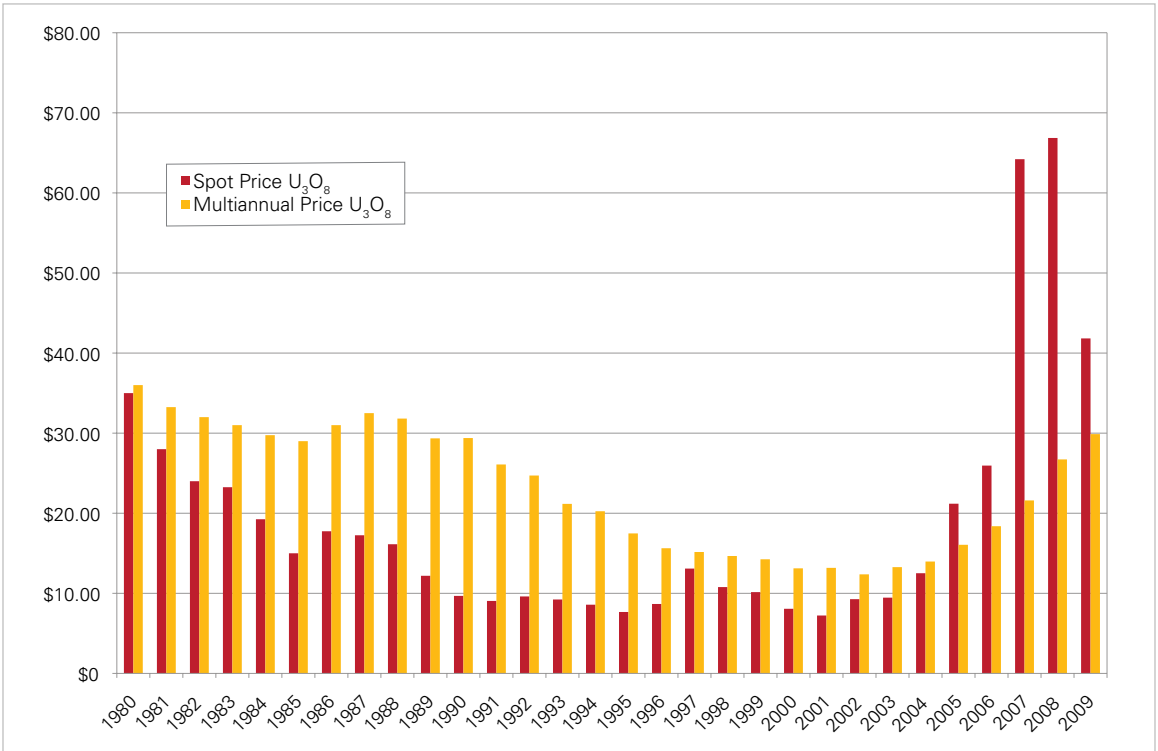


Figure 5: Uranium (U_3O_8) weighted average price, 1980 to 2010. *Source:* EURATOM Supply Agency Annual Report 2010, Annex 3: ESA average prices for natural uranium, ec.europa.eu/euratom/ar/last.pdf.

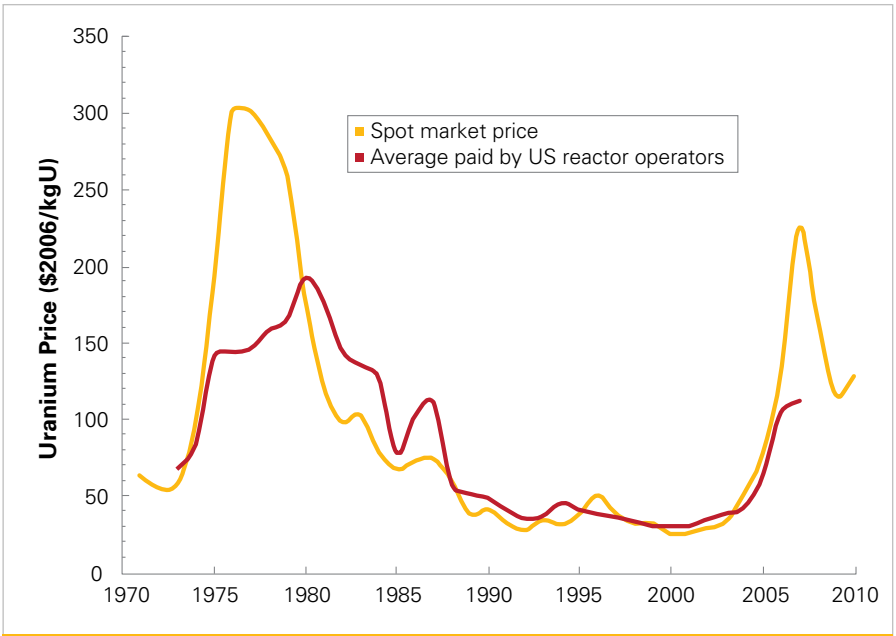


Figure 6: Uranium spot price and average price paid by U.S. reactor operators, 1971 to 2009. *Source:* IPFM, 2010. Need more info

China, East Asia, and India—even after the Japanese nuclear disaster—some uranium investors predict a tightening supply and steadily rising uranium prices in the near future.[34]

NRDC does not necessarily agree with the rising uranium price scenario, given the shaky nature of the "nuclear renaissance" and the likelihood that the new sources of mined uranium will enter a market priced at around $50 per pound for uranium concentrate. Certainly from the perspective of the United States, it is unclear how extensively our own domestic uranium industry will be revived. A 2010 report by the Massachusetts Institute of Technology (MIT) concluded that uranium resources recoverable at or under $130 per kilogram ($50 per pound) would likely total on the order of 13 million tons. Given current global nuclear capacity of 377 gigawatts electric (GWe), an assumed future global nuclear capacity utilization of 85 percent (historically this figure has been lower), and uranium consumption averaging 200 metric tons per GWe per year, then this 13 million tons of relatively cheap uranium would last for about 200 years. Alternatively, it could support a doubling of global nuclear capacity for 100 years. In other words, beyond intervals of 5 to 10 years in which global uranium mining capacity might temporarily fail to keep pace with the addition of new reactor capacity, there is no reason to expect a longterm dramatic rise in the price of uranium to begin anytime soon. Therefore a bonanza for western states with uranium resources appears unlikely.[35]

From a domestic perspective, during the 1960s, 1970s, and early 1980s, U.S. uranium mines could and did produce more than 35 million pounds of uranium per year. By contrast, between 1993 and 2009, U.S. uranium production averaged only 3.9 million pounds per year.[36] Since the first mines were dug in the 1940s, New Mexico has always been among the top uranium-producing states. Recently, Texas and Wyoming have produced the most uranium, although overall uranium production is significantly below historical highs.[37]

Table 1: Number of operating uranium mines in the United States for 2007, 2008, and 2009 by mine type, and total uranium production.

Number of Mines Operated	2007	2008	2009
Underground	6	10	14
Open Pit	0	0	0
In-Situ Leach	5	6	4
Other*	1	1	2
Total Mine Production (thousand pounds U_3O_8)	**4,541**	**3,879**	**4,145**

"Includes sources of uranium from mine water, mill site cleanup and mill tailings, and well-field restoration. Source: U.S. DOE/EIA.

Due to the rapid growth of large ISL mining operations in Kazakhstan, ISL mining now accounts for 41 percent of global uranium production, followed by conventional underground mining at 28 percent, open-pit mining at 25 percent, and "by-product" mining (i.e., the production of uranium in conjunction with the mining of other minerals, such as copper or phosphates) at 5 percent.[38] Nonetheless, in the United States, conventional underground mines produced more uranium concentrate than did ISL operations between 2007 and 2009 (Table 1).[39] While thousands of claims have been filed, it is unclear how many are seriously being pursued despite the resources available.[40]

The forecast of a nuclear renaissance has led to interest in siting new uranium mines and associated facilities in areas both within and outside the traditional mining regions of the U.S. West.[41] The number of working ISL operations has fluctuated as the volatility of uranium prices has pushed facilities in and out of production. In 1982 there were 18 facilities. That number was down to four by 1992 and to two by 2003. In 2009 only four ISL mines were in operation, but approximately 45 ISL projects—two-thirds of which are in Wyoming—are now in the planning stages. The number will remain a moving target as the price of uranium rises and falls.

Apart from these plans, roughly 55 properties are considered uranium deposits amenable to ISL mining, with approximately half of them in Wyoming and others in Arizona, New Mexico, and Texas.[42] Table 2 provides a list of operating, planned, potential, and closed ISL operations in the United States; these are mapped in Figures 7 and 8. These 125 ISL operations fall within eight states: Arizona (9 potential), Colorado (3 planned), Montana (1 planned), Nebraska (1 operating and 5 planned), New Mexico (4 planned and 6 potential), South Dakota (1 planned), Texas (5 operating, 3 planned, 12 potential, and 12 closed), and Wyoming (6 operating, 28 planned, 27 potential, and 2 closed).

Table 2: NRDC ISL Mine Database of in-situ leach mines and facilities: operational, planned, potential, and closed.

In-Situ Leach Site	Status	Corporate	State	County
Alta Mesa	Operational	Mestena Uranium LLC	Texas	Brooks
Crow Butte	Operational	Cameco Corp.	Nebraska	Dawes
Christensen Ranch	Operational	Uranium One USA, Inc.		
Hobson	Operational	South Texas Mining Venture	Texas	Karnes
Kingsville Dome	Operational (in standby)	Uranium Resources Inc.	Texas	Kleberg
Irigaray Ranch	Operational	Uranium One USA, Inc.	Wyoming	
Johnson				
La Palangana	Operational	South Texas Mining Venture	Texas	Duval
Rosita	Operational (in standby)	Uranium Resources Inc.	Texas	Duval
Smith Ranch ISL Wellfield	Operational	Cameco Corp.	Wyoming	Converse
Smith Ranch ISL Satellite Facility SR-1	Operational	Cameco Corp.	Wyoming	Converse
Smith Ranch—Highland Ranch ISL Satellite No. 2	Operational	Cameco Corp.	Wyoming	Converse
Smith Ranch—Highland Ranch ISL Satellite No. 3	Operational	Cameco Corp.	Wyoming	Converse
Smith Ranch Central Processing Plant (CPP)	Operational	Cameco Corp.	Wyoming	Converse
Allemand-Ross (Satellite)—Bear Creek	Planned (Expansion)	Uranium One	Wyoming	Converse
Allemand-Ross (Satellite)—Sand Draw	Planned (Expansion)	Uranium One	Wyoming	Converse
Alzada	Planned	Bayswater Uranium Corp.	Montana	Carter
Antelope	Planned (Developing/ Application in Review)	Uranium One	Wyoming	Sweetwater and Fremont
Antelope—Jab	Planned (Developing/ Application in Review)	Uranium One	Wyoming	Sweetwater
Antelope—Sheep Mountain	Planned (Developing/ Application in Review)	Uranium One	Wyoming	Sweetwater
Antelope—Twin Butte	Planned (Developing/ Application in Review)	Uranium One	Wyoming	Sweetwater
Bison Basin Project	Planned	WildHorse Energy	Wyoming	Sweetwater
Centennial Project, Powertech Project near Fort Collins—North Zone	Planned	Powertech Uranium Corp.	Colorado	Weld

(Table 2 Continued) NRDC ISL Mine Database of in-situ leach mines and facilities: operational, planned, potential, and closed.

In-Situ Leach Site	Status	Corporate	State	County
Centennial Project, Powertech Project near Fort Collins—South Zone	Planned	Powertech Uranium Corp.	Colorado	Weld
Church Rock	Planned	Hydro Resources, Inc./ Strathmore Mineral Corp.	New Mexico	McKinley
Crow Butte—North Trend	Planned (Expansion, Application Received)	Cameco (Crow Butte Resources, Inc.)	Nebraska	Dawes
Crow Butte—Marsland	Planned (Expansion)	Cameco (Crow Butte Resources, Inc.)	Nebraska	Dawes
Crow Butte—Three Crow	Planned (Expansion)	Cameco (Crow Butte Resources, Inc.)	Nebraska	Dawes
Crownpoint	Planned (Partially Permitted and Licensed)	Hydro Resources, Inc./ Uranium Resources Inc.	New Mexico	McKinley
Crownpoint Section 19/29	Planned (Licensed)	Hydro Resources, Inc./ NZ Uranium LLC	New Mexico	McKinley
Dewey—Burdock	Planned (Application in Review)	Powertech Uranium Corp.	South Dakota	Custer and Fall River
Gas Hills Uranium Mining District	Planned (Under Construction)	Strathmore Mineral Corp.	Wyoming	Fremont
Goliad Uranium	Planned (Partially Permitted and Licensed)	Uranium Energy Corp.	Texas	Goliad
Hank	Planned (Application in Review)	Cameco Corp.	Wyoming	Campbell
Jane Dough	Planned (Application Expected 2012)	Uranerz Energy	Wyoming	Johnson
La Palangana	Planned (Permitted and Licensed)	Uranium Energy Corp./ Uranium One	Texas	Duval
Last Chance #3 and #4	Planned (Application in Review)	Nuvemco LLC	Colorado	Montrose
Lost Creek	Planned (Expansion, Application Received)	Ur-Energy USA, Inc./Lost Creek ISR LLC	Wyoming	Sweetwater
Lost Soldier	Planned (Expansion)	Ur-Energy USA, Inc.	Wyoming	Sweetwater
Ludeman	Planned (Expansion)	Uranium One	Wyoming	Converse
Marsland (Satellite)	Planned (Expansion)	Cameco Corp.	Nebraska	Dawes
Moore Ranch Extraction Site (Planned)	Application Complete for Moore Ranch	Uranium One Americas, Inc./ Energy Metals	Wyoming	Campbell
Nichols Ranch ISR Project	Planned (Application in Review)	Cameco Corp./Uranium Energy Corp.	Wyoming	Johnson
North Butte/Brown Ranch Uranium Deposit	Planned	Cameco Corp.	Wyoming	Campbell
North Trend (Satellite)	Planned (Expansion)	Cameco Corp.	Nebraska	Dawes
Pine Tree	Planned	Strathmore Mineral Corp.	Wyoming	Campbell
Reno Creek	Planned	Strathmore Mineral Corp.	Wyoming	Campbell
Reynolds Ranch (Satellite)	Planned (Licensed)	Cameco Corp.	Wyoming	Converse
Ross	Planned	Strata Energy, Inc.	Wyoming	Oshoto-Crook County
Ruby Ranch	Planned (Expansion)	Cameco (Power Resources, Inc.)	Wyoming	Campbell County
Ruth	Planned (Licensed)	Power Resources, Inc.	Wyoming	Johnson
Ruth Uranium Deposit	Planned	Cameco Corp.	Wyoming	Johnson
Smith Ranch ISL (Satellite No. 1)	Planned	Cameco Corp.	Wyoming	Converse
Smith Ranch ISL Satellite Facility SR-2 (Proposed)	Planned (Expansion)	Cameco Corp.	Wyoming	Converse

(Table 2 Continued) NRDC ISL Mine Database of in-situ leach mines and facilities: operational, planned, potential, and closed.

In-Situ Leach Site	Status	Corporate	State	County
Smith Ranch/Highland CPP	Planned (Expansion)	Cameco (Power Resources, Inc.)	Wyoming	Converse
Southwest Reno Creek	Planned	Strathmore Mineral Corp.	Wyoming	Campbell
Sweetwater Uranium Project	Planned	Rio Tinto Energy America	Wyoming	Sweetwater
West Alkalai Creek	Planned	Wildhorse Energy	Wyoming	Fremont
Aladdin	Potential (Deposit)	Powertech Uranium Corp.	Wyoming	Cook
Bootheel	Planned	Target Exploration & Mining Corp.	Wyoming	Albany
Buck Point	Potential (Deposit)	Target Exploration & Mining Corp.	Wyoming	Albany
Buckaroo Flats	Potential (Deposit)	Rodinia Minerals Inc.	Arizona	Gila
Burnt Wagon	Potential (Deposit)	Uranium Energy Corp.	Wyoming	Natrona
C de Baca	Potential (Deposit)	Max Resource Corp.	New Mexico	Socorro
C-Line	Potential (Deposit)	Cameco Corp.	Wyoming	Campbell
Collins Draw	Potential (Deposit)	Cameco Corp.	Wyoming	Campbell
Converse	Potential (Deposit)	New Horizons	Wyoming	Converse
Coon Creek	Potential (Deposit)	Rodinia Minerals Inc.	Arizona	Gila
Cyclone Rim	Potential (Deposit)	Cameco Corp.	Wyoming	Sweetwater
Dalton Pass	Potential (Deposit)	Strathmore Mineral Corp.	New Mexico	McKinley
Dewey Terrace	Potential (Deposit)	Powertech Uranium Corp.	Wyoming	Weston and Niobrara
Doughstick	Potential (Deposit)	Cameco Corp.	Wyoming	Campbell
Eagle	Potential (Deposit)	Cameco Corp.	Wyoming	Sweetwater
East Nichols	Potential (Deposit)	Cameco Corp.	Wyoming	Campbell
Elkhorn	Potential (Deposit)	Bayswater Uranium Corp.	Wyoming	Crook
Gas Hills	Planned	Cameco Corp.	Wyoming	Fremont
Hosta Butte	Potential (Deposit)	NZ Uranium LLC	New Mexico	McKinley
Middle Mountain	Potential (Deposit)	Rodinia Minerals Inc.	Arizona	Gila
Niles Ranch	Potential (Deposit)	Cameco Corp.	Wyoming	Campbell
North Nichols	Potential (Deposit)	Cameco Corp.	Wyoming	Johnson
North Reno	Potential (Deposit)	Cameco Corp.	Wyoming	Campbell
North Rolling Pin	Potential (Deposit)	Cameco Corp.	Wyoming	Campbell
Oak Creek	Potential (Deposit)	Rodinia Minerals Inc.	Arizona	Gila
Pendleton Mesa	Potential (Deposit)	Rodinia Minerals Inc.	Arizona	Gila
Peterson	Potential (Deposit)	Uranium One	Wyoming	Converse
Red Bluff	Potential (Deposit)	Rodinia Minerals Inc.	Arizona	Gila
Sand Creek	Potential (Deposit)	New Horizons	Wyoming	Converse
Shirley Basin	Potential (Deposit)	Strathmore Mineral Corp.	Wyoming	Carbon
Sky	Potential (Deposit)	Strathmore Mineral Corp.	Wyoming	Fremont
Suckerite	Potential (Deposit)	Rodinia Minerals Inc.	Arizona	Gila
Swinney Switch	Potential (Deposit)	Uranium One	Texas	Live Oak and Bee
Taylor Ranch	Potential (Deposit)	Cameco Corp.	Wyoming	Campbell

(Table 2 Continued) NRDC ISL Mine Database of in-situ leach mines and facilities: operational, planned, potential, and closed.

In-Situ Leach Site	Status	Corporate	State	County
Treeline	Potential (Deposit)	Western Uranium Corp.	New Mexico	McKinley and Cibola
Turnercrest	Potential (Deposit)	Magnum Minerals USA	Wyoming	Campbell
Verna Ann	Potential (Deposit)	Cameco Corp.	Wyoming	Campbell
West North Butte	Potential (Deposit)	Cameco Corp.	Wyoming	Campbell
Willow Creek	Planned, Application Received	Uranium One	Wyoming	Campbell
Workman North	Potential (Deposit)	Rodinia Minerals Inc.	Arizona	Gila
Workman South	Potential (Deposit)	Rodinia Minerals Inc.	Arizona	Gila
Texas RRC Uranium Exploration Permit Number 118C	Exploration Permit	URI, Inc.	Texas	Duval
Texas RRC Uranium Exploration Permit Number 121C	Exploration Permit	URI, Inc.	Texas	Kleberg
Texas RRC Uranium Exploration Permit Number 122C	Exploration Permit	URI, Inc.	Texas	Duval
Texas RRC Uranium Exploration Permit Number: 124E	Exploration Permit	South Texas Mining Venture	Texas	Duval
Texas RRC Uranium Exploration Permit Number 125C-1	Exploration Permit	Mestena	Texas	Brooks and Jim Hogg
Texas RRC Uranium Exploration Permit Number 134C	Exploration Permit	Signal Equities, LLC	Texas	Atascosa
Texas RRC Uranium Exploration Permit Number 135C	Exploration Permit	Signal Equities, LLC	Texas	Live Oak
Texas RRC Uranium Exploration Permit Number 136B	Exploration Permit	Uranerz Energy Corp.	Texas	Briscoe
Texas RRC Uranium Exploration Permit Number 137B	Exploration Permit	Signal Equities, LLC	Texas	Bee
Texas RRC Uranium Exploration Permit Number 141A	Exploration Permit	Uranium Energy Corp.	Texas	Karnes
Texas RRC Uranium Exploration Permit Number 142	Exploration Permit	Uranium Energy Corp.	Texas	Goliad
Texas RRC Uranium Exploration Permit Number 143	Exploration Permit	Signal Equities, LLC	Texas	Live Oak
Benavides	Closed (Reclamation)	Uranium Resources Inc.	Texas	Duval
Bruni	Closed	Areva NC	Texas	Duval
Burns Ranch/Clay West	Closed (Reclamation)	USX (U.S. Steel)	Texas	Live Oak
Christensen Ranch	Closed (Changing License to Operational)	Areva NC	Wyoming	Johnson
El Mesquite	Closed (Reclamation)	Areva NC	Texas	Duval
Holiday	Closed (Reclamation)	Areva NC	Texas	Duval
Irigaray	Closed (Reclamation)	Areva NC	Wyoming	Johnson
Lamprecht/Zamzow	Closed (Reclamation)	Intercontinental Energy	Texas	
Las Palmas	Closed (Reclamation)	Everest Minerals	Texas	Duval
Mt. Lucas	Closed (Reclamation)	Everest Minerals	Texas	Live Oak
O'Hern	Closed (Reclamation)	Areva NC	Texas	Webb
Tex-1	Closed (Reclamation)	Everest Minerals	Texas	xx missing info
Vasquez	Closed (Reclamation)	Uranium Resources Inc.	Texas	Duval
West Cole	Closed (Reclamation)	Areva NC	Texas	Duval and Webb

Sources: U.S. Environmental Protection Agency, U.S. Nuclear Regulatory Commission, U.S. Geological Survey,and specific license applications and environmental review documents.

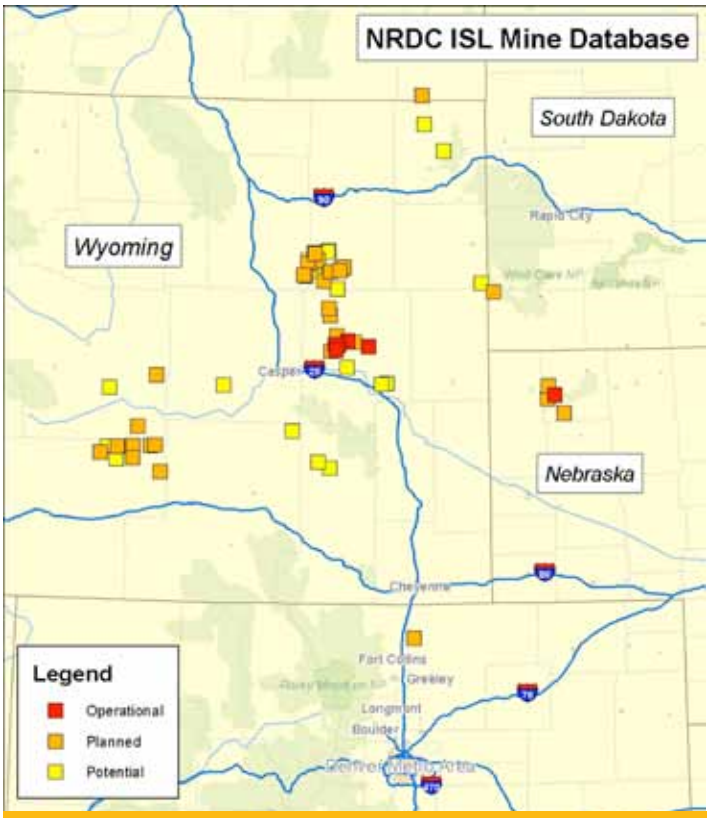


Figure 7: NRDC In-Situ Leach Mine Database operational, planned, and potential facilities for Wyoming and adjacent states.

Figure 8: NRDC In-Situ Leach Mine Database of in-situ leach mines: planned and potential facilities for New Mexico and adjacent states.

WORLDWIDE URANIUM RESOURCES AND POTENTIAL DOMESTIC IMPACT

About 62 percent of the world's annual mined uranium production in 2010 came from the three largest suppliers—Kazakhstan (33 percent), Canada (18 percent), and Australia (11 percent). The world uranium production and recoverable reserve data are shown in Table 3. For the past five years, U.S. nuclear power-reactor operators have purchased only about 15 percent of their needed uranium from domestic sources.[43] Worldwide identified uranium reserves, as reported by the Organization for Economic Co-operation and Development (OECD), show that in 2007 the United States had approximately 6 percent (342,000 tons) of the world's uranium reserves. None of these resources, however, falls into the lowest cost-of-recovery category for uranium (less than $18 per pound), under which 642,000 tons of world reserves fall. These and other factors make it difficult for American producers to compete in the world market.[44]

Looking forward, uranium production in the United States and elsewhere will be determined by nuclear energy development and the global uranium market. Uranium for nuclear energy is supplied not only from primary sources like mining operations but also from secondary sources of already mined and processed uranium, such as the blending down of highly enriched uranium from weapons programs and the blending up of uranium enrichment tailings. In 2010

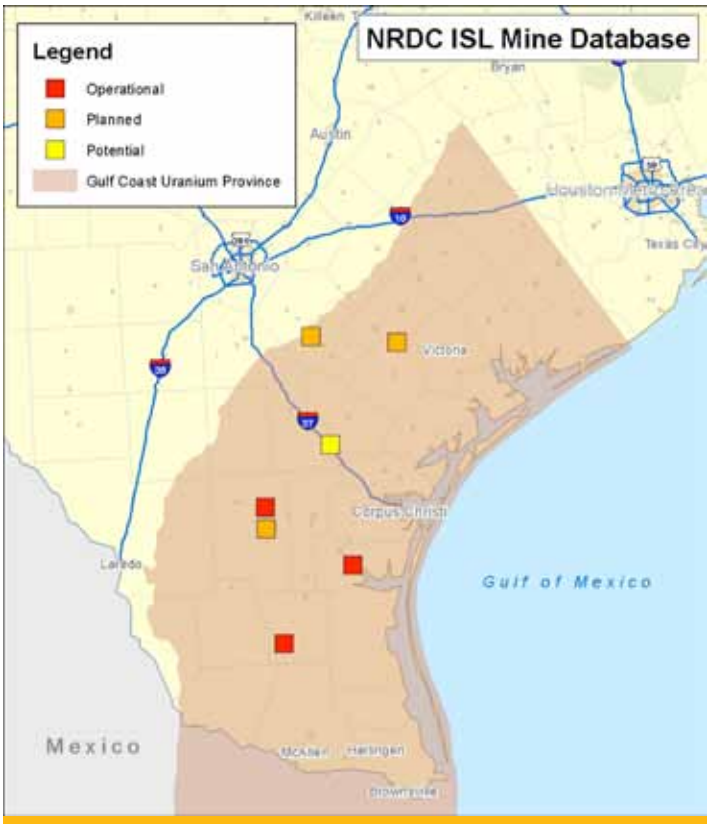


Figure 9: NRDC In-Situ Leach Mine Database operational, planned, and potential facilities for the Texas coastal plain.

Table 3: World uranium production and recoverable resource statistics by country.

Country	2010 Production from Mines (tonnes uranium)	Percent of World Production	2007 Known Recoverable Resources of Uranium (tonnes uranium)	Percent Total Resources
Kazakhstan	17,803	33.17	817,000	14.94%
Canada	9,783	18.23	423,000	7.73%
Australia	5,900	11.00	1,243,000	22.73%
Namibia	4,496	8.37	275,000	5.03%
Niger	4,198	7.82	546,000	9.98%
Russia	3,562	6.63	274,000	5.01%
Uzbekistan	2,400	4.47	111,000	2.03%
USA	1,660	3.09	342,000	6.25%
Ukraine (est.)	850	1.58	200,000	3.66%
China	827	1.54	68,000	1.24%
Malawi	670	1.24	N/A	N/A
South Africa	583	1.08	435,000	7.95%
India	400	0.74	73,000	1.33%
Czech Republic	254	0.47	N/A	N/A
Brazil	148	0.27	278,000	5.08%
Romania (est.)	77	0.14	N/A	N/A
Pakistan (est.)	45	0.08	N/A	N/A
France	7	0.01	N/A	N/A
Jordan	N/A	N/A	112,000	2.05%
Mongolia	N/A	N/A	62,000	1.13%
Other Countries	N/A	N/A	210,000	3.84%
World Total	**53,663**		**5,469,000**	

Sources: World Nuclear Association Market Report data at world-nuclear.org/info/inf23.html and, the Organisation for Economic Co-operation and Development (OECD), the Nuclear Energy Agency (NEA), and the International Atomic Energy Agency (IAEA), Uranium 2007: Resources, Production and Demand (the "Red Book").

uranium from mine production met 78 percent of the world's requirements for nuclear power, with the rest supplied by former weapons materials.[45]

It is NRDC's sense that there could be a measured increase in global demand for mined uranium due to the termination of the Russian-U.S. Megatons to Megawatts program and the continued growth of nuclear power in Asia. Whether there will be significant growth in demand in the United States and Europe looks much less certain, especially after the events of the Fukushima nuclear disaster in Japan. A key factor will be whether future supplies of mined uranium outside the United States will be sufficient to keep the moving average of uranium prices consistently below $35 to $45 per pound, which we understand to be roughly the price range required for profitable operation of most ISL recovery projects.

As shown in Figure 10, annual employment in the U.S. uranium mining industry is minimal, barely topping 1,000 person-years in all related activities, including post-mining reclamation.

Unless the United States envisions selling its uranium abroad to fuel Chinese and other foreign reactors–thereby defeating the "energy security" rationale for expanding domestic uranium production[46]–growth prospects for the U.S. uranium industry are tied either to underpricing and thereby replacing current uranium imports, or to competing effectively to satisfy projected increases in U.S. nuclear fuel demand. On that score, according to the U.S. Energy Information Administration (EIA), the prospect of a nuclear

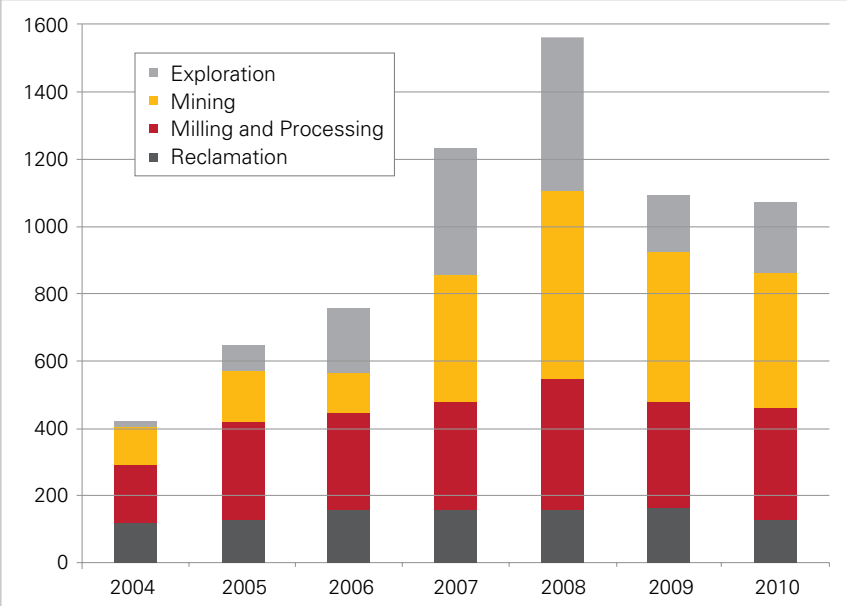


Figure 10: Uranium production industry employment in the United States, by category, 2004 to 2010. *Source:* U.S. Energy Information Adminstration, Form EIA-851A, *"Domestic Uranium Production Report" (2004-2010).*

renaissance in the United States is fading. The latest 2011 EIA "reference case" projection is for U.S. nuclear power capacity to grow from 101 GWe in 2009 to only 110.5 GWe in 2035. Under an "economy-wide" greenhouse gas pricing scenario in which there is an increase in the cost of fossil fuel alternatives, considered politically unlikely in the near term, the projected U.S. nuclear capacity in 2035 would be 130 GWe, a gradual 30 percent increase phased in over 25 years.[47] These are not scenarios that necessarily lead to sharp increases in uranium prices or domestic mining industry employment over the next decade.

Such modest potential economic gains from expanded uranium mining must be weighed against future mine cleanup costs; the potential costs of impairment to groundwater resources and real estate values; the potential to contaminate other valuable mineral deposits; and the potential damage to future agricultural, residential, and recreational uses of the land.

II. CONVENTIONAL URANIUM RECOVERY: ENVIRONMENTAL AND HEALTH IMPACTS

Although this report focuses largely on ISL mining and the need for regulatory reform, it is essential before proceeding further to have a basic understanding of the conventional uranium mining process and the legacy left by uranium mining and milling.

THE MINING PROCESS

Fundamentally, uranium in its dispersed natural state is a common, mildly radioactive, heavy element that exists in low concentrations in soil, rock, and water. For its primary uses in atomic weapons and nuclear power plants, uranium-bearing ore must be mined from the earth and then milled, or concentrated.

Uranium has generally been mined in one of four ways, depending on the depth and ore grade of the uranium deposit and the associated geology; these methods are surface mining, conventional underground mining, and heap leach mining. Each extraction technique has broad impacts on the human and natural environment.

Conventional Mining

- **Surface mining**, or open-pit mining, resembles strip mining for coal in the eastern United States. It is, quite simply, the surface removal of soil and rock overburden and extraction of ore that contains uranium. Scrapers, mechanical shovels, and trucks rip or blast free about 30 times as much topsoil and overburden as actual uranium ore. Once the ore body is exposed, it is excavated and hauled out of the pit for processing. The material left over after processing, called uranium tailings, is both radioactive and toxic.
- **Underground mining** techniques are used if the uranium ore is located deeper in the bedrock. This process involves extracting ore deposits through deep shafts and drifts (horizontal tunnels extending from the shafts). Trains, conveyor belts, elevators, trucks, or diesel-powered heavy equipment bring the mined ore to the surface and arrange it by grade in piles near the mine surface installation. It is then trucked to a mill where it goes through a series of processes to become uranium yellowcake. The non-uranium-grade ore that is brought to the surface is placed in waste-rock-specific dumps. While underground mining leaves much of the non-mine-grade ore in place and therefore creates less overburden and waste rock than does surface mining, it exposes underground workers to the highest levels of radon gas of any method. It also produces radioactive waste rock.

Heap Leach Mining

The third method, called heap leach mining, involves treating crushed ore on the surface with a wash of chemicals to extract uranium. Heap leaching was used on an experimental basis in the United States during the 1970s and 1980s, and the few sites where it was used in this country are now being decommissioned. There are, however, at least two sites—one in Wyoming and one in New Mexico—that have submitted letters of intent to present license applications to the NRC.[48]

Uranium Milling

After uranium ore is removed from land, it must be milled in order to separate the usable portions of uranium oxide (typically less than 1 percent of the material) from the waste rock. At a uranium mill, ore is first crushed and ground in order to enable further processing. Next, water or some other lixiviant—the leaching fluid or solution used to recover the uranium from the ore—is added in order to facilitate movement, reduce dust, and begin the leaching process.[49] The slurry generated through this process is then pumped into tanks for leaching.[50] In this way, the lixiviant becomes impregnated with uranium.

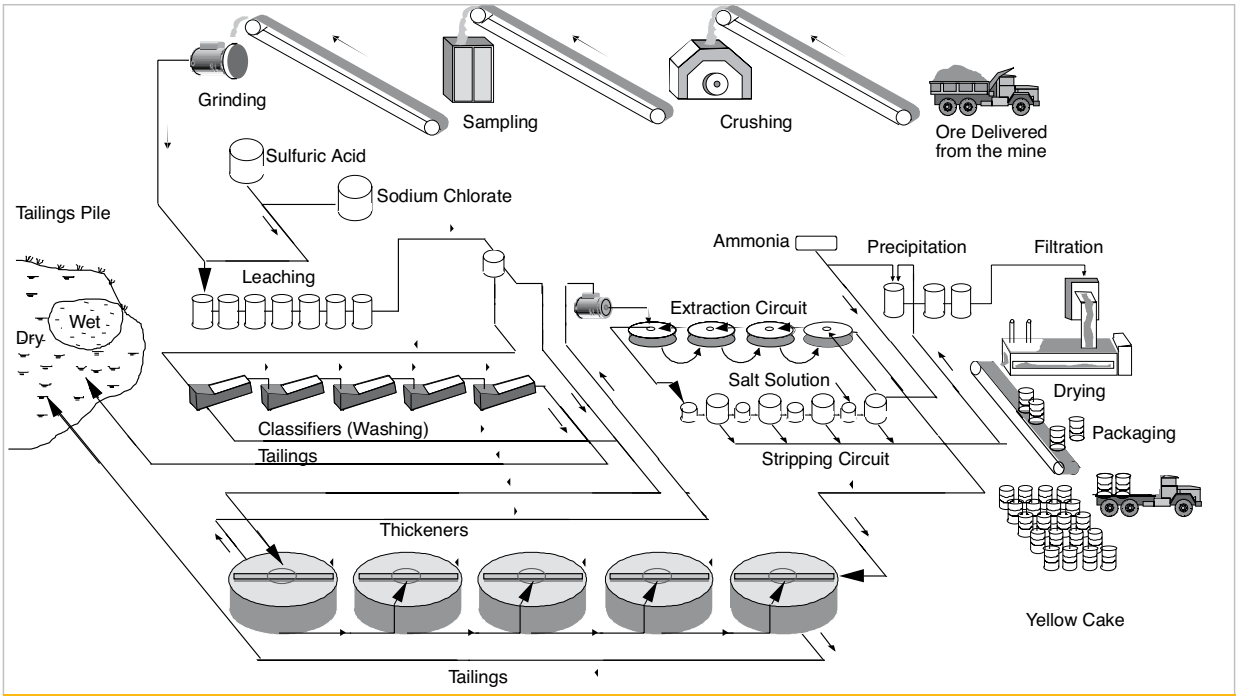


Figure 11: Schematic of the uranium milling process. *Source:* EIA, U.S. Department of Energy, *"Decommissioning of U.S. Uranium Production Facilities,"* February 1995.

The uranium is separated from the lixiviant to become yellowcake, a uranium oxide (U_3O_8) in either liquid or powder form; then it is placed in barrels and shipped to conversion and enrichment plants where it is fabricated into fuel for electricity production or nuclear weapons.[51] Figure 11 above from the Energy Department provides a basic graphic representation of the processes.

THE ENVIRONMENTAL IMPACTS

The environmental hazards from uranium recovery operations are real and widespread. Overall, open-pit and underground mining bring to the surface ore that bears significant concentrations of naturally occurring radioactive elements and potentially toxic heavy metals—materials that would otherwise have remained distributed and undisturbed within the earth's crust. The wastes from open-pit mining are extensive and have proved complicated to control over time. The primary environmental burden from open-pit mining has, of course, been management of the huge amounts of radioactive waste residues, or tailings, that uranium mills generate.[52]

Only a small fraction of the mined material contains the valuable uranium oxide; approximately one to five pounds are extracted from each ton of ore. The tailings from the milling process are normally dumped as sludge into special piles. In the past, these piles were abandoned and posed (and in some instances continue to pose) serious threats to public health and safety. The expediently engineered structures to contain the tailings have eroded over time and allowed radioactive waste to leak into the surrounding ecosystem,[53] fouling nearby groundwater and surface water and exposing entire communities to dangerous levels of radioactivity. The largest such piles in the United States and Canada contain up to 30 million tons of solid material.[54] Figure 12 is an aerial photograph of a producing conventional uranium mine in Utah, and Figure 13 is a satellite image of the only currently operating uranium mill in the United States.

The hazards from just one mine or incident can be significant and long lasting.[55] For instance, in the 1979 collapse of a tailings dam in Church Rock, New Mexico, 93 million gallons of radioactive and chemically contaminated liquid and 1,100 tons of solid radioactive tailings were deposited into the Rio Puerco, contaminating the river more than 60 miles downstream.[56] There are thousands of uranium mines in the western United States in need of remediation. Cleanup of conventional mines is, for the most part, happening under the Comprehensive Environmental Response, Compensation, and Liability Act, better known as Superfund.[57]

For decades the Navajo Nation has been especially affected by boom-and-bust uranium mining. On Navajo land alone, nearly four million tons of uranium ore were extracted from 1944 to 1986; left behind were more than 500 abandoned uranium mines, four inactive uranium milling sites, a former dump site, and the widespread contamination of land and water.[58] Only recently has the government attempted to assess and mitigate this contamination, but full reclamation of the land is unlikely.[59]

An additional consequence of uranium mining has been skyrocketing lung cancer rates among the estimated 3,000 to 5,000 Navajo who worked the mines, contributed to by the inhalation of ore dust.[60,61] Given the long history and the severity of uranium impacts on the Navajo people, in 2005 the Navajo Nation banned uranium mining and processing on Navajo lands until past harms have been fully remediated.[62]

Figure 12: Aerial photograph of the Pandora uranium mine in San Juan County, Utah, owned by Denison Mines. Pandora is accessed by spiral tunnels, or declines, from the surface and is connected underground with the adjacent Beaver mine, 1.5 kilometers northwest of Pandora and not visible here. Pandora, a mature conventional uranium mine with extensive underground workings, produced 52,000 tons of ore in 2008. *Source:* Google Earth.

Figure 13: Satellite image of the Denison Mines' White Mesa facility—the Satellite image of Denison Mines' White Mesa facility, the only conventional uranium mill currently operating in the United States. White Mesa uses sulfuric acid leaching to extract and recover uranium (as well as vanadium as a by-product). It is licensed to process and produce eight million pounds of U_3O_8 per year. *Source:* Google Earth.

In a 2007 statement before Congress, a senior representative of the Navajo Nation stated:

> Uranium mining and milling on and near the reservation has been a disaster for the Navajo people. The Department of the Interior has been in the pocket of the uranium industry, favoring its interests and breaching its trust duties to Navajo mineral owners. We are still undergoing what appears to be a never-ending federal experiment to see how much devastation can be endured by a people and a society from exposure to radiation in the air, in the water, in mines, and on the surface of the land. We are unwilling to be the subjects of that ongoing experiment any longer.[63]

Like the cleanup of abandoned mines, the remediation of processing (milling) facilities that dot the American West is extensive. For example, the 700-acre Uravan site in Montrose County, Colorado, began operating as a radium-recovery plant in 1912. From the early 1930s to the 1980s, the site was home to a uranium and vanadium processing facility. More than 10 million cubic yards of solid wastes containing radioactive elements, metals, and inorganic compounds were left at the site. Liquid wastes from seepage totaled more than 350 million gallons at the end of 2004. Contaminants included radioactive products such as raffinates (liquid wastes from the uranium processing operations), raffinate crystals (primarily ammonium sulfate compounds), and mill tailings containing uranium and radium. Other chemicals in the tailings and groundwater included heavy metals (lead, arsenic, cadmium, and vanadium), thorium, and residual salts. The EPA listed the site on Superfund's National Priorities List (NPL) in 1986.[64] Cleanup has taken decades, and the project is finally nearing closure. The extent of the cleanup is best described in an EPA Superfund document:

> Under the Consent Decree, Umetco [the owner] was required to complete the following general remedial activities as specified in the RAP [Remedial Action Plan], as amended:
>
> - Remove and clean up dispersed materials and contaminated soil from approximately 400 acres.

- Relocate more than 3 million cubic yards of mill wastes and contaminated materials to secure repositories on Club Mesa.
- Construct waste and tailing repository covers, liquid evaporation and retention ponds and permanent runoff control structures, utilizing more than 1.7 million cubic yards of earthen materials.
- Construct five double-lined ponds (totaling 40 acres) for the evaporation of hillside seepage, tailing pile seepage and extracted groundwater.
- Construct and use a new repository in the "B-Plant" area capable of disposing in excess of 1.8 million cubic yards of evaporative pond demolition debris and radioactive waste.
- Demolish and remove about 50 major mill facility structures and buildings, including the process systems and circuits, and remove over 260 buildings in the town of Uravan.
- Collect over 70 million gallons of hillside and tailing seepage, containing approximately 6,000 tons of contaminated inorganic compounds. Hillside and tailing seepage that was collected was transferred to Club Ranch Ponds for management by evaporation.
- Extract approximately 245 million gallons of contaminated liquids from the groundwater with the removal of approximately 14,500 tons of contaminated inorganic compounds. Contaminated groundwater that was collected was transferred to Club Ranch Ponds for management by evaporation.[65]

Noteworthy is the EPA's demand that 260 buildings be demolished because tailings were used as a construction material, a public health hazard in extremis.[66]

In sum, conventional mining and milling practices for military and civilian purposes left an extensive environmental legacy of radioactive and heavy metals pollution in the western United States and Canada. There have been several thorough assessments of this legacy, and we provide a short listing of some of the most useful in endnote 1.

III: IN-SITU LEACH MINING: THE ENVIRONMENTAL IMPACTS AND THE FAILURE OF THE NRC ENVIRONMENTAL REVIEW PROCESS

With the environmental and public health legacy of conventional uranium mining and milling in mind, it is critical to review the in-situ leach (ISL) mining process and examine: (1) whether current regulations are able to prevent the known harms of ISL mining and mitigate its other negative impacts; and (2) whether the environmental consequences of ISL uranium mining, particularly on ground aquifers, are sufficiently understood.

THE ISL URANIUM MINING PROCESS

In 1957 the mining industry began experimenting with ISL methods to recover uranium from low-grade ore in Wyoming. Early experimenting was simple: "They mixed up the sulfuric acid solution and just dumped it on the ground, and soaked it through the material and collected it in a little trench at the end."[67] With some technological advancement, the method proved successful at recovering lower-grade uranium ore at greater depths than was possible using traditional underground or pit mining.

Because ISL has been the generally cheaper way to mine moderate- to low-quality uranium deposits since the mid 1970s, developing new ISL mines has been preferred over developing new traditional surface mines and underground mines in the United States.[68] Of the new domestic uranium mines and expansion projects under consideration in the United States for the near term, the majority will be ISL. But even as domestic uranium recovery has moved away from conventional methods and toward ISL mining, worldwide there remains more conventional uranium mining.[69]

ISL combines the mining and milling processes by leaching uranium and other heavy metals off the surface of the host rock deep underground in the aquifer. The process, however, is used only when the source rocks (ore) meet certain conditions.

- The ore is too deep for traditional mining to be economical.
- The uranium is present in multilayered "roll front" deposits. Such deposits are formed when groundwater containing uranium moves through the subsurface (usually sandstone) and encounters an oxygen-deprived zone. When this occurs, the uranium is reduced from an oxidized state and precipitates out (along with other metals within the groundwater) to form a deposit that looks much like a crescent moon.[70]
- The ore body sits below the water table. Often, the aquifer that contains the deposits sits below an aquifer that is used as a source for domestic, industrial, and agricultural needs.[71]
- Considerable methane and hydrogen sulfide are associated with the ore.
- The ore is "low grade"—containing low amounts of uranium—and is too thin to be mined conventionally.
- The rock formation is highly permeable.[72]
- The deposit is thought to be confined above and below by more impermeable mudstone or shale.[73]

Uranium Roll Front

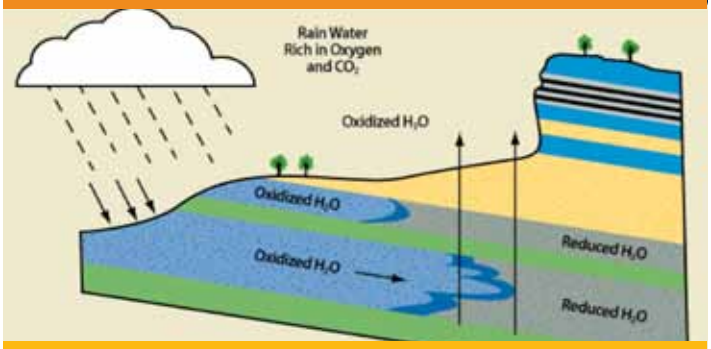


Figure 14: Schematic of the process by which uranium is deposited in roll-front ore bodies, as found in the Texas coastal plane. *Source:* Susan Combs, Texas Comptroller for Public Accounts, 2008.[74]

The ISL process involves drilling and operating hundreds of injection and production wells at each mining site. Mining the aquifer to recover uranium in this fashion changes the chemistry of the groundwater, with concentrations of uranium increased up to 100,000 times.[75] Levels of other naturally occurring radioactive elements and heavy metals are increased similarly.

The method extracts uranium by injecting a solution of water containing an acid or base solution (in the United States, this is a base that usually dissolved oxygen and sodium bicarbonate) into a uranium-bearing rock formation in an underground aquifer. This solution, or lixiviant, dissolves the uranium (and other heavy metals) from its host rock. Production wells, located between the injection wells, intercept the "pregnant" lixiviant and pump it to the surface. From there, the heavy-metal-rich liquid is piped to a centralized ion-exchange facility, which extracts the uranium. The "barren" lixiviant, stripped of uranium, is regenerated with oxygen and carbon dioxide and recirculated for continued leaching. The ion exchange resin, which becomes loaded with uranium, is stripped (or "eluted") of its uranium and returned to the well field facility. The resulting rich eluate is precipitated to produce yellowcake slurry. This slurry is dewatered and dried to a final drummed uranium concentrate, the raw material that, when converted to toxic uranium hexafluoride and heated to a gaseous state, is used as feed for the plants that enrich nuclear fuel. During the mining process, more water is produced from the ore-bearing formation than is reinjected. This net withdrawal, or "bleed," produces a cone of depression in the water table in the mining area and is intended to confine the fluid flow to the mining zone.

Notably, one environmental benefit of ISL mining over conventional forms of mining is the limited amount of solid waste. The EPA has identified ISL surface solid waste impacts as soils from site preparation; waste from drilling exploratory, injection, and production wells; and solids precipitated during the storage and processing of fluids in holding ponds.[76] The amounts can vary widely and are tied to the relative size of the ISL operation.

On the other hand, ISL operations contaminate the aquifer being mined, and the associated liquid waste is substantial. Well-field development (from the net withdrawal, or "bleed rate"), processing plant operations, and aquifer restoration activities all create liquid waste. By the industry's own estimate, an average ISL mine disposes at least 13 million gallons in deep-well injection.[77] However, the EPA, which has produced one of the few useful summaries of radionuclide data for ponds and injection wells, states that "[l]imited data are available on the volume of this material."[78] The NRC, as the primary regulator, has done little to rectify this paucity of data on the volumes of liquid wastes and their impacts.

The EPA is not alone in saying that the environmental impacts associated with ISL operations (such as the

Figure 15: Overview of a portion of Cameco's Crow Butte uranium in-situ leach facility in Dawes County, Nebraska. *Source:* Google Earth.

Figure 16: Aerial photo of the of processing plant (upper left) and two evaporation ponds (lower right) at Cameco's Crow Butte uranium in-situ leach facility in Dawes County, Nebraska. *Source:* Google Earth.

Figure 17: A portion of Uranium Resources Inc.'s Kingsville Dome in-situ leach facility in Kleberg County, Texas. *Source:* Google Earth.

Figure 18: A portion of Mestena Uranium's Alta Mesa in-situ leach facility in Brooks County, Texas. The processing plant is at lower left. *Source:* Google Earth.

restoration process, borehole cuttings, engineered ponds, deep-well injection of waste materials, and burial of solution flow lines) are poorly documented. International organizations are voicing similar concerns.[79] An extensive evaluation of these invasive activities and their effect, alone and in combination with other nearby resource-extraction activities, has not been undertaken by any of the government authorities that are charged with regulating the industry and protecting the interests of the environment and local communities. To highlight why this is important, later in this report we will explore some of the better-understood disruptions caused by ISL activity.

The visible footprint of ISL mining operations, as seen in the associated aerial photographs, illustrates the extent of industrial activity and the scale of potential aquifer contamination in the subsurface. Figures 15 and 16 display the infrastructure of ISL operations at Nebraska's Crow Butte site, including well fields, evaporation ponds, pump houses, and processing facilities. Figures 17 and 18 do the same for Texas's Kingsville Dome and Alta Mesa sites, respectively.

THE NRC'S ENVIRONMENTAL REVIEW PROCESS

As described in the previous section, ISL mining has environmental impacts that have yet to be thoroughly analyzed by the NRC, the agency charged with licensing the operations. In theory, the NRC is supposed to conduct formal and thorough evaluations of the environmental impacts of proposed ISL mining projects, in compliance with the National Environmental Policy Act (NEPA). In practice, however, the agency has failed to do so, in part because of a faulty regulatory structure. Nonetheless, the NRC is proceeding with licensing ISL operations.

HOW NEPA IS SUPPOSED TO WORK

NEPA serves to ensure that the federal government looks before it leaps prior to approving any project, whether that project is a federal highway, an offshore oil well, or an ISL uranium mine. Specifically, NEPA mandates a basic procedural framework—a public scoping to determine the range of agency activities and environmental impacts that should be included, followed by a draft environmental impact statement (EIS)—to help an agency in the decision-making process. To comply with NEPA, a draft EIS must set forth the purpose of and the need for a given project, take a hard look at environmental impacts, assess alternatives, examine mitigation measures, weigh the cumulative impacts of the project, and, finally, solicit and consider public comment on all these matters. Once that has been done, the agency revises its draft EIS in light of the comments received from

the public, state and local governments, and other federal agencies, and then issues a final EIS that includes formal responses to the comments received. Only then may the agency move forward with its preferred alternative, whatever that may be.

In most cases, citizens adversely affected by an agency's decision have the right to bring suit in federal court if they believe the legal requirements of NEPA have not been met by the agency. The process for challenging the environmental review documents from agencies such as the Department of the Interior or even the Department of Energy is relatively straightforward. Generally, an interested party comments on the draft EIS and awaits the government's response in its final document and associated "Response to Comments" portion of the EIS. If there are still points of substantial disagreement—for example, whether the agency considered a reasonable alternative course of action—the commenting party may move to file for judicial review in Federal district court.

HOW THE NUCLEAR REGULATORY COMMISSION'S ENVIRONMENTAL REVIEW WORKS

In contrast to this norm for most federal agencies, the NRC's process for challenging NEPA findings is much more convoluted and burdensome for members of the public. The industry applicant subject to regulation must file an environmental report (ER) that essentially acts as the rough draft for the NRC's draft EIS.[80] The ER submission is contemporaneous with the license application, which triggers a brief window of time in which the public must qualify as a "party" to the licensing proceeding in order to challenge the conclusions of an EIS that has not yet been issued. Thus, a legal challenge to the agency's compliance with NEPA can go forward only in the context of an individual licensing proceeding in which the plaintiffs have gained standing by having their "contentions" admitted into the proceeding by a "licensing board" made up of the NRC's own administrative law judges. Notably, the commencement of licensing proceedings for ISL mines, nuclear reactors, or enrichment facilities (at least in every instance NRDC has seen) long predates the issuance of a draft EIS associated with the project, often by a year or more.

How this works out in practical terms is remarkable. Consider the likely scenario of a member of the public who thinks an environmental analysis is legally inadequate and wants to take an agency to court. Generally speaking, within the framework of our legal system, the member of the public would simply file comments on the agency's EIS and then, if necessary, file a legal challenge once the agency finalizes the EIS and issues a Record of Decision based on it. In the NRC context, however, this person is out of luck, as the NRC holds that any environmental challenges arising under NEPA must be based on the precursor ER filed by the applicant. This is true even though the obligations imposed on the applicant are contained in NRC's regulations (10 C.F.R § 51) and not in NEPA's.

If the potential objecting person has not been admitted as an "intervenor" in the licensing hearing and filed timely comments on the industry's ER years before the arrival of the agency's NEPA documents, the NRC can choose to ignore those comments without meaningful opportunity for judicial redress. This denial of due process for ordinary citizens runs counter to bedrock NEPA law and is currently being challenged in the NRC's administrative court.[81]

Making the situation even more complex, the NRC contends that challenges to the impact statement are untimely if not filed shortly after the draft impact statement is issued and improper after the final EIS has been issued, unless the final impact statement contains positions not previously identifiable from the draft.[82]

A noted legal scholar on such matters, Anthony Roisman, succinctly describes how strange the process can become for the public:

> When the NRC Staff issues a draft impact statement under NEPA, contentions can be based on the draft only if it can be shown that they are based on information or conclusions that differ significantly from the information contained in the applicant's environmental report. However, a contention that challenges the applicant's environmental report because it does not comply with NEPA is rejected because an applicant cannot be required to comply with NEPA. So, how does a NEPA challenge become a contention if the staff merely parrots what the applicant has said in the environmental report? These multiple hurdles that interveners face are not merely annoying, they are resource intensive and sap the limited resources of interveners on procedural issues, making it less likely they will have resources to address the substantive issues. Because they are procedural hurdles, they also challenge the *pro se* intervener, without legal assistance, to meet every technical requirement, each of which is "strict by design," thus creating multiple opportunities for the applicant and NRC Staff to find a "flaw" in the intervener's pleading. This allows an applicant or NRC Staff to expose a procedural misstep, while avoiding a hearing on the substantive concerns that have motivated the public participation by the intervener.[83]

This is an untenable situation for interested members of the public. NEPA reviews are rendered superfluous except for how they relate to individual licensing proceedings, where members of the public can participate only at enormous cost in lawyers, technical experts, and time. One concrete effect of this regulatory structure is that NRC has managed to avoid assessing ISL uranium mining's environmental impacts, especially in the broader context of its occurrence in the iconic landscapes and arid natural habitats of the western United States.

HOW THE NUCLEAR REGULATORY COMMISSION'S GENERIC ENVIRONMENTAL IMPACT STATEMENT BECAME PROBLEMATIC

In 2007, facing new applications for ISL mines after years of regulatory inaction, the NRC began work on the *Generic Environmental Impact Statement for In-Situ Leach Uranium Milling Facilities* (hereinafter described as the GEIS).[84] The draft was completed in July 2008. It was followed in July 2009 by the final GEIS and several site-specific environmental analyses that incorporate the larger document's findings.

The final GEIS should have served as a thorough review of environmental impacts, assessing the hazards and benefits of ISL mining and providing reasonable alternatives. Unfortunately, it failed to accomplish these goals, even though it was prepared in order to comply with NEPA. NRDC and regional public interest organizations commented on the GEIS during its development, but our suggestions for a searching review that could inform better environmental decision-making were disregarded. One key example is the way NRC altered the stated purpose of the document as it transitioned from draft to final form.

Originally, the NRC intended to prepare a document that would "identify and evaluate the potential environmental impacts associated with construction, operation, aquifer restoration, and decommissioning of in-situ uranium recovery facilities."[85] NRDC and others filed extensive comments on this draft version and requested that the NRC, with its (comparatively) substantial federal resources, provide precisely the detailed history and thorough environmental assessment that had been lacking to date. When it became apparent that investigating, identifying, and evaluating alternatives to those environmental impacts was a sizable task, the agency issued a final GEIS that—while hardly differing in substance from the July 2008 draft—significantly restated and narrowed its purpose to avoid the detailed environmental evaluation it had originally promised. The NRC's stated purpose for the GEIS now reads:

> 10 CFR Part 51 regulations require evaluating the environmental impacts of the ISL facility as part of the licensing process. Recognizing that the technology for ISL uranium milling is relatively standardized, that the applications may be submitted over a relatively short period of time, and that the potential ISL facilities would be located in relatively discrete regions of the western United States, NRC decided to prepare a GEIS to avoid unnecessary duplicative efforts and to identify environmental issues of concern to focus on in site-specific environmental reviews. In this way, NRC could increase the efficiency and consistency in its site-specific environmental review of license applications for ISL facilities and so provide an option for applicants to use and licensees to continue to use the ISL process for uranium recovery.[86]

NRDC and others in the public interest community did not agree with this response. In short, the NRC effort devolved from identifying and evaluating the potential environmental impacts associated with ISL uranium mining to one where the agency sought to avoid duplicative reviews and thereby increase the efficiency of its NEPA reviews so that industry could "use the ISL process."

The few changes that were made from the draft to the final were almost wholly cosmetic. The final GEIS's "Response to Comments" section was devoted to the NEPA version of kicking the can down the road, stating repeatedly that a more thorough environmental review would be forthcoming in site-specific analyses. Sadly, those site-specific reviews have only produced documents that reference back to the original GEIS, cycling an interested reader back and forth between inadequate analyses.[87]

TECHNICAL ANALYSIS OF IN-SITU LEACH CONTAMINATION OF GROUNDWATER AQUIFERS

In order to improve our technical understanding of the impacts of ISL uranium mining and the NRC's failed EIS process on groundwater aquifers, NRDC worked with a University of Colorado hydrogeologist, Dr. Roseanna Neupauer, to do some preliminary analysis and modeling of groundwater flow at an ISL mine.[88] Dr. Neupauer chose to study the Christensen Ranch ISL site in Wyoming, basing her simulations and modeling on available data from the site's 1992 permit application and a pump test that was conducted in November of that year. She noted in her report that the Wyoming site was chosen for these simulations because of the availability of the pump test data in addition to the limited information available in the permit application. She also pointed out that the pump test data were confined to the southern portion of Mine Unit 2 at the Christensen Ranch, so she was able to make no claim as to whether the information was representative of the entirety of Mine Unit 2, much less the rest of the ISL site. Finally, Dr. Neupauer stated that "[s]ome of the necessary data were not available, so estimates were made using the best available data and the judgment of the modeler."[89]

What we learned from Dr. Neupauer buttressed our desire to ensure that the regulatory process for ISL mining be substantially improved. Specifically, she modeled ISL mining operations and then restoration operations including groundwater sweep, reverse osmosis, and recirculation, and predicted the groundwater and solute movement for an additional 20 years after completion of restoration. While we were somewhat comforted that her initial analysis in this one instance showed that the spread of contamination was likely to be relatively slow, her results indicate that contaminants will remain in the aquifer after all efforts at restoration and will migrate through the aquifer into the future.

Of even greater concern for us was the paucity of information available to Dr. Neupauer and, we assume, to the regulators. She noted that a comprehensive modeling exercise was impossible because of insufficient data on the spatial distribution of various chemical parameters or on

the chemistry of the injection solution used by the industry. After describing several limitations inherent in the study as a result of the scant data, Dr. Neupauer noted that "diffusion [of chemicals] out of the immobile region can occur over many years or decades; thus even if the water in the mobile zone appears clean, it may become contaminated over time by this diffusive process. This process was not modeled in these simulations, but it would further increase the concentration of lixiviant in the post-restoration aquifer."[90]

As we detail later in this report, Dr. Neupauer's experience is consistent with that of experts at the USGS and elsewhere. The ability to accurately assess the long-term environmental and public health impacts of ISL mining will depend on both a thorough catalog of past aquifer impacts and the ability of regulatory agencies to obtain comprehensive and publicly transparent data on groundwater quality and the geologic properties of the aquifer *before* the permitting stage. Currently, the public documents available to Dr. Neupauer, the USGS, and any member of the public are insufficient to perform anything more than a limited analysis.

THE IN-SITU LEACH URANIUM MINING PROCESS AND ITS ENVIRONMENTAL IMPACTS

As described in Chapter 1, the ISL process involves drilling and operating hundreds of injection and production wells at each mining site. Mining the aquifer to recover uranium in this fashion changes the chemistry of the groundwater, increasing concentrations of uranium significantly.[91] Levels of other naturally occurring radioactive elements and heavy metals are increased similarly. These environmental impacts are detailed in the pages that follow.

1. In-Situ Leach Mining Alters Groundwater Chemistry

All stages of ISL mining impact surrounding water quality because the process invades ore deposits and fundamentally alters groundwater chemistry. The NRC itself acknowledges these effects in its regulatory guidance, discussed in Chapter 4.[92] While the injected solution—generally a base in U.S. mines rather than an acid—may be composed of relatively benign chemicals, its leaching results in significantly polluted aquifers by oxidizing and freeing heavy metals that were once locked and immobile in host rock.

Chemical reactions take place between the solution and the host rock at the time of injection. Contaminants that escape from the site during injection, as well as contaminants that migrate naturally after mining has stopped, change water quality.[93] The consequences from injection alone are serious. Due to the change in the aquifer's ability to produce "reducing" conditions during mining, post-mining water quality within the deposit will be substantially different from what it was before mining.[94] Altering groundwater chemistry has significant short- and long-term impacts and merits a searching analysis for the reasons discussed in the following sections.

2. In-Situ Leach Mining Causes Repeated "Spills, Leaks, and Excursions" of Contaminants

Aboveground spills and belowground excursions of lixiviant can have serious impacts on both surface and groundwater quality. These occur with some regularity at ISL operations, but more complete information is necessary to understand the extent of the environmental harm. Thus far, the NRC has failed to conduct a full environmental analysis of ISL uranium mining, including a comprehensive review of the problem of spills, excursions, and leaks.

While spills can cause environmental harm, they are generally aboveground; consequently they can be visually monitored and are physically easier to address. Underground excursions are more problematic and are of two kinds: vertical and horizontal. Vertical excursions occur as lixiviant migrates through an improperly sealed well or an incomplete confining layer of an aquifer; horizontal (or lateral) excursions occur when injection and extraction pumping rates are imbalanced and the lixiviant has momentum to disperse.[95] Monitoring wells set around the injection wells can detect the slow leaching of foreign, oxidizing liquid into the balanced natural chemistry of the groundwater. Such detection serves to identify excursions but triggers only after-the-fact actions.

Excursions and leaks have been serious ongoing problems for many ISL facilities. In issuing a 2007 Notice of Violation to the Cameco Corporation's Smith Ranch-Highland ISL mine, the state of Wyoming noted:

> ***Over the years there have been an inordinate number of spills, leaks and other releases at this operation. Some 80 spills have been reported, in addition to numerous pond leaks, well casing failures and excursions. Unfortunately, it appears that such occurrences have become routine. The LQD [Land Quality Division] currently has two large three-ring binders full of spill reports from the Smith Ranch-Highland operations.[96]***

When commenting on the NRC's draft GEIS, NRDC requested that the NRC provide a list of all excursions reported, with the licensee's explanation of the excursion and the regulatory response. This simple but important information was not provided in the final GEIS. The NRC noted curtly that it had merely written a "historical overview" of excursions in Wyoming and Nebraska and claimed that any excursions in the Agreement States, such as Texas, were outside the scope of the agency's review.[97]

Whether the information on ISL mine performance came from Agreement States or states where the NRC directly regulated mining operations was beside the point. If a federal agency is performing what is ostensibly a national review of the environmental impact of ISL uranium mining, then collecting all pertinent data on ISL operations is within the comparatively well-financed capacity of the NRC.

The regulations that purport to govern such matters are also lacking. While the NRC has established guidelines (as opposed to regulations) for wells that might monitor the contaminated aquifers of ISL mines, there are no explicit regulatory standards at the federal level for monitoring wells. Theoretically, monitoring wells should be placed close enough to the well field to ensure quick detection of contamination, but far enough away so that false alarms are minimized.[98] According to NRC guidance, monitoring wells should be 250 to 500 feet from the well field and be spaced some 400 feet apart. Whether this guidance is adequate is not clear. The multiple violations cited by Wyoming at the Smith Ranch-Highland ISL mine suggest that it is not. Early detection of excursions may depend on a number of factors, including the thickness of the aquifer monitored, the distance between the monitor wells and the well field and the spacing of monitor wells, the frequency of monitor-well sampling, the water-quality parameters being sampled, and the concentrations of the parameters chosen to signal an excursion.[99]

As we noted, the original intent of the NRC's GEIS was to "identify and evaluate the potential environmental impacts associated with construction, operation, aquifer restoration, and decommissioning of in-situ uranium recovery facilities."[100] The NRC has neither catalogued nor assessed the environmental harm from spills, leaks, and excursions at ISL facilities, stating that a more thorough environmental review would be forthcoming in site-specific analyses and that the "monitoring and reporting requirements" would be tailored to individual facilities "on a case-by-case basis." This response provides no meaningful evaluation of the environmental impact at existing ISL sites. Given this history, the NRC's pledge to address these "details" on a case-by-case basis at each new mine site, without reference to a comprehensive understanding of what has already occurred at existing ISL operations, raises doubts as to the NRC's commitment to fulfilling its public health and safety mandate.

3. In-Situ Leach Mining Uses Scarce Groundwater

ISL mining uses significant amounts of groundwater, both during the mining process and throughout the restoration period. The NRC's GEIS document did not offer a detailed historical analysis of water use at varying ISL sites; rather, it presented a hypothetical scenario for consumptive use (that is, the amount of water not returned to the production aquifer) based on NRC licensed flow rates for ISL facilities that range from about 15,100 to 34,000 liters per minute [4,000 to 9,000 gallons per minute].[101] The NRC's assertion is that most of this water will be returned to the contaminated aquifer during operations. NRC goes on to acknowledge that groundwater consumptive use is generally reported to be greater during aquifer restoration than during mining operations.[102] This is true because in the restoration phase of "groundwater sweep," contaminated water is drained from the aquifer and not reinjected, so that uncontaminated water will be drawn into the aquifer.[103] The NRC discussed operations at Wyoming's Irigaray Ranch mine, where 545 million gallons of water was removed from nine well fields where groundwater sweep was performed.[104]

Concluding that the groundwater consumptive-use impact from ISL operations and restoration will be small to moderate, the NRC suggests a hypothetical facility in various stages of operation and restoration at individual well fields. The agency posits that "consumption of 280 million L [74 million gallons, or 230 acre-feet] in 1 year of restoration would be roughly equivalent to the water used to irrigate 29 hectares [72 acres] in New Mexico for one year. Potential environmental impacts are affected by the restoration techniques chosen, the severity and extent of contamination, and the current and future use of the production and surrounding aquifers in the vicinity of the ISL facility or at the regional scale."[105]

We could find only limited information on the matter. As discussed later in this chapter, in light of the fact that contamination is significant at every ISL mined aquifer, and that restoration has almost always continued far beyond what was originally planned, NRDC suggests that the NRC refine its analysis, thoroughly compiling the historical record of groundwater use at ISL sites to inform any hypothetical scenarios. NRDC's collaborators have noted the same paucity of information. In an ongoing ISL licensing proceeding in South Dakota, an expert for the Oglala Sioux tribe noted in a filing that there was great uncertainty in the ISL mining applicant's estimates of water use, such that it was impossible for the regulator, and certainly the public, to meaningfully evaluate the environmental impact. Using the industry's own figures from the license application, the expert noted a potential range of nearly 600 million gallons to almost 3 billion gallons over the proposed 17-year life of the project.[106] The expert went on to note:

> These inconsistencies [in estimates of water use] need to be rectified to enable effective public and NRC staff review. Clearly, both of these estimates indicate that vast quantities of groundwater will be extracted from these aquifers over the long term, and it seems overly optimistic to simply state that no significant impacts will occur. At a minimum, Powertech should be required to construct a credible, project water balance and to more seriously investigate the potential that such large-volume water use might impact local/regional groundwater levels. At present, I see no evidence that the Application contains a reliable compilation of baseline water level data for the surrounding domestic and agricultural wells (see discussion below). Without such reliable, summarized data, there will be no viable method to demonstrate that groundwater levels (and related pumping costs) have not been impacted by project-related activities.[107]

Throughout the western United States, water scarcity is a major concern. Increased groundwater withdrawals in the West come with economic, environmental, and social consequences, and the population of the West continues to increase.[108] In many cases, water resources have already been overallocated in high-population areas, and many communities are unsustainably drawing upon groundwater from storage.[109]

Alpine snowpack and ice bring water and life to the West, an area known for drought and low precipitation. The melting snowpack of the western mountain ranges delivers freshwater to rivers that provide the region with as much as 75 percent of its water supply.[110] In addition to current scarcity problems, climate change threatens to reshape the supply and quality of available water. Rising temperatures are predicted to reduce alpine snowpack, cause earlier and larger peak stream flows, potentially reduce total stream flows, create greater evaporation losses, degrade ecosystem health, cause sea level rise and more extreme weather events, and lead to hotter, drier summers.[111] The past decade's most significant international assessment of life in a carbon-constrained future pointed out that the evidence overwhelmingly indicates that greenhouse warming will alter the supply of and demand for water, the quality of water, and the health and functioning of aquatic ecosystems.[112]

An analysis performed in 2010 by the consulting firm Tetra Tech for NRDC examined the effects of global warming on water supply and demand in the contiguous United States. The study found that more than 1,100 counties—one-third of all counties in the lower 48 states—will face higher risks of water shortages by midcentury as the result of global warming, and more than 400 of these counties will face extremely high risks of water shortages.[113] This analysis developed a new Water Supply Sustainability Index based on the following criteria: projected water demand, groundwater use, susceptibility to drought, projected increase in freshwater withdrawals, and projected increase in summer water deficit.[114] Tetra Tech classified the risk to water sustainability for counties meeting two of these criteria as "moderate," counties meeting three criteria were classified as "high," and those meeting four or more were classified as "extreme." Counties meeting less than two criteria were considered by Tetra Tech to have low risk to water sustainability.

Table 4 lists the counties with operating, planned, or potential ISL sites from the NRDC ISL Mine Database, the total number of ISL sites within the county, and the calculated risk to water sustainability. A total of 40 ISL sites fall within counties for which an extreme risk to water sustainability is predicted, and an additional 22 ISL sites fall within counties for which a high risk is predicted. Figure 19 shows point locations for operational, planned, and proposed ISL facilities from the NRDC database superimposed on the Tetra Tech Water Supply Sustainability Index for 2050, including the impacts of climate change. In general, more than two-thirds of current or future ISL mining sites fall within counties for which moderate or greater risks to water sustainability are predicted for 2050, taking into account the impacts of climate change.

Facing these complex circumstances, water managers have a challenging task ahead of them. Policymakers in each state must evaluate their resources and water allocations to ensure reliable overall supplies, anticipate future growth, and safeguard their economies during times of drought. The state of Texas issued a report in 2009 highlighting the cost of water scarcity. Among its findings was that "each of the several one- or two-year droughts in Texas in the past decade has cost agricultural producers and businesses impacted by them between $1 billion and $4 billion annually."[115] And although roughly 20 million acre-feet of water are permitted for consumption annually, the report estimated that in 2010 there would be only around 13.3 million acre-feet of total surface water on hand during times of drought. By 2060 this will lead to inadequate water supplies for an estimated 85 percent of the Texas population.[116] The area of south Texas that has recently suffered severe drought substantially overlaps the state's existing and likely ISL uranium mining areas.

Water scarcity issues alone should cause governments and communities to rethink whether uranium development and other water-intensive natural resource extraction techniques (such as coal-bed methane recovery and fracking of shale-gas deposits) represent a wise course of action. The tradeoff between resource extraction and groundwater protection is only one of several complicated issues that face state resource professionals. With respect to groundwater scarcity, the crucial point is that even if there is a period of significant growth in the market for uranium, ISL uranium mining will

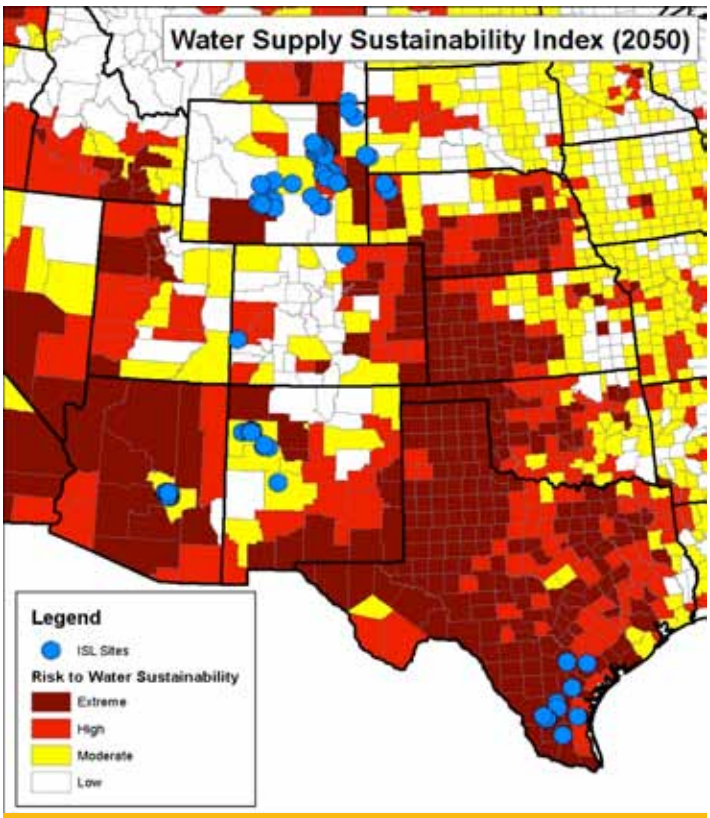


Figure 19: NRDC in-situ leach Mine Database overlaid on a map of risk to water sustainability in the year 2050, taking into account the impacts of climate change.

Table 4: Summary data for in-situ leach sites within counties and the predicted risk to water sustainability from the effects of climate change.		
Location	**Number of Operational, Planned, or Potential In-Situ Leach Sites**	**Risk to Water Sustainabiilty in 2050 With Impacts of Climate Change**
Brooks County, Texas	1	Extreme
Campbell County, Wyoming	18	Extreme
Duval County, Texas	6	Extreme
Goliad County, Texas	1	Extreme
Karnes County, Texas	1	Extreme
Kleberg County, Texas	1	Extreme
Live Oak County, Texas	1	Extreme
Sweetwater County, Wyoming	9	Extreme
Webb County, Texas	2	Extreme
Total In-Situ Leach Sites in Counties With Extreme Water Scarcity Predictions for 2050: 40		
Converse County, Wyoming	13	High
Dawes County, Nebraska	6	High
Montrose County, Colorado	1	High
Weld County, Colorado	2	High
Total In-Situ Leach Sites in Counties With High Water Scarcity Predictions for 2050: 22		
Cibola County, New Mexico	2	Moderate
Fall River County, South Dakota	1	Moderate
Gila County, Arizona	9	Moderate
McKinley County, New Mexico	7	Moderate
Natrona County, Wyoming	1	Moderate
Socorro County, New Mexico	1	Moderate
Weston County, Wyoming	1	Moderate
Total In-Situ Leach Sites in Counties With Moderate Water Scarcity Predictions for 2050: 22		
Albany County, Wyoming	2	Low
Carbon County, Wyoming	1	Low
Carter County, Montana	1	Low
Crook County, Wyoming	2	Low
Fremont County, Wyoming	4	Low
Johnson County, Wyoming	6	Low
Total In-Situ Leach Sites in Counties With Low Water Scarcity Predictions for 2050: 16		

constitute only a minor fraction of the uranium resources used in the United States, much less the rest of the world. It makes no sense to contaminate scarce western groundwater and harm iconic western landscapes for uranium production that amounts to a small fraction of global uranium output and U.S. consumption, and that does not fundamentally alter U.S. dependence on foreign sources of uranium. Even if a much higher degree of U.S. uranium self-sufficiency were, in principle, achievable economically, one would still want to weigh the environmental costs, especially the critical alternative uses for all the groundwater resources that would be impaired by stepped-up ISL mining activity.

4. In-Situ Leach Mining Creates Waste

In addition to using scarce groundwater and altering the delicate geochemistry of aquifers, ISL mining is a source of waste. The NRC's GEIS provides one estimate of solid-waste volumes from the decommissioning and reclamation of ISL mines, and another of the more substantial liquid wastes, but the agency decided to forgo the detailed data collection and analysis of historical ISL sites that could have provided valuable insights.[117,118] The EPA, in its 2008 review of uranium recovery, stated that it did not have sufficient data to estimate the amount of solid and liquid wastes generated by previous and currently operating mines.[119]

The solid waste generated from ISL uranium mining is composed largely of soil and bedrock from ground-level site preparation and construction. Excavating these materials exposes them to the wind and rain. Solid waste also accumulates from drilling injection and production wells and from the radioactive solids that precipitate out of leachate solution during processing and storage in holding ponds. These wastes are placed into pits and buried during reclamation. The solids that accumulate at the bottom of these pits can be "slightly" radioactive.[120] The leachate solution that mine operators inject into the ground to recover uranium also recovers some radium. The exact amount is unknown.[121]

Liquid radioactive waste from ISL mining, a more serious matter simply because of its greater volume, is generated from well fields, processing plants, and aquifer restoration. ISL operators typically collect radioactive sludge in evaporation ponds that have liners to prevent leaching into the ground, or inject the wastewater into disposal wells deep underground. As with solid waste, the EPA reports that only limited data are available on the volume of this material. The issue merits additional study. [122]

For example, a well-known and far-reaching environmental consequence of ISL uranium mining is the chemical by-product selenium, which is liberated from the rock formation during ISL mining. One U.S. Fish & Wildlife Service study looked directly at the question of wastewater from an ISL operation in Wyoming. The report notes that "the effects of selenium on fish and aquatic migratory birds have been well documented. Selenium concentrations greater than 2 µg/L in water are known to impair water bird reproduction and survival due to the high potential for dietary toxicity through food chain bioaccumulation."[123] Increased amounts of selenium in the soil and water have had documented adverse effects on wildlife in ISL mining areas.[124] The combination of wastewater and the tendency for spills to occur—even small ones that are quickly contained—can have a cumulative negative impact on the environment.[125]

5. In-Situ Leach Mining Contaminates Aquifers

At the heart of ISL mining's environmental impact is the enduring alteration and degradation of the aquifer in which the mining has taken place. Although uranium mine operators are required to remediate the contaminated water once mining is finished, a complete cleanup of the subsurface contamination back to original pre-mining (or baseline) conditions has never been accomplished.[126] The specifics of the legal requirements (or lack thereof) will be discussed in some detail in the regulatory section to follow, but neither the industry nor the regulators have responded effectively to repeated failures to restore groundwater.

The NRC evades responsibility for weak cleanup standards at ISL sites by stating that it has not "to date" granted an "alternative concentration limit" (ACL) to an operational ISL facility.[127] The NRC's response avoids the obvious fact

Figure 20: Aerial photo of the Highland Ranch project, showing ISL well complexes (lower left), a purge storage reservoir (center), and a pivot irrigation field (top) where in-situ leach leaching solutions are disposed of through irrigation after treatment. The U.S. Fish & Wildlife Service has documented the bioaccumulation of radioactive selenium in the food chain within in-situ leach pivot irrigation fields. *Source:* Ramirez and Rogers, *Selenium in a Wyoming Grassland Community Receiving Wastewater From an In Situ Uranium Mine.*

that the agency has ceded authority to several states—Texas, Wyoming, Nebraska—and at every other ISL mine we could locate, it has allowed more contaminants to be left in the aquifer when restoration failed. As will be detailed, this occurred even after efforts at restoration substantially exceeded initial estimates and license requirements. Call the weakened standard an ACL, a variance, or any other name. The result is the same: a contaminated aquifer where restoration efforts failed. The NRC admits that in its short study of 11 restorations at three ISL facilities in Wyoming and Nebraska, "data show that over 60 percent of the constituents were restored to their preoperational concentrations."[128] Of course, this also means that about 40 percent of measured constituents were *not* restored to baseline conditions and that concessions to the licensee were made. The NRC's short study and its more extensive GEIS discussed throughout this paper have failed to thoroughly investigate the potential harms of this incomplete restoration of contaminated groundwater.

The industry's response to the failure of groundwater restoration relies on the blessing of the regulators. One license applicant pointed out that "there have been no *significant*, adverse impacts to adjacent, non-exempt USDWs [underground sources of drinking water] *outside* the recovery zone and into the related area of review (AOR) from ISL operations *in the United States* [emphasis added]."[129] This statement is both an acknowledgement and a claim. It is a tacit acknowledgement that the mined aquifer—which received an SDWA exemption from either the state or the EPA—was not restored, and the terms of the license requiring restoration to background were not met. The response then claims that no drinking water aquifers have suffered significant adverse impacts beyond the "recovery zone" (itself more extensive than the mined area) within the required "area of review." Note that the statement avoids the question of what constitutes "significant" adverse impacts, and further qualifies the assurance by limiting it to ISL operations "in the United States," when in reality the largest ISL operations are located overseas.

Fundamentally, we don't know enough about the extent or significance of the adverse impacts of ISL mining on adjacent drinking waters, as the NRC's final GEIS did not undertake an analysis. No entity has conducted a thorough regulatory assessment to investigate the current state of aquifers in proximity to ISL operations. In contrast, we *do* know that the mined aquifers are contaminated.

Once exempted from the protections of the SDWA, and with an NRC (or Agreement State) materials license in hand, the ISL industry seems sure to produce aquifers that cannot be used as sources of drinking water for generations. Considering the existing and impending threats of water scarcity and the certainty of contamination, the situation warrants a more protective approach that grants aquifer exemptions to mining operators only in rare instances. The next section of this chapter discusses this in greater detail.

LIMITED REVIEW OF IN-SITU LEACH SITES ILLUSTRATES THAT GROUNDWATER HAS NOT BEEN RESTORED

Despite repeated requests from NRDC and others, the NRC has yet to conduct the thorough analysis of ISL groundwater restoration and results that we believe is necessary to continue licensing new mines.[130] NRDC believes it is crucial that a detailed cataloguing of ISL restoration history take place so that informed decisions can be made regarding the efficacy of current techniques and adequacy of relevant standards. In public hearings before the NRC commissioners, NRDC urged the agency to examine and present to the public a history of ISL uranium mining operations that showed groundwater conditions before and after mining. Furthermore, NRDC believes that the NRC should provide:

(1) A complete listing of all mines where baseline and relevant pollution standards— called maximum contaminant level (MCL) standards—were not met.

(2) A complete listing of all mines—regulated either by the NRC or by an Agreement State—where alternative concentration limits (ACLs), or any otherwise-named variance or relaxation of original standards, were used.

(3) Thorough analysis of the post-closure monitoring of all ISL mines in all states, including an assessment of the current state of contamination and ongoing restoration.

(4) Thorough analysis of the short- and long-term environmental impacts that have resulted from the applications of the current regulatory regime, performed in conjunction with other federal and state regulators. Until NRC addresses this most fundamental issue, it cannot properly assess the impact ISL mines have on the environment, and without proper assessment of such impacts, NRC should not be issuing ISL uranium mining licenses.

Moreover, in light of the historical record of human and environmental harm from uranium mining and the agency's statutory charge to protect the public from radiological and other nuclear fuel cycle hazards, we urge the NRC to work quickly to improve and strengthen what are currently inadequate regulations.

NRDC has neither the resources nor the staff to conduct a comprehensive assessment. As explained in Chapter 2, NRDC and the Southwest Research and Information Center (SRIC) extracted as much public data about the impact of ISL mining from NRC and state records as was readily available to both organizations. Though not comprehensive, the effort is consistent with the limited studies done by other entities.

In sum, NRDC and SRIC did not find a single ISL operation where an aquifer was restored to its pre-mining state for all contaminants. Keeping in mind NRC's assertion that "to date" it has not granted an alternative concentration limit to an operational ISL facility, we found several examples similar to this one for the Benavides and Longoria ISL projects in Texas:

"Division of Environmental Programs have reviewed the letter dated 5/12/87 from the Texas Water Commission (TWC), enclosing a request from URI for increasing the uranium value in the restoration table for the Longoria production area No. 1 aquifer to 3.0 mg/l. The earlier uranium value was 2.0 mg/l (see memo dated 5/4/87), which itself was a revision from the baseline value of 0.047 mg/l. The new uranium value is more realistic in terms of achievability in comparison with TWC approved levels for other restoration parameters. No federal drinking water limits exist for uranium."[131]

The NRC may not have granted that particular relaxation of the standard, but Texas is an Agreement State and may not operate outside of the bounds that NRC regulations prescribe.[132] The Texas document is not an anomaly, but it was difficult to locate data on ISL restoration as it has yet to be collected by federal agencies. Combing through the NRC website and other public records, however, one can begin to construct a picture.

We found that mines in Nebraska have not been any more successful at aquifer restoration than those in Texas. Presenting the specific numbers for clarity's sake, at the Crow Butte Uranium Project, the baseline (the pre-mining water quality) for uranium was set at 0.092 mg/l. However, in 1999, during the stabilization period after restoration ceased (and this is one of the relatively few times we found stabilization data), concentrations of uranium ranged from 1.09 to 2.33 mg/l.[133] In 2002, the values ranged between 1.6 and 1.8 mg/l. Despite a demonstrated failure to restore groundwater quality to baseline conditions, NRC accepted the restoration plan.[134]

The relaxing of standards is not an exception limited to a few states. The common practice for the NRC or the Agreement State to deem an aquifer "restored" despite severely elevated concentrations of uranium, radium-226, selenium, and other harmful constituents continued at the Smith Ranch–Highland Uranium Project in Wyoming. There, the baseline for selenium was originally set at 0.001 mg/l; after restoration, the selenium concentration was 0.070 mg/L. Radium was 675 pCi/L at baseline and 1,153 pCi/L after restoration. Uranium was 0.05 mg/l at baseline and 3.53 mg/l after restoration.[135] Power Resources, Inc. failed to come anywhere close to meeting baseline conditions, yet the aquifer was labeled "restored."[136]

At the Irigaray mine, also in Wyoming, the NRC and the Wyoming Department of Environmental Quality allowed licensee COGEMA to restore groundwater to baseline "class of use" when COGEMA failed to restore the actual baseline conditions.[137] The NRC's technical report on the restoration stated that "when comparing pre-mining baseline ranges to post-mining stabilization ranges, several constituents did not meet primary restoration targets. When comparing the post-mining stabilization means for constituents in production units 1 through 9 in round 4 to pre-mining baseline means in production units 1 through 9, *nearly half of the constituents exceed the mean values.*"[138] At COGEMA's nearby Christensen Ranch project, groundwater concentrations of selenium, uranium, and radium-226 (as well as iron, manganese, and total dissolved solids) all exceeded target restoration values and applicable state or federal standards, even after COGEMA claimed to have "completed aquifer restoration."[139]

FEDERAL REVIEWS ARE CONSISTENT WITH THE NATURAL RESOURCES DEFENSE COUNCIL'S CONCLUSION

Our finding that groundwater has not been restored at ISL operations is consistent with the NRC's acknowledgment that some 40 percent of measured constituents could not be restored to baseline conditions and that concessions were made to the licensee on several parameters.[140]

Our review is also consistent with one done by the USGS. In 2008 the agency conducted a study of groundwater restoration at ISL mines in Texas, which has a history of not requiring restoration of contaminated groundwater to pre-mining conditions.[141] Additionally, Texas's recordkeeping is poor. The state's ISL restoration data are, according to USGS, "poorly organized and difficult to search," and much of the information is simply missing.[142] Where records were available to the USGS, they paint a bleak picture. Of 36 uranium mining sites authorized by Texas, 27 were actually developed, resulting in the construction of 77 well fields.[143] Baseline and amended restoration values are available for all 27 developed ISL sites. However, "final value" records are available for only 22 of the 77 well fields (representing just 13 of the 36 mines).[144] And of those mines for which records were available, "no well field… returned every element to baseline."[145]

A typical example occurred at the Zamzow well field, where the baseline for uranium was set at 0.171 mg/L.[146] The term *baseline* is actually a misnomer in that it does not refer to what we suspect is the real pre-mining baseline concentration of constituents in groundwater over the entirety of the aquifer. This suspicion is based on the USGS's reporting. As the USGS describes the process, "restoration values are initially set as baseline, with operators selecting the highest average concentration from either the production or mine area as their restoration goal."[147] We presume this means that instead of having to establish a baseline water quality for the whole project area and inclusive of a wide

swath of the affected aquifer, the applicant can select a baseline from the immediate production area of the ore-bearing portion of the aquifer, allowing for an inflated standard. And under this standard, the Texas Commission on Environmental Quality Underground Injection Control program later granted Zamzow an amended limit of 3.00 mg/L., 17.5 times as high as the pre-mining "baseline" value.[148] NRDC has no data on the final value achieved at Zamzow.

According to the USGS, Texas is not applying clear standards. The USGS states that "there is no clear relationship between the final value achieved for uranium in groundwater at the [well fields], and the amended restoration goals. Amended restoration goals do not reflect the degree of restoration achieved at the [well fields] in Texas for which final values were available."[149] Nor, we would add, is there adequate objective evidence that either the original or amended restoration goals are an accurate reflection of the area's pre-mining water quality, or are themselves sufficiently protective of present and future groundwater uses.

PRIVATE REVIEWS IN TEXAS ARE CONSISTENT WITH THE LIMITED REVIEWS CONDUCTED BY FEDERAL AGENCIES

Another study on aquifer restoration in Texas, conducted by Southwest Groundwater Consulting in 2008, found that ISL mining operations were consistently unable to meet original restoration standards and routinely granted amended standards that were far more lenient.[150] The study examined the concentration of uranium and radium-226 (as well as arsenic and sulfate) at the following Texas mines: Benavides 1, Benavides 2, Benavides 3, Benavides 4, Brelum 1, Brelum 2, Bruni 1, Bruni 6, El Mesquite, Longoria 1, Longoria 2, O'Hern, and Rosita.[151] In all cases, Texas granted the industry license-holder amended (and weakened) restoration values for an aquifer that remained contaminated. In all but two cases, the last sampled concentration of uranium exceeded both the original restoration value and the amended restoration value.[152] In all cases, the last sampled concentration of radium-226 exceeded both the original restoration value and the amended restoration value.[153]

In short, with Texas as a prime example, ISL uranium mining has no enforceable or meaningful standards for establishing pre-mining water quality and ensuring groundwater restoration. According to the limited data set available for review, the regulator allows licensees to set artificially inflated baselines as a target for restoration. The regulator then relaxes that standard by routinely allowing the licensee to amend its target to a much higher concentration level. Licensees then fail, in 100 percent of cases, to meet even that relaxed standard for key parameters, again foreclosing meaningful future use of the aquifer.

DETAILED ANALYSIS OF IN-SITU LEACH URANIUM MINING'S ENVIRONMENTAL IMPACTS IS NEEDED

Countering the suggestions and pressure from public interest groups to conduct a searching NEPA analysis, uranium and mining industry advocates assert that ISL mining is an "environmentally benign" practice.[154] NRDC's review—a preliminary effort done in part to fill in the analysis left vacant by the NRC's final GEIS—indicates that ISL mining degrades the groundwater systems where the mining takes place and does so in a region already suffering from environmental harm inflicted by the extraction of oil, gas, coal-bed methane, and other resources. As yet, there has been no comprehensive review of ISL industry practices or assessment of potential options for lessening or remediating its environmental harm. Such a detailed, technical review is beyond the capacities of a single NGO, but it is hoped that this paper can spur the long-overdue interagency assessment necessary to ensure that the uranium mining industry does not repeat the mistakes of the past.[155,156]

IV. THE REGULATORY PREDICAMENT

As Chapters 2 and 3 make clear, the regulatory system for uranium ISL mining is inadequate. Industry notes that under the current system, it must obtain multiple permits from different regulatory authorities—the NRC, the EPA, state environment departments, and state engineers—but on a practical level, the paper burden is not nearly as heavy as industry suggests. Examining documents in the ongoing Dewey Burdock ISL application in South Dakota, it is apparent that industry submitted many of the same documents to the state or the EPA for the operation's Underground Injection Control application as it did for its NRC materials license. More important than the question of the paperwork burden on the industry is whether the regulatory scheme is failing to protect human health and the environment and overdue for revision.

REGULATING URANIUM RECOVERY—THE DIVISION OF AUTHORITY

The current regulatory system, which manages to be complicated and dysfunctional at the same time, presents a picture that appears restrictive but fundamentally is not. The system needs to be reformed before additional ISL mines are licensed.

THE INITIAL STATUTORY CONTROLS—1978'S URANIUM MILL TAILINGS RADIATION CONTROL ACT

As discussed earlier in this report, the first imposition of any environmental control on conventional uranium recovery came with the Uranium Mill Tailings Radiation Control Act (UMTRCA). UMTRCA is divided into two titles. Title I addresses mill sites that were abandoned by 1978. The EPA was directed to promulgate radiation and hazardous waste standards for remediation, and DOE was to perform the cleanup of abandoned tailings sites (25 former AEA sites) subject to NRC licensing.[157] Title II focuses on uranium milling facilities operating after 1978. It established the framework for NRC and Agreement States to regulate mill tailings and other wastes at mills licensed by the NRC at the time of UMTRCA's passage, and to adopt the subsequent standards set by the EPA.[158] To insure the long-term stabilization and maintenance of the mill sites and to pass on industry's costs, ownership of the tailings passes to an agency of the federal government—such as the DOE—or the state after a mill is decommissioned. To date, no state has become a perpetual custodian of a uranium mill site. As noted above, this law and the subsequent regulations issued by the NRC and the EPA have never specifically addressed ISL mining operations.

IN-SITU LEACH MINING REGULATION: NRC STATUTORY AUTHORITY

Under its AEA authority (Chapters 7 and 8 of the AEA, "Source Material" and "Byproduct Material," respectively), the NRC regulates uranium recovery when it involves conventional milling (concentration) of uranium ore or ISL mining under its regulations for Domestic Licensing of Source Material.[159] Despite a growing use of the ISL technique over the past two decades (and the past few years in particular), the NRC has not altered its source material licensing regulations to account for the impacts of ISL mining.

Rather than promulgate new rules that would address ISL mining, the NRC has used its 10 CFR Part 40 rules (meant for mill tailings) and agency guidance and specific license conditions to regulate ISL mining in an ad hoc fashion.

IN-SITU LEACH MINING REGULATION: EPA STATUTORY AUTHORITY

Under UMTRCA, the EPA has the responsibility to establish standards for public exposure to radioactive materials originating from mill tailings, and cleanup and control standards for inactive uranium tailings sites and operating sites. The EPA's regulations in 40 CFR 192 apply to remediation of such properties and address emissions of radon, as well as allowable concentrations of radionuclides, metals, and other contaminants in surface water and groundwater.[160]

Despite the ability to do so under 40 CFR 192, the EPA has yet to establish radiation protection or other standards specific to ISL mining. Fortunately, EPA commenced an effort to draft such revised rules in 2009, and we understand the agency is now formulating specific groundwater protection rules for ISL operations. A draft rule is expected early in 2012.

Currently, however, since the UMTRCA regulations have yet to address ISL mining, the EPA's chief involvement with ISL mining has been through its SDWA authority and its Underground Injection Control (UIC) regulations. States can be the relevant permitting authority for this matter if the state has assumed the EPA's authority for implementing the SDWA. Here, the ISL uranium mining company must apply to the EPA or its delegated state for approval of underground injection of solutions that will contaminate the exempted aquifer.

The EPA's UIC regulations are designed to protect underground sources of drinking water (USDWs) by prohibiting the direct injection or migration of foreign fluids into these aquifers. A USDW is defined as any aquifer or portion thereof that supplies a public water system or contains fewer than 10,000mg/l total dissolved solids (TDS). The EPA stated that "an aquifer may be exempted from UIC regulation if it is shown to be completely isolated with no possible future uses."[161] The theory is that such an aquifer cannot and will not serve as a source of drinking water because it is situated at a depth or location that makes recovery of the water technically or economically impractical.

For years the discovery of producible mineral deposits led to what amounted to an automatic exemption, even in the arid West. That practice, however, is changing as calculations of technical and economic impracticability evolve over time in light of the increasing scarcity and value of groundwater resources. In some states the scrutiny given to UIC permits is increasing. For example, South Dakota has twice rejected an application submitted by the ISL operator Powertech for a UIC permit. The company's application included substantially the same (and in large part identical) information as that submitted to the NRC on its ISL license application. The state bluntly noted that Powertech's scientific and baseline characterization information "lacks sufficient detail to address fundamental questions related to whether Powertech can conduct the project in a controlled manner to protect groundwater resources."[162]

Unfortunately, bowing to industry pressure, the state legislature took the unusual step of stripping its own state agency, the South Dakota Department of Environment and Natural Resources, of the authority to make such regulatory decisions.[163] South Dakota Governor Dennis Daugaard signed this provision into law in March 2011. Now, the authority to make such decisions rests with the EPA's regional office, and Powertech has submitted its application.

THE REGULATORY SCHEME FOR IN-SITU LEACH MINES IN ACTION AND HOW THEY RELATE TO GROUNDWATER

To recap, the unfortunate regulatory scheme works as follows. The NRC licenses and regulates ISL operations under standards written for conventional uranium mills. By statute, the NRC must also adopt EPA standards, also written for uranium mills, but then use those standards for ISL operations. To present what the industry applicant must do to obtain an ISL license, the NRC issues a guidance document.[164]

The site remediation program (SRP) guidance details how the agency will interpret its requirements for groundwater restoration under 10 CFR Part 40 (the NRC regulations for nuclear "materials" licenses). First, the SRP provides that after an ISL mining and milling operation has concluded, the site must be cleaned up, or "decommissioned," and groundwater quality must be restored.[165] The NRC guidance posits that even after receiving an aquifer exemption under the SDWA, an ISL uranium mine should restore the contaminated groundwater aquifer to NRC-approved background values.[166] Such a level of protection for the scarce resource would ensure that adjacent groundwater aquifers are safeguarded and that other potential future uses of the mined aquifer are not compromised.

The NRC states that if the contaminated groundwater cannot be restored to the NRC-approved background level, then the aquifer must be restored to the maximum concentration levels set in 10 C.F.R. § 40, Appendix A, Table 5C. And if that standard is not achievable—as the NRC notes, "these two options may not be practically achievable at a specific site—then the licensee may propose an alternate concentration limit that it will argue presents no significant hazard."[167]

As described previously, in every instance that NRDC has been able to locate, the industry has defaulted to alternative concentration limits (ACLs) for key parameters such as uranium or radium with no agency complaint. Agreement States such as Texas have adopted similar rules that allow the industry to be relieved of its burden to restore contaminated groundwater.[168]

The combination of an aquifer exemption (making the licensee exempt from water quality standards) and a relaxed NRC regulatory scheme allowing alternative limits for key parameters results in aquifer contamination where the ore is mined. If there ever were a need in Wyoming, New Mexico, or South Dakota to access the water in the aquifer where uranium mining took place for agricultural and possibly even

drinking water uses, our survey and initial study suggest that such an option would be foreclosed. The increasing scarcity of water in the American West is a crucial national issue, and all sources—be they surface water or groundwater—should receive the utmost protection.

THE NEED FOR RULES

Since at least the late 1990s, the commissioners of the NRC have shown concern about the "complex and unmanageable" regulatory system under which ISL mines operate and groundwater restoration is currently managed.[169] In 2003 the NRC sought to delegate regulation of groundwater protection to non-Agreement States through memorandums of understanding. This approach hit numerous roadblocks and was ultimately unsuccessful. In that same year, there was also a downturn in the market price of yellowcake, which contributed to the commissioners' decision to defer a rulemaking for ISL facilities.

In 2006, Commissioner Jeffrey Merrifield called for a rulemaking to solve the problems plaguing the regulation and protection of groundwater at ISL mining facilities. He stated,

> ***While the staff has done its best to regulate ISL licensees through the generally applicable requirements in Part 40 and imposition of license conditions, our failure to promulgate specific regulations for ISLs has resulted in an inconsistent and ineffective regulatory program. We have been attempting to force a square peg into a round hole for years, and I believe we should finally remedy this situation through notice and comment rulemaking.[170]***

Subsequently the NRC commissioners "directed the NRC staff to initiate a rulemaking effort specifically tailored to groundwater protection programs in the well-field production zone at ISL uranium recovery facilities."[171] In 2007 the NRC staff met several times with representatives of the EPA and the National Mining Association to "reach a consensus on a rulemaking strategy."[172]

Though it was more than four years ago that the NRC commissioners instructed staff to begin work on a groundwater protection rule for ISL uranium mining facilities, no such rule has been promulgated, despite repeated requests from the public for the issuance of a draft rule for public comment.[173] In March 2010, NRC staff testified before the commissioners at a briefing on uranium recovery that they "anticipate providing that rule to the Commission in draft form in April of this year."[174] In fact, NRC has formed a working group, "to revise Appendix A in 10 CFR Part 40 to clarify the regulations related to groundwater protection at in-situ leach uranium recovery facilities in order to improve regulatory efficiency."[175] But still, no changes have been made, and the NRC continues to review and grant ISL licenses while taking the side of industry on substantive issues, as recently evidenced in filings in the Dewey Burdock ISL application.

NRDC has identified two straightforward reasons for the current regulatory morass. First, the weak regulatory regime exists because ISL uranium mining was not in widespread use when conventional uranium mining was first subjected to any oversight beyond that of promoting and guaranteeing the viability of a market. Laws to protect public health and the environment from uranium mining and milling impacts were not drafted and passed until several decades of harm had already been inflicted across the American West. Those laws that were passed have rarely been updated and have been haphazardly enforced, with little accountability for lax decisions and a decided unwillingness among regulators to enforce protective standards. The NRC, the EPA, the DOI, the DOE, and the Bureau of Indian Affairs (under its trust responsibility) all hold portions of accountability for the regulation of past, present, and future harm resulting from uranium recovery.

The second reason for the ongoing failure to address the impact of ISL mining is that the existing regulatory schemes are assembled from an archaic set of jurisdictional concerns. NRC jurisdiction over uranium milling (and eventually ISL mining)—and not over conventional uranium mining—is founded on the perceived national need for the federal government to have full authority over nuclear materials in order to ensure the smooth operation of our weapons and commercial nuclear industries. The EPA's authority, granted in 1978, has been superimposed on the NRC process, with at best grudging acceptance by the nuclear agency. The result is a complicated set of standards assembled from regulations intended for differing areas. Whether the current situation exists by intent or happenstance is almost beside the point. The focus must be on curing these archaic deficiencies and swiftly developing a more protective regulatory framework for uranium recovery of all types, before even more environmental damage is done.

Thankfully, there is progress as, previously noted. EPA finally began work on revising the standards that apply to uranium recovery (40 CFR 192). When the EPA issues its draft standards in early 2012, the NRC, for its part, should commence work on its own long-overdue regulatory requirements for ISL uranium mining. Such a rulemaking can track with EPA's proposed standards and be finalized after EPA concludes its process in 2012. Unless the federal government revises the regulatory scheme for ISL uranium mining, damage will likely continue as uranium ore will be recovered by both conventional and unconventional means well into the future. The time to rectify the inadequacies of the regulatory structure has long since arrived, and even with its scant regulatory history, ISL uranium mining has a troubled past that merits specific treatment.

V. EFFECTS OF MULTIPLE RESOURCE EXTRACTION IN ONE AREA

ISL uranium mining does not exist in a vacuum. The environmental impacts of uranium recovery must be assessed in conjunction with other historical, ongoing, and reasonably foreseeable effects of natural resource extraction in the areas of proposed mining. As with the many technical issues associated with groundwater restoration detailed in Chapter 2, the NRC's GEIS on ISL uranium recovery provided an opportunity to address the cumulative impact for all methods of resource extraction activities. On this crucial issue the NRC failed.

In its final GEIS, the NRC stated that it does not regulate conventional types of mining (uranium or otherwise), abandoned mining sites, or any other type of resource extraction, but the agency seemingly agreed to address the issue of the cumulative impacts of all of these activities in subsequent site-specific environmental reviews. Unfortunately, when the first site-specific reviews were issued, the NRC failed to do a satisfactory job of exploring the cumulative impacts of mining in the affected areas. The NRC's effort at analyzing the cumulative impacts of ISL operations and other forms of extractive industries in close proximity consisted of nothing more than references to other environmental impact statements prepared by other agencies and unsupported statements that impacts might be "moderate" or "not expected to be significant."

THE NUCLEAR REGULATORY COMMISSION'S *SUPPLEMENTAL* ENVIRONMENTAL REVIEWS

The first site-specific NEPA reviews performed subsequent to the final GEIS dealt with three ISL operations in Wyoming, including the proposed Lost Creek mine. There are eight ISL facilities and seven conventional uranium mining facilities in close proximity to Lost Creek, and an additional five proposed ISL and conventional uranium mining operations in various stages of the licensing process. Yet the Supplemental EIS done for just one of these mines claims there will be "no cumulative effect on land use."[176] The NRC also states that small impacts to surface water from the Lost Creek project will contribute to small to moderate potential impacts to the Battle Springs Flat drainage area for past, present, and reasonably foreseeable future actions. The cumulative groundwater impact is predicted to be moderate. These claims were unsupported in the supplemental EIS done for the individual mine. NRDC responded to the NRC that with potentially 20 mining operations in one area, and factoring in construction, transportation, and routine operations, it was unclear how the agency reached its conclusions regarding "small to moderate" impacts, leaving subsequent agency actions open to the charge of being arbitrary and capricious.

Another supplemental review performed no better. The Moore Ranch ISL operation in Wyoming illustrates why a connected and cumulative impact analysis needs to be done. There are 17 coal mining operations in the same general area, as well as 472 oil and gas production units in the wider Powder River Basin and 534 coal-bed methane wells within two miles of the boundary of the proposed license area. As shown in Figure 23, the Smith Ranch ISL complex has more than 100 oil and gas well sites in close proximity. And yet again, with no supporting analysis, the NRC states that cumulative impacts on land and groundwater are estimated to be moderate.[177] The NRC's precise language is that impacts are "sufficient to alter noticeably, but not destabilize important attributes of the resource considered."[178] As a general matter, it is not entirely clear to NRDC what "alter noticeably but not destabilize" means. Moreover, the NRC's

conclusion, based on no detailed impacts to groundwater, surface water, air, soils, wildlife habitat, or other technical criteria, leaves the reader and interested public without any certain sense the agency has taken a hard look at the potential environmental impacts and what alternatives or mitigation strategies might be available.

The Powder River Basin is also home to the proposed Nichols Ranch project. The Nichols Ranch area includes 20 traditional uranium mines—only two of which are operational—five ISL mines, and "prolific" coal-bed methane production consisting of approximately 44 leases.[179] This is a substantial density of mining activities. Again the NRC anticipates no significant cumulative impacts but provides no analytical support for this conclusion.

It is important to note that coal-bed methane production in proximity to ISL mining not only increases the severity of drawdown to local groundwater, but also creates a risk for cross-contamination. Despite repeated requests from NRDC and others, at no point has the NRC analyzed this issue. The NRDC's understanding is that coal-bed methane wells are being drilled in close proximity to the proposed ISL operations, sometimes in the same geologic formation, suggesting at minimum a need for serious and publicly transparent agency consultation and analysis. The NRDC sees no evidence of this in the documents.

There is also a risk of leaks and spills from coal-bed methane operations that could contaminate upper aquifers. In order to produce the methane, large volumes of water must first be recovered from the coal deposits. As is well documented, coal-bed methane gas operators do not have a strong record of environmental safety compliance in Wyoming. A press report stated: "In February 2008, the federal Bureau of Land Management's Buffalo field office issued a memo to coal-bed methane gas operators stating, 'Recently, there have been an extraordinary number of spills and undesirable events reported to the Buffalo field office.'"[180] Moreover, the Wyoming Department of Environmental Quality issued a notice of violation to Williams Production RMT Co., the largest coal-bed methane producer in Wyoming's Powder River Basin, for spilling 10,000 barrels of coal-bed methane waste in western Campbell County. If this wastewater was contaminated by concurrent or previous ISL operations, the environmental consequences of such a spill would be significant.

In short, the NRC chose simply to list other projects in the area that "may" have cumulative impacts on the region. The NRC does not discuss the contaminants released by coal-bed methane operations or even which aquifers and surface waters are affected by them. Regional aquifer drawdowns are not discussed or analyzed. Nor does the NRC analyze how the significantly elevated levels of uranium, radium, or other pollutants that result from ISL mining will impact the region when combined with contaminants from coal-bed methane production. Similarly, there are issues with oil and gas exploration that the NRC fails to explore. And no mention is made of the fact that groundwater has suffered substantial adverse effects as the result of previous uranium mining.

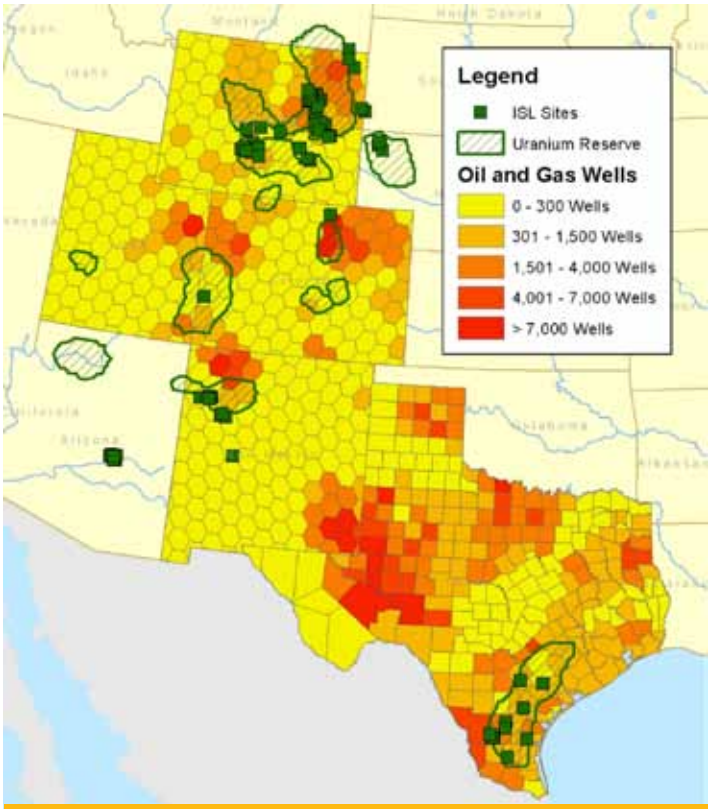


Figure 21: In-situ leach locations overlaid on a density map of oil and gas wells and mines.

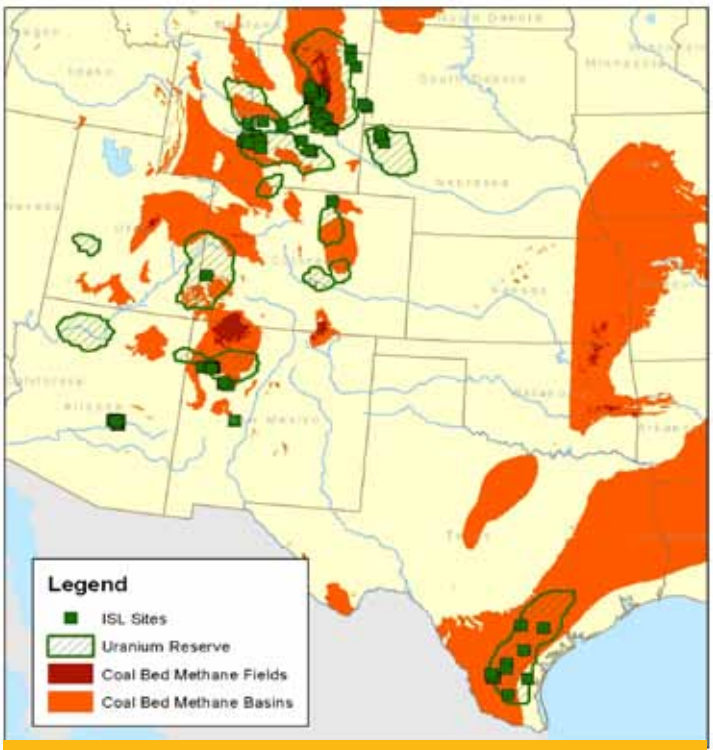


Figure 22: In-situ leach locations overlaid on a map of coal-bed methane fields and basins.

NRC must provide a thorough accounting of the "time, type, place, and scale" of the mining and other disturbances in the project areas and, most important, explain the data on which it bases its conclusions.

So what should be done? Mining for metals, natural gas, and oil is ubiquitous across this region (and has been for generations), and the interactive and combined effects that this activity is having underground should be thoroughly studied.

As just one example of matters the GEIS could have taken up, one of the least studied and understood aspects of impacts to groundwater that occur from ISL mining is the change in the reducing capacity of the remaining water in the system. The reducing or "redox" capacity of groundwater substantially impacts water quality because of its effect on the mobility of various chemicals. Toxic chemicals that seep into the environment as a result of oil and gas drilling activities are more mobile when faced with elevated contaminant conditions from in-situ mining. Oil spills and gas wells can introduce contaminants into soils or water. Oil and gas extraction techniques, including the hydraulic fracturing that occurs in coal-bed methane fields and other formations, can also change the redox state of these formations and mobilize naturally occurring contaminants. Liquid and solid waste products are often dumped into open pits in the ground, and toxic fluids can seep into the groundwater when these pits are not properly lined. Stormwater can carry these toxic materials to other locations.[181] Thanks to the carrying and movement capacity of groundwater, these extraction activities could interact underground. Figures 21, 22, and 23 graphically illustrate this point.

But ultimately, it is the interaction of all the new activities that we think merits immediate consideration by all the relevant federal agencies. In Wyoming alone, the number of oil and gas extraction operations that have come in and out of operation since 1900 exceeds 110,000.[182]

And while these resource extraction technologies—ISL uranium mining, the mining of other minerals, coal-bed methane recovery, oil and natural gas extraction, coal strip mining—are all happening in and around one another, there exists no serious consideration of the cumulative environmental impacts. Individual projects do not occur in a vacuum, but the federal agencies entrusted with safeguarding our precious natural resources treat them as though they do.

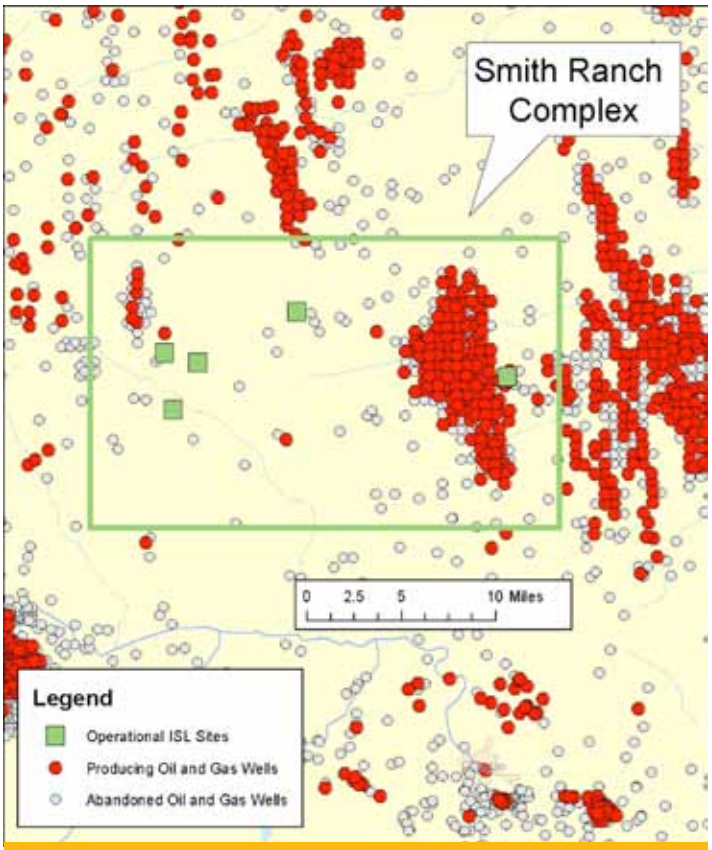


Figure 23: Smith Ranch in-situ leach complex and nearby producing or abandoned oil and gas wells.

VI. CONCLUSIONS AND POLICY RECOMMENDATIONS

ISL uranium mining, alone and in concert with other resource extraction activities, contaminates groundwater. ISL operations in the United States have repeatedly failed to restore aquifers to a pre-mining state, often leaving them unusable for any alternative future use. ISL uranium mining is a poor choice to contaminate scarce western groundwater and harm iconic western landscapes chasing an increase in domestic uranium production that will provide only a small number of short-term jobs and will not fundamentally alter U.S. dependence on foreign sources of uranium.

Considering uranium recovery's poor environmental record, the federal government has an obligation to impose a more protective regulatory framework on all types of uranium recovery before more environmental damage is done. Therefore, NRDC recommends a moratorium on any new ISL uranium mining licenses until such time as:

(1) the federal government adopts key elements of Colorado's 2008 Land & Water Stewardship Act, which requires substantially more stringent protections than currently exist in law;

(2) EPA standards and NRC regulations are updated to reflect the best available data on what is required to protect the environment from the contamination inflicted by all types of uranium recovery; and

(3) the White House Council on Environmental Quality (CEQ) has undertaken a full interagency review of the cumulative and connected impacts of all current Federal programs and proposed agency actions to facilitate and regulate extraction of mineral and fossil-energy resources in the arid West, including but not limited to the NRC's program to license new uranium recovery operations.

Congress could, and should, drive the process forward vigorously. Clear and quick adoption of key elements of Colorado's Land & Water Stewardship Act of 2008 would provide substantial, meaningful protections that do not currently exist in law. For example, Congress should require any applicant to describe at least five ISL mining operations that demonstrate the ability to conduct the proposed mining operation without any leakage, migration, or excursion outside the permitted area of any leaching solutions or groundwater containing minerals, radionuclides, or other constituents liberated or introduced by the mine. Congress should also require that any applicant provide the detailed and transparent data on original water quality that is required by the Colorado law.[183] If the relevant congressional committees are unwilling to take up the matter, then there is no reason why the relevant federal agencies could not adopt many of these sensible requirements via regulation.

With respect to updating the existing regulatory regime for both conventional and unconventional uranium recovery, two agencies and several states figure prominently. The EPA, which is required by law to set standards for the protection of public health and the environment at uranium and thorium milling and ISL mining sites, should press ahead with developing more protective regulations. Such regulations should include not only outright prohibitions on ISL mining in underground sources of drinking water, but also careful

attention to the complexity of underground aquifers and potential drinking water sources. Also, EPA should be clear in requiring groundwater restoration that addresses both the contaminated ore zone and any adjacent portion of the aquifer affected by the ISL mining. Importantly, EPA's restoration standards must be keyed to the overall water quality *throughout* the aquifer, not just an arbitrarily limited mining site presented by the applicant. By law, the NRC must implement those EPA standards at the uranium mills and ISL sites it regulates. As soon as the EPA issues its new standards *in draft form*, the NRC should immediately commence its rulemaking to issue long-overdue requirements specific to ISL uranium mining. And for their part, states' adoption of improved mining laws would be of enormous benefit.[184] Colorado recently enacted a uranium mining law and has recently concluded its public process for regulations to implement that law.[185]

Finally, with respect to conducting an appropriate environmental review of the purpose, need, alternatives to, and cumulative impacts of ISL uranium mining, we have concluded that the issue must be analyzed in its totality. The CEQ should direct a full interagency review of the cumulative and connected environmental impacts of the Federal government's programs and proposed actions to facilitate and regulate the extraction of mineral and fossil-energy resources in the arid West. This interagency review should address the national purposes and needs served by these programs and proposed actions; long- and short-term environmental impacts on critical natural resources, such as groundwater, air quality, animal habitat, and vegetation; and reasonable alternatives that might better protect these resources.

The environmental review effort should include participation from the EPA, the NRC, the Department of the Interior's Bureau of Land Management (BLM) and Bureau of Indian Affairs (BIA), the U.S. Geological Survey, and the Department of Agriculture's Forest Service. Importantly, when the EPA participates in the suggested interagency NEPA review, it will quickly become apparent that the EPA must also revise its regulations for aquifer exemptions from the Safe Drinking Water Act.

The need for this substantial interagency review was made evident by NRC's multiple failures in carrying out its environmental review obligations for ISL uranium mining and milling. The NRC should shelve its inadequate final GEIS and finally perform, in conjunction with other concerned federal agencies, a long-overdue environmental impact analysis of western resource extraction technologies that affect overlapping and adjacent areas. Such a review should analyze the full extent of the cumulative impacts that are by default overlooked in environmental analyses of individual projects or even programmatic reviews of singular resources, such as uranium or natural gas.

Given the inherent environmental risks of ISL mining, pursuit of these recommendations is no guarantee that we will avoid a repetition of past mistakes with uranium recovery. But 60 years after the original boom cycle, ensuring that the domestic uranium recovery industry is meaningfully regulated is the bare minimum standard of protection that the federal government owes its citizens.

ACKNOWLEDGMENTS

The authors would like to extend their thanks to the TAUPO Fidelity Fund and the Beatrice R. and Joseph A. Coleman Foundation for their generous support for the preparation of this report, and to NRDC's Nuclear Program Director Christopher Paine and Senior Analyst Stan Norris for the very substantial service they rendered in editing it. We would also like to thank former NRDC staff and interns Alyssa Go, Abby King, and John Dick, who collected much of the data in the report. Consulting hydrogeologist Roseanna Neupauer of the University of Colorado provided important technical support for the conceptual modeling of groundwater flows at an ISL mine but is in no way responsible for the body or conclusions of this report, which are entirely our own.

VII. APPENDIX A: DEGRADATION OF GROUNDWATER QUALITY FROM URANIUM IN-SITU LEACH MINING

ROSEANNA M. NEUPAUER
MAY 1, 2009

1 Introduction

Uranium in-situ leach (ISL) mining has been tested or used at several sites throughout the United States to extract uranium (U) from roll front deposits, and is proposed for use at several more sites. A roll front deposit forms in the subsurface where uranium minerals that are in the reduced oxidation state, U(IV), are encountered by oxygenated groundwater. The oxic groundwater oxidizes the uranium to U(VI), which is soluble in water. Thus, uranium in the form of U(VI) is transported downgradient with the groundwater until it reaches a zone that is depleted in oxygen. There, uranium is reduced to U(IV) and precipitates out of solution, forming a roll front deposit.

In ISL mining, an oxygenated acid or alkaline solution (lixiviant) is injected into the subsurface through one or more wells, is pumped through the ore formation, and is extracted at several pumping wells. As the solution travels through the ore formation, it oxidizes the mineralized uranium to its more soluble form, U(VI), which is dissolved in the solution and extracted at the pumping wells. Uranium is then recovered from the extracted solution. In the U.S., alkaline lixiviant is used instead because the use of acid lixiviant renders post-mining restoration more difficult (Taylor et al., 2004). Sulfuric acid lixiviant was tested at two sites (Nine Mile Lake and Reno Ranch in Wyoming). Due to the presence of calcium carbonate at the site, the acid lixiviant cause gypsum precipitation on well screens and within the aquifer, reducing the permeability (Mudd, 2001).

During the ISL process, the groundwater chemistry in the vicinity of the ore deposit is altered. After mining is completed, the groundwater should ideally be restored to its pre-mining conditions. However, complete restoration is not always possible, so groundwater is often restored to conditions that satisfy the water quality requirements for the pre-mining class of use.

The typical restoration process at an ISL site follows several stages. In the first stage, called groundwater sweep, water is pumped out of the extraction wells, but no water is injected into the injection wells. This step induces the flow of water toward the extraction wells, drawing the remaining lixiviant out of the aquifer, and sweeping ambient groundwater through the ore zone. In the second stage, the groundwater treatment stage, pumping is continued, and the pumped water is treated and reinjected through the injection wells. A reductant can be added to the reinjected water to enhance chemical reduction of species that were oxidized in the uranium extraction process. Common forms of treatment are reverse osmosis and ion exchange. A final restoration stage may include wellfield recirculation where water is produced at the extraction wells and reinjected without treatment at the injection wells. The purpose of this stage is to homogenize the groundwater within the ISL zone. In the final stabilization phase, monitoring is continued for approximately six months to one year to show that the chemical concentrations of various constituents in the groundwater have stabilized.

The purpose of this document is to report on water quality impacts of uranium in-situ leach mining based on data from existing ISL sites, focusing on pre-mining characterization and post-mining restoration. Water quality effects are mainly due to chemical reactions between the lixiviant and the host rock, excursions of lixiviant during injection, or natural migration of lixiviant and

other mining-affected groundwater after mining has stopped (Davis and Curtis, 2007). This report addresses the determination of baseline water quality, the establishing of restoration targets, and potential water quality impacts due to ISL mining.

2 Baseline Water Quality Assessment

The primary goal for restoration of ISL mining sites is to restore the groundwater quality to pre-mining conditions. Thus, establishing the baseline water quality is a critical step for protecting the quality of the groundwater.

The U.S. Nuclear Regulatory Commission (NRC) has established guidelines for baseline water quality sampling. To establish baseline water quality, chemical constituents that are expected to increase in concentration due to mining activities should be sampled in the ore zone and surrounding aquifers (Lusher, 2003). Typical water quality parameters include common constituents (alkalinity, bicarbonate, calcium, carbonate, chloride, magnesium, nitrate, potassium, sodium, sulfate); trace and minor elements (arsenic, barium, boron, cadmium, chromium, copper, fluoride, iron, lead, manganese, mercury, molybdenum, nickel, radium-226, selenium, silver, uranium, vanadium, zinc); physical indicators (specific conductivity, total dissolved solids (TDS), pH). The spatial and temporal distribution of sample points should be selected to provide enough data to adequately evaluate natural spatial and temporal variations in constituent concentrations. An acceptable set of samples should include all perimeter monitoring wells, all upper and lower aquifer monitoring wells, and at least one well per acre in each well field. For larger sites, less dense sampling is allowable, but the density must be no less than one well per four acres. Sampling should be conducted at least four times. For each constituent, the average value and range of values is reported (Lusher, 2003).

In the subsurface, physical and chemical properties can vary substantially over small distances. In particular, a roll front deposit is characterized by oxidizing conditions upgradient of the roll front and reducing conditions downgradient of the roll front; however the interface between redox states is not necessarily at the roll front. A sharp front between ore-bearing and non-ore-bearing sandstone typically exists at the upgradient side of the roll front deposit; but the uranium concentration on the downgradient (reduced) side is gradational (Dahlkamp, 2003, Davis and Curtis, 2007). Since uranium and other metals are highly affected by redox state, the spatial variability in the redox state within the deposit greatly affects the concentrations of chemical constituents. Therefore, the baseline water quality may not necessarily be properly characterized by the sparse sample distribution stated in the NRC guidelines.

For example, At Crow Butte mine in Nebraska, baseline groundwater quality for Mine Unit 1 was measured for 34 constituents (those listed above, plus sodium, potassium, nitrite, and excluding silver) from twelve wells scattered approximately uniformly throughout the site. Each well was assumed to be representative of a circular region with an area of one acre. While the majority of the site was covered within these one-acre circles, some regions were covered by two or more one-acre circles; while other regions were not covered by any. For several of the constituents, the concentrations were relatively uniform throughout the sampled area, varying by a small percentage. For some constituents, however, the concentrations varied by one half to one order of magnitude (carbonate, nitrate, arsenic, chromium, lead, molybdenum, vanadium, zinc, uranium, radium-226) (Crow Butte Resources, Inc., 2000).

The redox condition of groundwater is critical to the mobility of many chemicals. Since roll front deposits are characterized by sharp changes in redox conditions, an assessment of the pre-

mining redox state, including its spatial variability, seems critical for the complete characterization of pre-mining conditions.

3 Restoration Goals

The primary target restoration values for each parameter is the arithmetic average of the baseline water quality samples for that parameter. Of all the restored ISL mining sites that have been studied for this report, none have met the primary restoration targets. Instead, secondary target restoration values may be established. These secondary targets are typically based on the class-of-use standard for the aquifer; however, other methods have been used to establish adjusted target restoration values.

For example, Title 118 of the Nebraska Department of Environmental Quality (NDEQ) establishes numerical groundwater quality standards for several parameters (NDEQ, 1996). At the Crow Butte facility, groundwater must be restored to these standards. However, if the sampled baseline water quality value exceeds these standards, the target restoration value is set at the baseline mean plus two standard deviations (Crow Butte Resources, Inc., 2000). For parameters that do not have standards set in Title 118 (e.g., calcium, magnesium), the restoration goal is established according to the baseline average. For Crow Butte, the restoration goals for calcium, magnesium, potassium, and sodium were set to ten times the baseline average, to account for the variability in the concentration of these ions as a function of pH (Crow Butte Resources, Inc., 2000). Note, however, that the post-restoration average values of these constituents were no more than 30% (less than two standard deviations) above the pre-mining baseline value.

At Bison Basin (Wyoming), target restoration values appear to be set to the highest baseline value or the drinking water standard (Altair Resources, Inc., 1988).[1]

In Texas, several ISL mining sites have been under restoration, although very little data are available. The baseline water quality was established for 26 constituents, and these were set as the restoration goals. In many cases, however, the restoration goals were amended to higher concentrations, often substantially higher, than baseline values (Southwest Groundwater Consulting, 2008). No information is available regarding the justification of these amendments.

At Christensen Ranch, Mine Unit 2 (Wyoming), the Mine Unit was divided into MU2 North and MU2 South, with MU2 North having eight baseline monitoring wells, and MU2 South having 17. Thirty-five water quality parameters were sampled in each well, and the average values were calculate separately for MU2 North and for MU2 south. These averages were then averaged to obtain the restoration goal for the entire Mine Unit, even though MU2 South had twice as many wells as MU2 North. After restoration, the primary restoration goals were not met for all constituents, so secondary restoration goals of Wyoming Department of Environmental Quality standards or EPA Maximum Contaminant Levels (MCLs) were used (COGEMA, 2008b).

At Smith Ranch Highland Uranium Project (Wyoming), A-Wellfield, secondary restoration goals were set to Class IV(A) standards, which characterizes the water as suitable for industry. The class of use was determined based on elevated levels of radium in the baseline water quality (Janosko, 2004).

Ideally, restoration of ISL mining sites would return the groundwater to its baseline water

[1]The copy of the report that is available on ADAMS is missing several sections, so a complete analysis was not possible.

quality. As stated above, restoration to this level has not been achieved, so restoration targets for some constituents are set based on the class of use of the groundwater. Although this results in sites having lower post-restoration water quality as compared with pre-mining conditions, it is consistent with other water uses in which water is removed from a water body for its productive use, and then returned to the same or different water body. In this situation, the water must meet the water quality standards of the water body to which it is returned, regardless of the quality of the water that was removed.

4 Potential Water Quality Impacts of ISL Mining

Under natural conditions, a roll front uranium deposit typically has oxidizing conditions upgradient of the deposit and reducing downgradient of the deposit. During the ISL mining process, an oxidant is injected into the subsurface via the alkaline lixiviant, thereby changing the geochemistry of the groundwater. Due to the change in redox conditions during mining, the post-mining water quality within the deposit will be substantially different than the pre-mining conditions.

The most serious impacts of ISL mining on groundwater quality include the off-site migration of the lixiviant during production, and the migration of altered groundwater after production has ceased. To address the first concern, monitoring wells are placed around the production area and above and below it to monitor for excursions. To address the second concern, groundwater restoration activities are conducted to return the groundwater to conditions more similar to the pre-mining state.

Vertical and Horizontal Excursions of the Lixiviant. Perimeter wells are installed around production zones to detect horizontal excursions of lixiviant migrating out of the production zone, while monitoring wells are installed in the aquifers above and below the production zone to detect vertical excursions. If water quality in a monitoring well exceeds pre-specified upper control limits for selected constituents, measures must be taken to correct the problem. Causes of vertical excursions include vertical migration through improperly sealed wells and incomplete confining layers (Thompson et al., 2007).

The most common cause of a lateral excursion is an imbalance between injection rates and extraction rates (Thompson et al., 2007). Corrective action in this case may be a reduction in the injection rate or an increase in the extraction rate in nearby wells. In the absence of a background hydraulic gradient, a five-spot pattern with injection wells at the corners injecting at equal rates Q and a production well in the center extracting water at a rate $4Q$, all injected water will be extracted at the production well. However, if there is a background hydraulic gradient (either the ambient hydraulic gradient or the gradient induced by production of adjacent patterns or mine units), some of the injected solution will bypass the production well. An example is shown in Figure 1a. In the absence of pumping, water flows from left to right with a hydraulic gradient of 0.0017 ft/ft. Four injection wells are located at the locations shown by the circles, injecting at a rate Q. One extraction well is located at the location shown by the square, and is producing at a rate $4Q$. The travel path of 32 water particles (eight around each injection well) are tracked from the location marked with a triangle until they reach the extraction well or the domain boundary. Note that five of the particles bypass the extraction well and exit the right boundary. To reduce the likelihood of this bypass, the extraction well can be pumped at a higher rate. Figure 1b shows the effects of production at a rate of $5Q$. In this case, most of the water particles reach the extraction

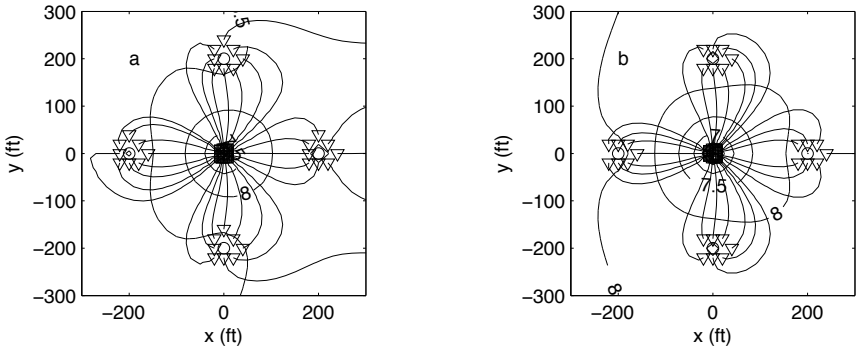


Figure 1: Example of water flow paths in a five-spot pattern. (a) extraction rate equal to the sum of the injection rates. (b) extraction rate exceeding the sum of the injection rates. Circles denote injection well locations. Square denotes extraction well location. Triangles denote starting point of water particles. Solid lines denote water particle paths. Number lines denote head contours in ft.

well. This example is for illustrative purposes only. The actual flow paths depends on the injection and pumping rates, background hydraulic gradient, hydraulic conductivity, heterogeneity, etc.

The NRC has established guidelines for the placement of perimeter monitoring wells, stating that wells should be placed sufficiently close to the well field to provide timely detection, and be spaced sufficient close to so that excursions are not likely to be missed. Groundwater flow direction and velocity should be considered in determining the appropriate position of monitoring wells (Lusher, 2003).

At Crow Butte Mine Unit 1, the production area covers an area of approximately 1000 ft by 750 ft. Eleven monitoring wells were placed around the perimeter, in an approximately circular pattern with a radius of approximately 700 ft. The monitoring wells are separated by approximately 400 ft (Crow Butte Resources, Inc., 2000). At Christensen Ranch, each Mine Unit production area is surrounded by a perimeter monitoring well ring that is approximately 500 ft from the active production zone, with wells separated by 400 ft to 1000 ft (COGEMA, 2008a).

Hydraulic properties of subsurface materials vary spatially, with water preferentially following more highly permeable flow paths. The shape of roll front deposits are evidence of differential flow paths of groundwater. The deposits generally consist of several interconnected rolls that are formed by differential flow paths through the sandstone that are controlled by thin clay beds that separate the sandstone into local hydrologic subunits over distances of tens to hundreds of meters (Dahlkamp, 1993; Davis and Curtis, 2007). These small scale heterogeneities can result in bifurcating flow paths, possibly producing fast paths through interconnected arrangements of more highly permeable materials. Although the monitoring well rings are capable of detecting elevated concentrations in bulk flow, their wide spacing may render them inefficient in detecting more localized excursions. Note that although small scale heterogeneities can significantly influence the travel paths of dissolved chemicals, subsurface properties in general cannot be characterized at these small scales.

A related issue is the placement of the screened interval for the monitoring wells. If the monitoring well is screened over the entire aquifer thickness, the samples collected from the monitoring well are mixtures of water from the entire aquifer thickness. If concentrations vary vertically, higher concentration water will be diluted with lower concentration water, and excursions may go unde-

tected, or their detection may be delayed. On the other hand, if monitoring wells are screened only over a short length, less dilution will occur, but high concentration water may pass above or below the well screen, again going undetected (Lusher, 2003).

Incomplete Restoration of the Subsurface. As stated above, no aquifers have been restored to pre-mining conditions; however, some have been restored to secondary restoration goals, while other exceed the targets for a few constituents. Some examples are provided here.

At Crow Butte, Mine Unit 1, post-mining water quality showed that the average concentrations of most constituents were 2.5 to 3.5 times higher than the baseline average concentrations. Exceptions included calcium, magnesium, and uranium, with concentrations seven to ten times higher than baseline; and carbonate and fluoride, with concentrations below baseline. The restoration process included groundwater sweep with pumping at one well, groundwater treatment with reverse osmosis and ion exchange with reinjected water containing a sodium sulfide reductant, followed by recirculation. Of the 34 parameters sampled in the baseline water quality analysis, 25 were at or below their baseline water quality value after restoration. Seven constituents were above baseline but met the secondary restoration goals (arsenic, radium-226, vanadium, calcium, potassium, magnesium, and uranium). Two constituents (alkalinity and bicarbonate) exceeded the baseline water quality (by 6% and 9%, respectively), and no permit standards had been established for these parameters. After restoration, wells were sampled monthly for an additional six months during the stabilization period. For several of the constituents (alkalinity, ammonium, bicarbonate, calcium, carbonate, chloride, iron, magnesium, manganese, molybdenum, pH, potassium, radium-226, sodium, conductivity, sulfate, TDS, uranium), the concentrations showed an increasing trend, although concentrations remained below the restoration targets (Crow Butte Resources, Inc., 2000). Additional sampling conducted three years later showed that concentration of all species, except iron, either decreased or showed no additional increase. Iron concentrations were expected to decrease eventually as the redox state stabilizes to more reducing conditions (Crow Butte Resources, Inc., 2002).

Christensen Ranch contains five different mine units (MU) covering approximately 200 acres. Restoration was conducted using groundwater sweep, followed by groundwater treatment using reverse osmosis with permeate reinjection, using a hydrogen sulfide reductant in the reinjected water as necessary. This was followed by recirculation, which was curtailed after it was noticed that recirculation led to increased levels of oxygen, which would lead to increased mobility of uranium. Primary target restoration values for 35 parameters were based on baseline means; secondary restoration goals were set according to Wyoming Department of Environmental Quality (WDEQ) and U.S. EPA standards. In 2001, the WDEQ classifications were modified so that radium-226 is not considered treatable; thus, all mine units are Class IV due to high uranium concentrations. For some mine units, the class-of-use had been determined prior to 2001 as Class I (MU2, twelve wells in MU4, thirteen wells in MU5) or Class III (two wells in MU6) (COGEMA, 2008a,b). After restoration, 21 to 27 of 35 constituents were at or below the primary restoration values at the five different mine units; one to three parameters exceeded the primary restoration values but not the WDEQ Class I or EPA MCL standards; four to six constituents exceeded the primary restoration values but do not have a WDEQ class I standard or EPA MCL; finally one to six constituents exceeded both the primary restoration standard and the WDEQ Class I standard or EPA MCL. These constituents included TDS (MU4), iron (MU2, MU4), manganese (all MUs), selenium (MU4, MU5, MU6), uranium (MU2, MU4, MU5, MU6), and radium (MU2, MU4) (COGEMA 2008a,b).

For the Bison Basin Project, restoration was conducted via groundwater treatment using reverse osmosis. Water quality data for 31 constituents sampled during the stability period are available for four wells. The target restoration value, which was often set to the highest baseline value or the drinking water standard, was exceeded for arsenic (one well), boron, fluoride, iron (two wells), manganese, and radium (one well) (Altair Resources, Inc., 1988).

At the Smith Ranch Highland Uranium Project A-Wellfield, restoration was conducted using groundwater sweep, reverse osmosis, and reductant recirculation. The site was determined to be Class IV(A), suitable for industry use, by the WDEQ. After restoration, 20 of the 35 constituents were returned to their baseline conditions. Eleven others were returned to Class I standards, one to Class II standards, and one to Class III standards. Manganese is above the Class II standard, but no Class III standard exists. The remaining constituent is radium, which is above the average baseline value (Janosko, 2004).

Potential for Long-Term Groundwater Quality Impact. At some sites, for constituents whose concentrations remained above restoration goals, additional studies were done to demonstrate that the potential for long-term degradation of groundwater quality was minimal.

At Smith Ranch Highland Uranium Project A-Wellfield, the post-restoration concentration of uranium was 675 pCi/L, which is well above the Class I standard of 5 pCi/L. At the monitoring well ring, concentrations of radium ranged from 3.7 pCi/L to 9.3 pCi/L, indicating that attenuation of radium occurs downgradient of the ore zone. The conclusion is that although the concentrations of radium in the ore zone are quite high, they will be diluted by the time the water in the ore zone reaches the monitoring well ring (Janosko, 2004).

At the Irigaray site in Wyoming, concentrations of some constituents remained above WDEQ Class I standard after restoration of the wellfield. Groundwater flow and transport modeling was conducted to assess the long-term impact of these elevated concentrations. The aquifer was assumed to be homogeneous. The transport model simulated the movement of selenium, manganese, uranium, radium-226, and total dissolved solids. The initial condition was a uniform distribution of each of these constituents throughout the ore zone, with a concentration based on the measurements taken during the stabilization phase. No redox reactions were considered. All constituents were assumed to undergo linear equilibrium sorption, where the concentration in the sorbed phase, C_s, is linearly proportional to the aqueous phase concentration, C, through the relationship $C_s = K_d C$, where K_d is the distribution coefficient. The linear equilibrium sorption assumption leads to a retardation of the solute movement by a factor of $R = 1 + \rho_b K_d/\theta$ where ρ_b is the bulk density of the solid matrix and θ is porosity. Thus, a lower K_d results in high concentrations in the aqueous phase and faster travel times though the aquifer. A single value of K_d (and therefore R) was used for each constituent; low values were used to be conservative. Values used for the distribution coefficient were $K_d = 0.1$ L/kg for selenium, $K_d = 0$ for manganese and TDS, $K_d = 0.5$ L/kg for uranium, and $K_d = 5$ L/kg for radium-226. Concentrations were simulated throughout the aquifer for 300 years, and breakthrough curves were calculated at observation points located 400 ft from the wellfield. The results show that all constituents will be below the WDEQ Class I standards when they reach the observation points. For radium-226, the travel time is so low that the radium from the source zone does not reach the observation points within the 300-year simulation time frame (Petrotek, 2004).

At the Christensen Ranch site, primary and secondary restoration standards were exceeded for TDS, iron, manganese, selenium, uranium, and radium. Because of the proximity to Irigaray,

the modeling studies at Irigaray were assumed to be consistent with conditions at Christensen Ranch. It was assumed that the same reduction in concentration between the source zone and the observation point location 400 ft from the source zone would be seen at Christensen Ranch as was seen at Irigaray (COGEMA, 2008b). At Mine Unit 2, this reduction would lead to iron concentrations below the regulatory standards, but uranium and manganese would remain above the standards. It was assumed that the reducing conditions would limit the mobility of uranium, while the health risk of manganese would be minimal. Radium was not included in the analysis (COGEMA 2008a).

The substantial reduction in simulated concentration at the observation points is caused by dispersion, which is the spreading of the contaminant plume as it moves through the aquifer. Dispersion is caused by small scale velocity variation, and is treated mathematically in such a way that the centroid of a contaminant plume travels with the mean groundwater velocity, and the plume spreads out along the flow direction and in the directions perpendicular to flow. The resulting simulated solute concentrations are smoothly varying in space. In reality, solute flows preferentially through more highly permeable zones and will follow a more circuitous path than is described mathematically. This behavior results in sharper variations in concentration than are predicted with numerical simulations. The results of a transport simulation represent an "average" distribution of solute; however, in reality, the some regions will have substantially higher concentrations than the simulated predictions and other regions will have substantially lower concentrations than the simulated predictions.

Note that the Irigaray modeling study used a finite difference grid with block of 25 ft $\times$ 25 ft $\times$ 21 ft in the ore layer. Thus, the simulated concentration represents the average concentration over a volume of 13,125 ft^3. Given the likelihood of small scale physical and chemical heterogeneities in the subsurface, solute concentrations can vary substantially over this volume.

In the subsurface, there are likely to be interconnected high permeability zones that cause the groundwater and solute to travel very quickly through the aquifer. There are also likely to be extended regions of low permeability that the flow paths tend to avoid, but that the solute may enter by molecular diffusion. Once inside these zones, the solute remains relatively immobile as compared with the rest of the aquifer; however, as solute concentrations in the adjacent aquifer decrease over time, the solute will slowly diffuse out of the immobile zone. The combination of these two occurrences lead to higher concentrations of solute that arrive at downgradient locations more quickly than is predicted from a numerical simulation (due to fast paths), and a long, slow decrease in concentration at a downgradient point as the previously-immobile solute continues to diffuse out of the immobile zone. Given that groundwater velocities are quite slow (approximately 5 m/yr in the Irigaray model), the duration of the post-restoration stabilization period (6 months to one year) may not be long enough for groundwater and solute from the production zone to reach the monitoring well ring. Long-term monitoring may be necessary to ensure that contamination does not migrate off-site.

The groundwater sweep phase of aquifer restoration draws fresh water into the mined zone and theoretically displaces the lixiviant. However, some lixiviant may be trapped in the low permeability (immobile) zones, particularly if the mining phase was long relative to the restoration phase, providing ample time for the lixiviant to diffuse into the lower permeability materials. Since the lixiviant contains oxidant, as it is released out of the immobile zones back into the now-reducing aquifer, the redox state of the surrounding water can change, and uranium (and other metals) can be oxidized into its more mobile state. This would lead to a delayed release of mobile uranium from

the ore zone. Again, long-term monitoring may be necessary to ensure that the quality of water is not compromised.

In the Irigaray modeling study, selenium, uranium, and radium-226 were assumed to follow a linear equilibrium sorption isotherm. Several studies have found that the distribution coefficient, K_d, of uranium is dependent upon pH (Echevarria et al., 2001; Davis et al., 2004; Um et al., 2007), ionic strength (Um et al., 2007), and chemical composition of the water (Davis et al., 2004; Um et al., 2007). Multiple studies (e.g., Davis et al., 2004; Um et al., 2007) recommended against using a single value of K_d, noting that it can vary over four orders of magnitude over a range of pH and carbonate concentrations (Davis et al., 2004).

5 Summary

It has been shown at several ISL sites that post-restoration water quality cannot be returned to pre-mining conditions; however, secondary restoration standards can often be met, at least for most constituents. Water quality issues that warrant further attention include:

- The redox state of groundwater substantially impacts the water quality because of its effect of the mobility of various chemicals. To fully assess the pre-mining baseline water quality, the post-restoration water quality, and the potential for future water quality degradation, the redox conditions, including their spatial variability, should be established.
- Subsurface physical and chemical properties vary spatially. Although a complete representation of the spatial variability is not possible, a better characterization of the spatial variability can be obtained with a more dense sampling network, and if the characterization of spatial variations is included in the pre-mining baseline water quality and post-restoration assessment.
- Depending on the hydraulic gradient and the pumping and injection rates, some injected lixiviant may bypass the extraction wells. Pumping at rates that exceed injection is a measure to reduce the probability of bypass.
- Groundwater travels very slowly and sorbing solutes in the groundwater travel even more slowly; thus, long-term monitoring may be necessary to protect water quality in the future. Likewise, solutes that are trapped in immobile regions will be released slowly and may cause future degradation of water quality. Long-term monitoring can monitor for these solutes as well.

References

[1] Altair Resources, Inc., *Bison Basin Decommissioning Project, Phase I, Final Report*, June 1988, ADAMS ML010530105.

[2] COGEMA Mining, Inc., *Restoration Data Package, Mine Unit 2, Christensen Ranch Project*, March 5, 2008a, ADAMS ML081060131.

[3] COGEMA Mining, Inc., *Wellfield Restoration Report, Christensen Ranch Project, Wyoming*, March 5, 2008b, ADAMS ML081060131.

[4] Crow Butte Resources, Inc., *Mine Unit 1 Restoration Report Crow Butte Uranium Project*, January 10, 2000, ADAMS ML0033677938.

[5] Crow Butte Resources, Inc., *Additional Stability Monitoring Data for Mine Unit 1 Groundwater Restoration*, October 11, 2002, ADAMS ML022980095.

[6] Dahlkamp, F.J., *Uranium Ore Deposits*, Springer-Verlag, New York, 1993.

[7] Davis, J.A. and G.P. Curtis, *Consideration of Geochemical Issues in Groundwater Restoration at Uranium In-Situ Leach Mining Facilities*, U.S. Nuclear Regulatory Commission, NUREG/CR-6870, 2007.

[8] Davis, J.A., D.E. Meece, M. Kohler, and G.P. Curtis, Approaches to surface complexation modeling of Uranium(VI) adsorption on aquifer sediments, *Geochimica et Cosmochimica Acta*, 68, 3621–3641, 2004.

[9] Echevarria, G., M.I. Sheppard, and J.L. Morel, Effect of pH on the sorption of uranium in soils, *Journal of Environmental Radioactivity*, 52, 257–264, 2001.

[10] Janosko, G.S., letter report to W.F. Kearney, Review of Power Resources Inc.'s A-Wellfield Ground Water Restoration Report for the Smith Ranch-Highland Uranium Project (TAC LU0032), June 29, 2004, ADAMS ML041840470.

[11] Lusher, J., *Standard Review Plan for In Situ Leach Uranium Extraction License Applications*, NUREG-1569, U.S. Nuclear Regulatory Commission, Washington, DC, 2003.

[12] Mudd, G.M., Critical review of acid in situ leach uranium mining, 1, USA and Australia, *Environmental Geology*, 41, 390-403, doi:10.1007/s002540100406, 2001.

[13] NDEQ, *Title 118 - Ground Water Quality Standards and Use Classification*, July 29, 1996, www.deq.state.ne.us/RuleAndR.nsf/pages/118-Ch-4, accessed April, 2009.

[14] Petrotek Engineering Corporation, *Groundwater Flow and Solute Transport Modeling Report, Irigaray ISL Operation*, November 11, 2005, ADAMS ML053270045.

[15] Southwest Groundwater Consulting, Inc., *Report on Findings Related to the Restoration of Groundwater at In-Situ Uranium Mines in South Texas*, September 29, 2008.

[16] Taylor, G., V. Farrington, P. Woods, R. Ring, R. Molloy, *Review of Environmental Impacts of the Acid In-situ Leach Uranium Mining Process*, CSIRO Land and Water Client Report, August 2004.

[17] Thompson, A.J., C.S. Pugsley, Tetra Tech Inc., and K. Sweeney, *Generic Environmental Report in Support of the Nuclear Regulatory Commission's Generic Environmental Impact Statement for In Situ Uranium Recovery Facilities*, National Mining Association, Washington, DC, November 30, 2007.

[18] Um, W., R.J. Serne, and K.M. Krupka, Surface complexation modeling of U(VI) sorption to Hanford sediment with varying geochemical conditions, *Environmental Science and Technology*, 41, 3587–3592, 2007.

VIII. APPENDIX B: GROUNDWATER FLOW AND TRANSPORT MODELING OF URANIUM ISL MINING

ROSEANNA M. NEUPAUER
FEBRUARY 1, 2010

Introduction

Uranium in-situ leach (ISL) mining has been tested or used at several sites throughout the United States to extract uranium (U) from roll front deposits, and is proposed for use at several more sites. In ISL mining, a lixiviant is injected into the subsurface through one or more wells, is pumped through the ore formation, and is extracted at several pumping wells. As the solution travels through the ore formation, it oxidizes the mineralized uranium, U(IV), to its more soluble form, U(VI), which is dissolved in the solution and extracted at the pumping wells. Uranium is then recovered from the extracted solution. The lixiviant is commonly comprised of water with added oxygen and carbon dioxide or sodium bicarbonate to mobilize the uranium (EPA, 2007).

During the ISL process, the groundwater chemistry in the vicinity of the ore deposit is altered. After mining is completed, the groundwater should ideally be restored to its pre-mining conditions. The typical restoration process at an ISL site follows several stages. In the first stage, called groundwater sweep, water is pumped out of the extraction wells, but no water is injected into the injection wells. This step induces the flow of water toward the extraction wells, drawing the remaining lixiviant out of the aquifer, and sweeping ambient groundwater through the ore zone. In the second stage, the groundwater treatment stage, pumping is continued, and the pumped water is treated and reinjected through the injection wells. A reductant can be added to the reinjected water to enhance chemical reduction of species that were oxidized in the uranium extraction process. Common forms of treatment are reverse osmosis and ion exchange. A final restoration stage may include wellfield recirculation where water is produced at the extraction wells and reinjected without treatment at the injection wells. The purpose of this stage is to homogenize the groundwater within the ISL zone. In the final stabilization phase, monitoring is continued for approximately six months to one year to show that the chemical concentrations of various constituents in the groundwater have stabilized. Complete restoration has not been documented at any ISL mining site.

The purpose of this report is to document findings of a groundwater modeling study that investigated the effects of ISL mining on groundwater quality. Groundwater flow and transport simulations were run for an ISL mine using available data from Christensen Ranch, Phase 1, Mine Unit 2. The simulations and modeling results are based on available data from the permit application (Malapai, 1992) and from a pump test (Hydro, 1993) that was conducted in November 1992. This site was chosen for these simulations because of the availability of pump test data, which provided spatial data on a finer resolution than what was available in the permit application. The pump test was conducted in the southern portion of Mine Unit 2, so it may not be representative of the entire Mine Unit. Some of the necessary data were not available, so estimates were made using the best available data and the judgment of the modeler.

Physical and Chemical Processes Affecting Chemical Migration

Before mining activities begin, the potential for groundwater contamination in the vicinity of and downgradient of the ISL mine can be assessed through groundwater modeling in which the movement of dissolved chemicals in the subsurface is simulated. The movement of dissolved chemicals depends on physical processes and chemical reactions:

- Physical Processes
    - **Advection.** As groundwater flows through the subsurface, any chemical that is dissolved in the groundwater will be transported along with the groundwater. This process is called advection. The direction and rate at which the dissolved chemicals are advected depends on the direction and rate of groundwater flow and on the porosity (ratio of the volume of pores to the total volume) in the subsurface material.
    - **Dispersion**. The subsurface is comprised of solid materials with open pores through which water flows. As groundwater flows through the subsurface, it cannot follow a straight path because it must flow around the solid grains. In addition, on the pore scale, not all water particles travel at the same velocity; those traveling near the pore wall travel more slowly than those traveling near the center of the pore. This small-scale variation in both magnitude and direction of pore-scale velocity leads to spreading of a dissolved chemical, which is called dispersion. More spreading takes place in the direction of flow than in the direction transverse to flow. On a larger scale, water will preferentially flow toward more permeable materials and away from less permeable materials, leading to spreading on a larger scale.
- Chemical Reactions
    - **Sorption.** Some chemicals that are dissolved in water will come out of solution and attach to the solid surface of the rock as they travel through the subsurface. This process is called sorption. The mass of the chemical that sorbs onto a solid surface is related to the aqueous concentration of the chemical. As the aqueous concentration increases, the sorbed phase mass also increases; and as the aqueous concentration decreases, the sorbed phase mass decreases as mass desorbs. The end result of the sorption process is that the movement of chemicals may be slow relative to the movement of water.
    - **Chemical Reactions.** Many chemicals near an ISL mine site can react with oxygen or other species to be converted into different chemical species. The reactions that occur and the rates at which they occur depend on the dissolved oxygen concentration (DO), pH, reduction potential (Eh), and other factors.

To adequately assess the potential for groundwater contamination, all of these processes must be simulated in a groundwater model.

Data Needs for Groundwater Flow Simulation

The first step in groundwater modeling is to simulate the flow of groundwater. The rate and direction of groundwater movement controls the rate and direction of the movement of dissolved chemicals, and it also controls the movement of chemical species and measures (DO, pH, etc.)

that may react with the chemicals of interest. To adequately simulate the movement of groundwater, the following types of information are needed:

- **Formation thickness**. The subsurface can typically be divided into hydrogeologic units, some that transmit water easily (aquifers) and others that do not (aquitards). The thickness of a hydrogeologic unit is important in the quantity of water available in the unit, the total flow rate or velocity of water through the unit, and the hydraulic connection between adjacent units.

- **Ambient hydraulic head distribution and ambient hydraulic gradient.** The energy state of water is called "hydraulic head" (or just "head"), represents the height above a datum that water would rise in an open tube inserted into the aquifer at that point. Water flows from high head to low head, so the driving force of groundwater flow is the spatial rate of change of head, or the hydraulic gradient. Prior to any pumping at an ISL mining site, the magnitude and direction of groundwater flows is controlled by the ambient hydraulic gradient, i.e., the change in head determined by natural conditions such as surface water bodies that fix the head at discharge points or recharge points, natural recharge, and other sources of water. The ambient hydraulic gradient may change with time, e.g., as a result of increased recharge in the upstream reaches of the aquifer due to snowmelt in the spring and increased recharge due to irrigation of farmland in downstream reaches in the summer. In a groundwater flow model, the boundaries of the model domain are often represented as specified head boundaries, i.e., the user specifies the head at the boundary and the model is used to calculate head at all interior points in the domain. In some cases, the model domain boundary is a physical boundary with a known hydraulic head, such as a large lake; in other cases, the model domain boundaries are arbitrarily set and the values of the hydraulic head at the boundaries are specified by interpolating values from head measurements taken from wells that are located inside and outside of the domain.

- **Hydraulic conductivity.** Hydraulic conductivity is a measure of a material's ability to transmit water. Some materials may transmit water more easily in one direction than in another; these materials are called anisotropic. Within a formation, the hydraulic conductivity can vary in space, even if the formation is made up of a single material type. Hydraulic conductivity can be even more spatially variable if the formation contains more than one material type, e.g., sand deposit with fingers of silt. Furthermore, the transition from one material type to another may be gradual, leading to a gradual spatial variation in hydraulic conductivity. Hydraulic conductivity of different materials can vary over several orders of magnitude. Water, and therefore dissolved chemicals in the water, will preferentially flow toward materials with higher hydraulic conductivity; thus the spatial distribution of hydraulic conductivity is an important factor in controlling both the direction and rate of groundwater flow. A related parameter is the transmissivity, which is the product of the hydraulic conductivity and the aquifer thickness.

- **Storage properties**. During injection and extraction of water, the head distribution in the aquifer is changed. Depending on the ability of the aquifer material to store and release water, which is called the specific storage, the head may quickly reach a new equilibrium

distribution or it may gradually approach this new equilibrium distribution. The specific storage may vary in space. A related parameter is the storage coefficient which is the product of the storage coefficient and the aquifer thickness.

- **Leakage across aquitards.** In general, water flow in aquifers has a strong horizontal component and a weak vertical component. The driving force for flow across an aquitard is the head difference between the underlying and overlying aquifers, and the flow rate is controlled by the thickness of the aquitard and the hydraulic conductivity of the aquitard, which is typically much lower than the hydraulic conductivity of the aquifer. Roll front deposits are often found in sandstone formations, which have high hydraulic conductivity. In an ideal ISL mine site, the sandstone formation is bounded above and below by units with very low hydraulic conductivity, preventing any migration of the lixiviant or uranium-rich solution into the overlying or underlying aquifers. The injection wells will create localized regions of high head and the extraction wells will create localized regions of low head; thus the hydraulic gradient between the sandstone unit and the overlying and underlying aquifers will be modified during ISL operations. To adequately address the potential for leakage of the lixiviant or uranium-rich solution into the overlying and underlying aquifers, the hydraulic conductivity and the thicknesses of the aquitards must be characterized.

- **Injection and extraction wells.** During ISL mine operations, lixiviant will be injected into multiple wells and uranium-rich solution will be extracted from multiple wells. Ideally all of the injected solution will be removed at the extraction wells. Because of the ambient gradient, the injected water will be influenced by the hydraulic gradient created by the injection and extraction wells and by the ambient hydraulic gradient. During ISL mining operation, the dominant influence on flow magnitude and direction in the mine area is the injection and pumping due to mining activities; however, the ambient gradient still influences the overall direction of flow. If the injection and pumping rates are low relative to the ambient groundwater flow, the influence of the ambient gradient will be relatively large, but if the injection and pumping rates are high, the influence of the ambient gradient will be small. Furthermore, if the ambient hydraulic gradient changes with time (as described above), the influence of the ambient gradient may change over time. The locations of all wells and the injection and extraction rates are needed to adequately determine the flow direction and magnitude during ISL production phase. In addition, the screened intervals of the wells may affect the flow field. If the extraction wells are not screened through the entire thickness of the formation, some water may bypass the wells by traveling above or below the screened interval.

- **Duration of the ISL operations.** If some lixiviant bypasses an extraction well, it may migrate off site. If the injection and extraction wells are operated for a short time, this lixiviant will not migrate far from the site and may be re-captured to some degree during restoration. If the wells are operated for a long time, the uncaptured lixiviant may migrate far beyond the site and may not be re-captured during restoration. The duration of the production phase will affect the potential travel distance of uncaptured lixiviant, and therefore will affect the size of the area that must be restored.

Survey of Available Geologic and Hydraulic Data at Christensen Ranch

Geologic and hydraulic data were obtained from Christensen Ranch, Phase 1, Mine Unit 2 (see Figure 1) in an attempt to simulate the chemical migration resulting from ISL mine operations and the ensuing restoration. Data were obtained from the permit application (Malapai, 1992) and pumping test records (Hydro, 1993) which are housed at the Wyoming Department of Environmental Quality, Land Quality Division. As is evident below, the data available from these records were not sufficient to fully characterize the subsurface properties or the ISL mining operations. This section describes the available data and assumptions made in parameterizing a groundwater flow model for the ISL operations at Mine Unit 2. The permit application presented data from several regional monitoring wells. In some cases (e.g., RM-2), the location of the well on drawings does not match the coordinates specified in a table. In this report, the coordinates in the table were assumed to be correct. The pumping test was conducted in the southern portion of Mine Unit 2, and did not include the entire mine unit. In the simulations conducted in this report, only the southern portion of Mine Unit 2 was simulated.

- **Formation Thickness.** The permit application contains a description of the regional geology and the site geology, including geophysical logs at several locations throughout the Christensen Ranch area. The geophysical logs are taken along transects at intervals of approximately 1000 ft. From the geophysical logs, a hydrostratigraphic cross-section was created showing three main sandstone units – "J", "K", and "L", from shallowest to deepest. A lignite layer underlies the "J" sandstone and a coal layer underlies the "L" sandstone. The sandstone units are discontinuous; throughout most of the area, they are divided in Upper and Lower subunits separated by aquitards. The "K" sandstone is the production unit for the ISL mine. The permit application also contains isopach maps of the top and bottom elevations of the "J", "K", and "L" units and the interbedded aquitards. The maps show elevations at 10' intervals. Although the cross section shows that the sandstone units are divided into two distinct subunits in many areas, the isopach maps do not show the vertical boundaries of the subunits. The isopach maps can be used to obtain information on aquifer thickness and top and bottom elevation of units for input into a groundwater flow model.

- **Hydraulic Head.** The permit application contains results of sampling at ten regional monitoring wells that were sampled throughout Christensen Ranch (see Figure 1). All ten wells were sampled in the production zone (Unit K); nine were sampled in the overlying Unit J, eight were sampled in the underlying Unit L. One regional well (RM-6) lies within the boundaries of Mine Unit 2. The regional hydraulic gradient shows that water flows from the southeast to the northwest (see Figure 2).

  Prior to the pump test, the head was sampled in several pumping and monitoring wells within Mine Unit 2 (see Figure 3). These wells were spaced approximately 200-400 ft apart, providing a more accurate representation of the hydraulic gradient around Mine Unit 2. Based on the hydraulic gradient determined from these data, the flow direction in the production zone is approximately due west, with a gradient of approximately 0.008 ft/ft (see Figure 4).

Note that the regional hydraulic gradient does not appear to be representative of the hydraulic gradient in Mine Unit 2. The differences can be due to variety of factors such as (1) temporally-varying regional hydraulic gradient, or (2) spatial variability in the hydraulic gradient that cannot be characterized from the coarse spacing of the regional wells.

- **Hydraulic Conductivity.** The permit application contains results of measurements of hydraulic conductivity at the ten regional monitoring wells. Measurements were made through falling head permeameter tests and results are shown in Figure 5. At some wells (RM-2, RM-5, RM-8, and RM-10), measurements were also made using pumping tests. The pumping test results are within a factor of two of the permeameter test results. Figure 5 shows that the hydraulic conductivity in Christensen Ranch varies spatially over about 1.5 orders of magnitude.

  Transmissivity was measured during a pumping test at Mine Unit 2. Five different wells were pumped during the 84.5-hour pumping test, and drawdown was observed at several monitoring wells and pumping wells (when the wells were not pumped). Drawdown data were analyzed using the Theis (Theis, 1935) and Cooper-Jacob (Cooper and Jacob, 1946) methods to estimate transmissivity and the storage coefficient. For many observation wells, drawdown data were not sufficient to estimate aquifer properties using these methods (e.g., drawdown was low and was influenced by other fluctuations; or the duration of the pumping test was too short). For wells that were analyzed using the Theis curve method, hydraulic conductivity values (based on estimated transmissivities and an aquifer thickness of 181 ft) are shown in Figure 6. At two pumping wells (2Y32-1 and 2Z35-1), the estimated hydraulic conductivity is lower than at the monitoring wells (0.11 ft/d as compared to 0.4 ft/d). This is likely due to the proximity of these wells to the pumping well and the short screened interval of these wells. The Theis method assumes that flow in the aquifer is approximately horizontal, but near the pumping well the flow is likely to have a strong vertical component. These two values are disregarded because they may not be representative of the actual aquifer properties.

  For comparison, the hydraulic conductivity measured using the falling head permeameter test at RM-6 is also shown in Figure 6. This hydraulic conductivity is lower than the values estimated from the pumping test. One possible explanation is that the falling head permeameter test samples a much smaller volume (many orders of magnitude smaller), so this value may not be representative of the aquifer as a whole.

  Anisotropy is defined as directional dependence of material property values. In an anisotropic aquifer, hydraulic conductivity (or transmissivity) varies with spatial orientation. Both the permit application and the pumping test results show the production unit to be anisotropic, both horizontally and vertically. The direction of maximum horizontal hydraulic conductivity is shown in Figure 5. The direction of the minimum horizontal hydraulic conductivity is perpendicular to that. The ratio the maximum to minimum horizontal hydraulic conductivities are also shown in Figure 5, along with the ratio of horizontal to vertical hydraulic conductivity are shown in Figure 5, where

available. At RM-6, no anisotropy information was available in the permit application; however an anisotropy orientation was available from the pumping test results.

- **Storage Coefficient.** The permit application shows measured values of the storage coefficient at four of the regional monitoring wells (Figure 7). The values differ by about a factor of four, and no measurement is provided at RM-6. At Mine Unit 2, the storage coefficient was measured during the pumping test for wells that were analyzed using the Theis method (Figure 8). These values are within about a factor of three of each other, and comparable to the values from the regional monitoring wells.

- **Leakage Across Aquitards.** The pumping test results show that the overlying and underlying aquitards hydraulically isolate the production unit. The pumping rates during the pumping test in the production unit were 15.0 gpm at 2Z34-1 for 84.5 hr, 19.2 gpm at 2AE16-1 and 9.6 gpm at 2X54-1 for the final 55.5 hours, and 12.2 gpm at 2AC24-1 and 6.7 gpm at 2W50-1 for the final 36.93 hours of the pumping test. At the end of the pumping test, the total pumping rate was 62.7 gpm (12,000 ft^3/d). If the ISL mine operations put more stress on the aquitards, with higher injection/extraction rates during the ISL mining operation or a different distribution of wells throughout the mine site, there may be a possibility of leakage across aquitards.

- **Injection and Extraction Wells.** No specific information was found on the locations of the ISL injection and extraction wells at Mine Unit 2. However, some figures in the permit application identified a series of points which are likely to be the ISL wells. The configuration follows the five-spot pattern in most places, so for the modeling effort, wells were assigned as either injection or extraction wells based on the five-spot pattern. The well locations and types are shown Figure 9 (Note the change in scale compared with other figures of Mine Unit 2). No information was available on the injection or extraction rates, so rates were assumed from extraction volumes stated in the permit application or the restoration reports. No information was available on the screened intervals of the wells, so they were assumed to be screened through the entire thickness of Unit K.

- **Duration of ISL Operations.** No information was found injection/extraction schedule for the ISL wells. It was assumed for the purpose of the model that all injection and extraction wells were used simultaneously, and their rates remained constant throughout the entire operation, which began in March 1993 and ended in May 1997 (COGEMA, 2008a).

Groundwater Flow Modeling of Christensen Ranch ISL Mine Operations

Groundwater flow was simulation using MODFLOW (McDonald and Harbaugh, 1988), which is a modular three-dimensional finite difference groundwater flow simulator. In this cell-centered finite difference model, the domain is discretized into rectangular grid blocks, and head is calculated in the each of the grid blocks. The graphical user interface, Argus ONE, was used to preprocess and post-process the simulation data.

Model Parameterization.

Based on the available data, the best option for parameterizing a groundwater flow model of the Mine Unit 2 area is to use the pumping test results and analysis because the data were collected at a finer resolution than the regional data. Since the area of interest (Mine Unit 2) is far from any natural hydrologic barriers, a model domain is arbitrary. For this model, a rectangular domain is used. Since the aquifer has horizontal anisotropy, the domain is aligned in the direction of the maximum hydraulic conductivity (i.e., 12^o north of east). The model domain is shown in Figure 1 and Figure 10. The domain was divided into 50 ft x 50 ft grid blocks for a preliminary simulation (described below). For the main simulation, the grid blocks in the region of the ISL production wells was further refined to 12.5 ft x 12.5 ft grid blocks, with a band of 25 ft x 25 ft grid blocks surrounding the fine-grid region.

An initial model was developed with five geologic units, which were, from top to bottom, Unit J sandstone, overlying aquitard, Unit K sandstone (production unit), underlying aquitard, and Unit L sandstone. The top and bottom elevations of each of these units were taken from the permit application. The permit application contained contour plots of the top and bottom elevations of the units. To obtain elevations to be used in the model, the elevations at each of the pumping and monitoring wells in Mine Unit 2 were estimated from the contour plots. Using these point values, elevations at the center of each grid block were interpolated using Algorithm 624 (Renka, 1984). After an initial test of the model (based on aquifer properties discussed below), it was found that very little leakage occurred across the overlying and underlying aquitards, so only Unit K was included in the main simulation. The top elevation and thickness of Unit K are shown in Figure 11 and Figure 12, respectively.

The boundary conditions for the model domain are defined as prescribed head boundaries along the entire perimeter of the domain. Prescribed head boundaries are used because the domain is far from any natural hydrologic boundaries. The prescribed head boundaries were obtained by interpolated the measured heads in Figure 4 onto the domain boundaries. The heads shown in red were not used in the interpolation because they appear to be anomalous. Because the measured heads are only on the interior of the domain, the interpolation method does preserve the hydraulic gradient throughout the whole domain. In order to preserve the hydraulic gradient, pseudopoints were placed outside the eastern and western boundaries of the domain with values of head set by imposing the average hydraulic gradient of 0.008 ft/ft in the $+x$-direction. For each pseudopoint, the head was calculated as $h = h_i + 0.008(x\text{-}x_i)$, where h_i and x_i are the head and easting for monitoring well i. A different monitoring well was used for each pseudopoint to allow for some natural variability. The pseudopoint locations and heads are shown in Figure 13. The map of the heads interpolated from these pseudopoints is shown in Figure 14. The heads in the cells along the domain boundary are the boundary conditions for the simulations.

Hydraulic conductivity was specified for each grid block based on data available from the pumping test. The pumping test results showed that Unit K has horizontal anisotropy with the maximum value of hydraulic conductivity, K_{max}, aligned 12^o north of east. The minimum value, K_{min}, of hydraulic conductivity is in the perpendicular direction, with the ratio $K_{max}/K_{min}=2.63$. The values shown in Figure 6 were assumed to be the geometric mean values K_G of the maximum and minimum hydraulic conductivities, i.e., $K_G^2 = K_{max} K_{max}$. With this relationship,

K_{max} =1.62K_G. The values for K_{max} at each of the sampled points were interpolated onto the grid blocks using inverse distance weighting of the five nearest data points. A map of the interpolated hydraulic conductivities is shown in Figure 15. These values are the hydraulic conductivities along the model rows, i.e., in the direction of the maximum hydraulic conductivity. The hydraulic conductivity along the columns was set using the ratio K_{max}/K_{min}=2.63. The ratio of horizontal to vertical hydraulic conductivity was set to 15, which is approximately the average of the three ratios shown in Figure 5.

Storage properties were assumed to be uniform throughout Unit K. Specific storage was set to 10^{-6} ft^{-1}. Assuming an aquifer thickness of approximately 180 ft, the storage coefficient is 1.8 x 10^{-4}, which is in the range of the values shown in Figure 8. Porosity was set to 0.26 (COGEMA, 2008b).

A steady state simulation was run without pumping to obtain a head distribution to use as the initial condition in the simulation of the ISL mining operations. For the steady state simulation, uniform discretization of 50 ft x 50 ft was used. The resulting head distribution is shown in Figure 14. The flow direction is approximately from east to west across the domain, consistent with the observations during the pumping test.

Simulations of ISL Mine Operations

The simulations of the ISL mine operations were run as transient simulations, with the initial head set to the head distribution shown in Figure 14. At the beginning of the simulation, all injection and extraction wells were turned on, and groundwater flow was simulated. The locations of the injection and extraction wells are shown in Figure 9. Recall that the exact locations, the injection and extraction rates, and whether each well was an injection or extraction well were unavailable. All wells were assumed to operate at a constant rate over the entire duration of the simulation. The total extraction rate was assumed to by 5% greater than the total injection rate.

In the permit application, a total pumping rate of 2500 gal/min was proposed in the Christensen Ranch amendment. The permit included four phases, of which Phase 1 covered approximately 31% of the total amendment area. Assuming that the total pumping rate for each phase is proportional to the amendment area, the total pumping rate for Phase 1 is estimated to be 775 gal/min. Phase 1 contained three mine units, so it was assumed that the total pumping rate was evenly distributed among the three mine units. Although this simulation only covered the southern portion of Mine Unit 2, no information is available regarding the location and number of wells in the northern portion, so all of the pumping in Mine Unit 2 is assigned to these southern wells in this simulation. The assumed well configuration in Figure 9 has 94 injection wells and 101 extraction wells. Assuming the same injection rate at each injection well, an injection rate of 2.75 gal/min (530 ft^3/d) is used at each injection well. Assuming the total extraction rate is 5% higher than the total injection rate, and uniformly dividing the extraction over the 101 extraction wells, an extraction rate of 2.69 gal/min (517 ft^3/d) is used at each extraction well.

Mine Unit 2 consists of four contiguous wellfield modules – MOD21, MOD22, MOD23, and MOD24. Operations began in March 1993 in MOD21, MOD22, and MOD23, and in July 1993 for MOD24, and continued until May 1997 (COGEMA, 2008a). It is unclear which wells belonged to which module, so it is assumed in this study that all wells were operated from March 1993 to May 1997, a total of four years and two months (50 months).

An initial test simulation was run with these pumping rates, using a uniform 50 ft x 50 ft grid block, and five layers (Unit J, overlying aquitard, Unit K, underlying aquitard, and Unit L). The purpose of the simulation was to evaluate the hydraulic connection between the production unit (Unit K) and the overlying and underlying aquitards (Unit J and Unit L). The simulation results showed no visible change in head in Unit L and only a slight change in head in Unit J; therefore, the production zone was assumed to be hydraulically isolated from the rest of the subsurface.

For the remaining simulations, groundwater flow and transport were only simulated in Unit K with the finer discretization shown in Figure 10, which will produce more accurate results near the wells. Figure 16 shows the head distribution in Unit K over the whole model domain after 50 months of operations, while Figure 17 shows an enlarged view of the head distribution near the ISL mining wells. The head distribution follows the same general trend as the ambient flow field, but head is elevated near the injection wells and lowered near the extraction wells. Figure 18 shows the results of particle tracking simulated using MODPATH (Pollock, 1994). At the start of the simulation (which coincides with the start of the ISL mine operations), eight passive particles were uniformly placed in the aquifer around each of the injection wells at a radius of 12.5 ft (the width of one grid block) from the center of the well. The particles were transported with the groundwater, and their paths over a 50-month period are shown in Figure 18. Many particles are removed at the extraction wells, but many particles remain in the aquifer.

Simulation of Restoration Operations

The restoration process for Mine Unit 2 is discussed in COGEMA (2008a). There were three distinct phases of restoration: groundwater sweep, reverse osmosis, and recirculation:

- *Groundwater Sweep*. The ISL mining operations were completed in May 1997, and a groundwater sweep phase began immediately afterwards at all wellfield modules. This phase involves extraction of groundwater with no re-injection for the purpose of replacing lixiviant-contaminated groundwater with native groundwater in the mined zone (COGEMA, 2008b). This phase lasted until July 1998 (14 months), during which 60,479,000 gallons of groundwater were extracted (COGEMA, 2008a). For the groundwater flow model, it was assumed that all 101 ISL extraction wells were extracting water at a continuous and uniform rate during this 14-month period, at a rate of 0.98 gal/min (188 ft^3/d) at each extraction well.

- *Reverse Osmosis*. The reverse osmosis (RO) phase began in October 2000 at MOD211 and in March and April 2001 at the other three modules and lasted until March 2002, with a total extraction of 295,891,000 gallons of water (COGEMA, 2008a). During this phase, water is extracted and treated at an above-ground treatment facility using reverse osmosis, and treated water is re-injected, with 10-30% over-recovery of water

(COGEMA, 2008b). For the groundwater flow model, it was assumed that the RO phase began in March 2001 at all wellfield modules (since no information was found that identified which wells belonged to each module) and ended in March 2002 (12 months operation), and use the same ISL injection and extraction wells. Assuming that the 101 ISL extraction wells were pumped at a continuous and uniform rate over 12 months to produce the stated volume of extracted water, each well was pumped at a rate of 5.57 gal/min (1073 ft^3/d). Assuming 20% over-recovery, only 246,575,800 gallons of water were reinjected at the ISL injection wells. Assuming water was reinjected at a continuous and uniform rate, the injection rate was 4.99 gal/min (961 ft^3/d) at each well.

- *Recirculation*. The recirculation phase began in April 2003 and continued until March 2004 (11 months), producing 37,091,000 gallons of water (COGEMA, 2008a). For the groundwater flow model, it was assumed that injection and extraction occurred at the same wells as in the RO phase, with the same ratio of extraction volume to injected volume, which is 0.78 gal/min (146 ft^3/d) extracted at each ISL extraction well and 0.68 gal/min (131 ft^3/d) injected at each ISL injection well.

Simulation of the restoration operations had five different stress period (i.e., periods in the simulation during which pumping rates were constant). Details of these stress periods are shown in Table 1.

Prediction

After the restoration simulations, the groundwater flow model was used to simulate groundwater movement for an additional 20 years to predict the movement of unrecovered contaminants. The same particles that were tracked in Figure 18 were tracked through the restoration operations and for an additional 20 years after the restoration operations ended. Their particle tracks are shown in Figure 19. The red triangle represents the particle position at the end of the ISL mining operations; the green diamond represents the particle position at the end of the groundwater sweep phase; the magenta hexagon represent the particle position at the end of the restoration phase. For particles that were removed at an extraction well, the line terminates at a well and does not necessarily have these markers. For particles that were still in the aquifer 20 years after the restoration operations were completed, the particle path line terminates somewhere other than at a well. Many particles are removed at the extraction wells during ISL mine operations or during the restoration operations; however, many particles remain in the aquifer even 20 years after restoration is completed. Note that all of these particles entered the aquifer immediately after ISL operations began; therefore they traveled the farthest during the mining operations and are least likely to be captured during the restoration operations. For comparison, Figure 20 shows the same type of particles tracks for particles that entered midway through the ISL mining operations. Here again, some particles remain in the aquifer 20 years after the restoration operations are completed, although the number is less than for those that entered at the start of the mining operations.

Data Needs for Solute Transport Simulation

- **Flow Field.** The groundwater flow field determines the groundwater velocity which controls the advection mass flux of dissolved chemicals and also affects the rate of dispersion. Since the groundwater flow field is obtained from the groundwater flow model, all of the data needs of the groundwater flow model affect solute transport.

- **Dispersivity.** The dispersion process is quantified by three parameters – longitudinal dispersivity, horizontal transverse dispersivity, and vertical transverse dispersivity – which characterize the degree of spreading in the direction of groundwater flow, in the horizontal direction transverse to groundwater flow, and in the vertical direction, respectively. The degree of spreading is most affected by the degree of heterogeneity of hydraulic conductivity of the aquifer. Stochastic theories (e.g., Gelhar, 1993) can be used to estimate the dispersivity based on the variability of the hydraulic conductivity, but typically, the dispersivity is not measured. A general rule-of-thumb that is often followed is that the longitudinal dispersivity is approximately 1/10 of the travel distance of the contaminant, with a 10:1 ratio of longitudinal to horizontal transverse dispersivities, and a 10:1 ratio of horizontal to vertical transverse dispersivities.

- **Background Concentrations.** A roll front deposit of uranium occurs where uranium-rich oxic groundwater encounters a zone that is depleted in oxygen. There uranium is reduced to U(IV) and precipitates out of solution to form the roll front deposit. By the nature of the roll front deposit, the geochemistry of the groundwater upgradient of the deposit is oxic, while the downgradient groundwater is reduced. Thus, the geochemistry at roll-front deposits is complex, with chemical conditions varying substantially in space. During ISL mining, lixiviant is injected into a roll front deposit to intentionally change the chemistry of the water, oxidizing the U(IV) to U(VI), which is mobile. The change in the chemistry of the water affects the solubility of uranium and other metals. Solubility depends the reducing potential (Eh) and pH, as well as ionic strength. Ideally, the site should be restored to its pre-mining conditions. Since the the geochemistry of the roll front deposit is complex, a complete spatial distribution of the concentration of metals, dissolved oxygen, pH, Eh, etc., is needed to make accurate predictions of the chemistry of the groundwater during mining operations, during restoration operations, and to assess the degree of restoration.

- **Chemical Reaction Rates**. To accurately predict the fate and transport of uranium and other metals, sorption parameters and reaction rates and pathways must be quantified. Several studies have found that the sorption of uranium is dependent upon pH (Echevarria et al., 2001; Davis et al., 2004; Um et al., 2007), ionic strength (Um et al., 2007), and chemical composition of the water (Davis et al., 2004; Um et al., 2007). The partition coefficient for sorption of uranium can vary over four orders of magnitude over a range of pH and carbonate concentrations (Davis et al., 2004). Thus, the accurate prediction of the reactions relies on an accurate and complete assessment of the groundwater chemistry.

- **Lixiviant Chemistry.** The chemicals in the lixiviant and their concentrations affect the chemistry of the groundwater and therefore the chemical reactions that occur during and after the ISL mining operations.

Survey of Available Geochemical Data at Christensen Ranch

- **Flow Field.** The data available for accurate simulation of the flow field at Christensen Ranch is discussed above.

- **Dispersivity.** Dispersivity is typically not measured in the field, and no dispersivity data are available for this location.

- **Background Concentrations.** The permit application contains water quality data conducted for a baseline water quality assessment. For each of the regional monitoring wells, samples were taken quarterly in Units J, K, and L. Chemical constituents that were sampled include pH, major ions (Ca, Mg, Na, K, CO_3, CO_3-total, HCO_3, SO_4, Cl, NH_4, NH_3, NO_2, NO_3, F, SiO_2, TDS, conductivity, alkalinity, hardness, sodium adsorption ratio, residual sodium carbonate), trace metals (Al, As, Ba, B, Cd, Co, Cr, Cu, Fe, Pb, Mn, Hg, Mo, Ni, Se, V, Zn), and radiometric (U, ^{226}Ra, ^{230}Th, ^{210}Po, ^{210}Pb, gross alpha). Measurements at a single location in a mine unit are not sufficient to characterize the highly variable groundwater chemistry at a roll front deposit. More dense sampling was conducted at specific sites. For example, the permit application includes baseline water quality data from the Willow Creek R&D site (located in the southern region of Phase 1). Results are compiled into mean values for wellfield wells, monitoring wells, shallow wells (Unit J), and deep wells (Unit K); however, only the mean value, and maximum and minimum values are reported. The spatial distribution of the chemical parameters was not found in the available information.

- **Chemical Reaction Rates**. No data were found regarding chemical reaction rates.

- **Lixiviant Chemistry.** According to the COGEMA (2008a), the lixiviant contained sodium bicarbonate and gaseous oxygen. No information was available on the concentration of these chemicals in the lixiviant.

Solute Transport Modeling of Christensen Ranch ISL Mine Operations

Because of the lack of spatial data on the pre-mining chemistry and the concentration data for the lixiviant, an accurate simulation of change in groundwater chemistry during and after the mining operations could not be conducted. Instead, a simulation is conducted to model the transport of lixiviant in the absence of any chemical reactions. During the simulation of ISL mining operations, the lixiviant is injected into the injection wells. The injected solution is assumed to contain 100% lixiviant (which is comprised of water, sodium bicarbonate, oxygen, and likely low concentrations of other chemicals). As the lixiviant is introduced to the aquifer, it displaces native groundwater, forming an interface between lixiviant and the native groundwater. At this interface, the native groundwater and lixiviant mix. Behind the interface, the water is nearly 100% lixiviant; ahead of the interface, the water is nearly 100% native groundwater; and along

the interface, the water is a mixture of native groundwater and lixiviant. The transport simulations in this report model the movement of this interface and the width of the mixed zone.

Transport Model Parameterization.

The flow field for the transport model was developed by the groundwater flow simulation. The only additional parameter needed to obtain the groundwater velocity from the flow simulation results is the porosity, which was taken as a uniform value of 0.26 (COGEMA 2008b). Dispersivity values were set to 10 ft for the longitudinal dispersivity and 1 ft for the horizontal transverse dispersivity. Note that with the assumption of fully-penetrating wells in Unit K, the lixiviant is assumed to be distributed uniformly over the thickness of Unit K, so vertical spreading does not occur.

Transport Simulations of ISL Mine Operations

To simulate the injection of lixiviant, a "concentration" of 100 (representing 100% lixiviant) is assigned to the water that is injected during the ISL mine operations. This "concentration" is injected at a constant rate over the entire stress period that simulation ISL mine operations. The results can be interpreted as the percentage of lixiviant in the groundwater. Where the percentage is high, a substantial change in groundwater chemistry is likely; where the percentage is low, the change in groundwater chemistry may not be significant. Lixiviant is either extracted at the extraction wells or it remains in the aquifer. MT3DMS (Zheng and Wang, 1999) was used to simulate the transport of lixiviant. The results are shown in Figure 21. The white/blue interface represents 1% of lixiviant in the solution, so this is essentially the interface between native groundwater and contaminated groundwater. The percentage of lixiviant in the water is high near the ISL wells; the contaminated zone extends slightly beyond the perimeter of the wellfield.

Transport Simulation of Restoration Operations

No lixiviant is introduced during restoration operations. During the groundwater sweep phase, lixiviant-containing groundwater is removed at extraction wells and is replaced by native groundwater that flows toward the wells. Thus this simulation models the movement of interface between lixiviant and native groundwater, as it gets drawn back toward the wells. In the RO phase, clean water is injected at the ISL injection wells, further driving the position of the interface toward the ISL extraction wells. Figure 22 shows the percentage of lixiviant in groundwater at the end of the restoration operations. The percentages are substantially reduced during the restoration period; however, an appreciable amount of lixiviant still remains in the aquifer.

Prediction of Solute Concentrations

After restoration operations are completed, any lixiviant remaining in the aquifer will be transported by the ambient groundwater flow. The final phase of the solute transport simulation models this movement. Figure 23 shows the percentage of lixiviant is the groundwater 20 years after restoration operations are completed. The plume travels downstream (west) relative to its

position at the end of the restoration phase. The amount of lixiviant is unchanged from Figure 22; however, the magnitudes are reduced due to dispersion. Although the restoration operations are designed to remove the lixiviant, some lixiviant remains in the aquifer. This is likely a result of two challenges. First, the ambient hydraulic gradient drives flow to the west. The restoration must draw the injected water back toward the extraction wells, and it must also overcome the ambient gradient. Secondly, the flow paths are different between the production and restoration phases; therefore the restoration does not simply "undo" the spread of lixiviant that occurred during production. Because of dispersion, lixiviant is spread through the aquifer during the production phase, and is continues to spread due to dispersion, but in different directions, in the restoration phase. In addition, there are two inactive periods – one after the groundwater sweep phase and one after the RO phase. During this time, the movement of the lixiviant is controlled by the ambient hydraulic gradient; thus the lixiviant is transported to the west and some lixiviant may bypass the extraction wells. For these reasons, the complete removal of lixiviant is unlikely. This situation is more pronounced for a high ambient hydraulic gradient relative to the gradient caused by pumping. Recall that only the southern portion of Mine Unit 2 is modeled here, but all of the pumping for all of Mine Unit 2 has been apportioned to these wells. With this assumption, the simulated hydraulic gradient caused by pumping is likely to be larger than the actual hydraulic gradient caused by pumping; therefore the observed impact of the ambient hydraulic gradient in these simulation results is conservative. The actual effect might be more pronounced with lower pumping rates.

Alternative Groundwater Flow Model

The purpose of this section is to demonstrate the importance of accurate data in setting up a groundwater flow simulation. If only the data from the permit application were used to parameterize the groundwater flow model, a different scenario would be modeled. The top and bottom elevations of Unit K and the storage properties do not change. The differences are highlighted here.

- **Prescribed Hydraulic Gradient**. The permit application data show a hydraulic gradient aligned approximately 45^{o} S of E (Figure 2) with a magnitude of 0.009 ft/ft.

- **Hydraulic Conductivity**. Based on the permit application, no information is available regarding the anisotropy at Mine Unit 2 (from sampling at RM-6), so Mine Unit 2 is assumed to be isotropic. Since only one hydraulic conductivity measurement from the regional monitoring wells is available near Mine Unit 2, the hydraulic conductivity is assumed to be homogeneous with a value of 0.077 ft/d (see Figure 5).

- **Grid**. For isotropic aquifers, the model domain should be aligned with the flow direction, so the grid is aligned at approximately 45^{o} N of W. The discretization is approximately 50 ft x 50 ft on the outer edges and is reduced to 13 ft x 13 ft in the interior of the domain. (See Figure 24).

- **Boundary Conditions**. The boundary conditions are still prescribed head boundaries, but they are based on the single head measurement from the regional monitoring well in the Mine Unit 2 area, and the specified hydraulic gradient.

The alternative groundwater flow model was used to simulate groundwater movement during mining operations, restoration operations, and for an additional 20 years after the completion of restoration to predict the movement of unrecovered contaminants. Particle tracks for particles introduced around each injection well at the start of mining operations are shown in Figure 25. In comparison to the particles in Figure 19, fewer particles remain in the aquifer 20 years after restoration was completed for this simulation; however, not all particles were removed during restoration.

The alternative model was used to simulate lixiviant movement. The results are shown in Figures 26 – 28 at the end of production, at the end of restoration, and at 20 years after the end of restoration, respectively. Again in this simulation, a sizeable amount of lixiviant remains in the aquifer after restoration and 20 years after the completion of restoration operations, although the concentrations are lower than in the previous simulation.

Discussion and Conclusions

Simulations of groundwater flow and contaminant transport were conducted for a region of Christensen Ranch, Wyoming. The simulations were based on data available from the permit application and from pump test data; however, there were limitations in the available data. The simulations modeled the injection of lixiviant and extraction of uranium-rich solution during ISL mining operations, restoration operations including groundwater sweep, reverse osmosis, and recirculation, and prediction of the groundwater and solute movement for an additional 20 years after completion of restoration. The results show that some lixiviant will remain in the aquifer after restoration, and this lixiviant will continue to migrate through the aquifer into the future.

A complete simulation of the chemical evolution of the contaminated region was not possible because there was insufficient data on the spatial distribution of various chemical parameters or on the chemistry of the lixiviant.

The simulations in this report did not include many complexities that could exist. For example, subsurface rocks often are characterized by mobile and immobile regions on the pore scale. Water flows through the interconnected pores that make up the mobile region; thus dissolved chemicals pass through the mobile region due to both advection and dispersion. The immobile region is made up of isolated pores that are not interconnected; dissolved chemicals can only enter or exit the immobile region through molecular diffusion which is a slow process. Chemicals can diffuse into the immobile region when concentrations in the adjacent mobile region are high, but once the concentration in the mobile region drops, chemicals diffuse slowly out of the immobile region. The diffusion out of the immobile region can occur over many years or decades; thus even if the water in the mobile zone appears clean, it may become contaminated over time by this diffusive process. This process was not modeled in these simulations, but it would further increase the concentration of lixiviant in the post-restoration aquifer.

References

COGEMA Mining, Inc., Restoration Data Package, Mine Unit 2, Christensen Ranch Project, March 5, 2008a, ADAMS ML081060131.

COGEMA Mining, Inc., Wellfield Restoration Report, Christensen Ranch Project, Wyoming, March 5, 2008b, ADAMS ML081060131.

Cooper, H.H. and C.E. Jacob, A generalized graphical method for evaluating formation constants and summarizing well field history, *Transactions, American Geophysical Union,* 27, 526, 1946.

Davis, J.A., D.E. Meece, M. Kohler, and G.P. Curtis, Approaches to surface complexation modeling of Uranium(VI) adsorption on aquifer sediments, *Geochimica et Cosmochimica Acta*, 68, 3621–3641, 2004.

Echevarria, G., M.I. Sheppard, and J.L. Morel, Effect of pH on the sorption of uranium in soils, *Journal of Environmental Radioactivity*, 52, 257–264, 2001.

U.S. Environmental Protection Agency (EPA), *Technical Report on Technologically Enhanced Naturally Occurring Radioactive Materials from Uranium Mining, Volume 1: Mining and Reclamation Background*, U.S. Environmental Protection Agency, Office of Radiation and Indoor Air, Radiation Protection Division (6608J), Washington, DC, EPA 402-R-08-005, 2007.

Gelhar, L.W., *Stochastic Subsurface Hydrology*, Prentice Hall, Englewood Cliffs, New Jersey, 1993.

Hydro Restoration Corporation, *Pump Test Analysis Mine Unit 2 – Southern Portion, Christensen Ranch Project, Johnson County, Wyoming, November 1992*, January 1993.

Malapai Resources Company, Christensen Ranch Amendment Application to WDEQ to Mine No. 478 and NRC License SUA-1341, 1988.

McDonald, M.G. and A.W. Harbaugh, Modular three-dimensional finite-difference groundwater flow model. Techniques of water-resources investigations of U.S. Geological Survey, Book 6, Chapter A-1, 1988.

Pollock, D.W., 1994, *User's Guide for MODPATH/MODPATH-PLOT, Version 3: A particle tracking post-processing package for MODFLOW*, the U.S. Geological Survey finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 94-464, 6 ch.

Renka, R.J. Algorithm 624: Triangulation and interpolation at arbitrarily distribution points in the plane, *ACM Transactions on Mathematical Software*, 10(4), 440-442, 1984.

Theis, C.V., The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage, *Transactions, American Geophysical Union*, 16, 519, 1935.

Um, W., R.J. Serne, and K.M. Krupka, Surface complexation modeling of U(VI) sorption to Hanford sediment with varying geochemical conditions, *Environmental Science and Technology*, 41, 3587–3592, 2007.

Zheng, C. and P.P. Wang, *MT3DMS: Documentation and User's Guide*, U.S. Army Corps of Engineers, Washington, DC, November 1999.

Table 1. Stress periods in the groundwater flow simulation.

Stress Period	Phase	Start Date	End Date	Duration (days)	Injection rate[1]	
					ISL injection wells gal/min (ft^3/d)	ISL extraction wells gal/min (ft^3/d)
1	ISL Operation	3/1993	5/1997	1520	2.75 (530)	-2.69 (-517)
2	Groundwater Sweep	5/1997	7/1998	425	0 (0)	-0.98 (-188)
3	Inactive Period	7/1998	3/2001	975	0 (0)	0 (0)
4	RO	3/2001	3/2002	365	4.99 (961)	-5.57 (-1073)
5	Inactive Period	3/2002	4/2003	395	0 (0)	0 (0)
6	Recirculation	4/2003	3/2004	335	0.68 (131)	-0.76 (146)
7	Prediction	3/2004	3/2024	7300	0 (0)	0 (0)

[1] Positive value indicated injection; negative value indicates extraction.

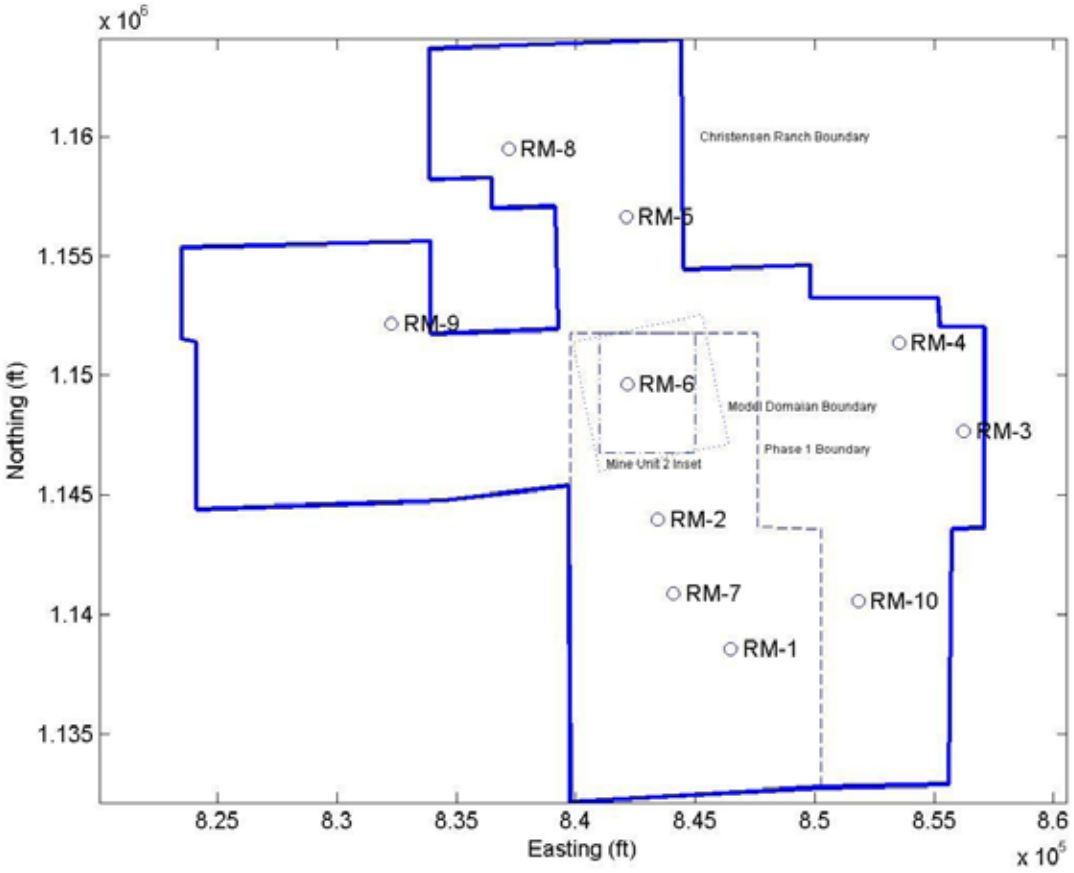


Figure 1. Location of the ten regional monitoring wells (circles) within the Christensen Ranch boundary (approximate). Dashed line represents the approximate boundary of Phase 1. Dot-dash line represents the inset for Mine Unit 2. Dotted line represents the model domain boundary.

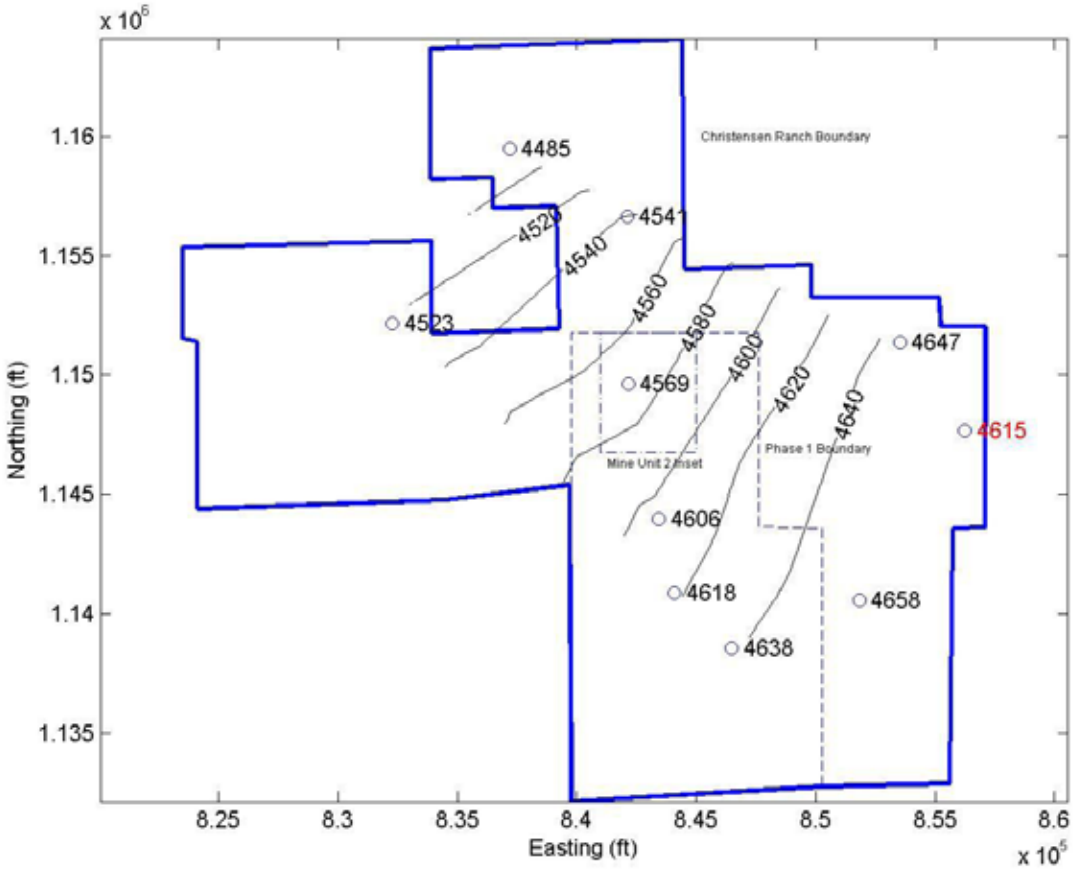


Figure 2. Measured head (in ft) at ten regional monitoring wells (circles) with interpolated equipotential lines. The groundwater flow direction is approximately perpendicular to the equipotential lines, i.e., from the southeast to the northwest. The head measurement at RM-3 (shown in red) is much lower than the measurements in neighboring wells, so it was not included in the interpolation.

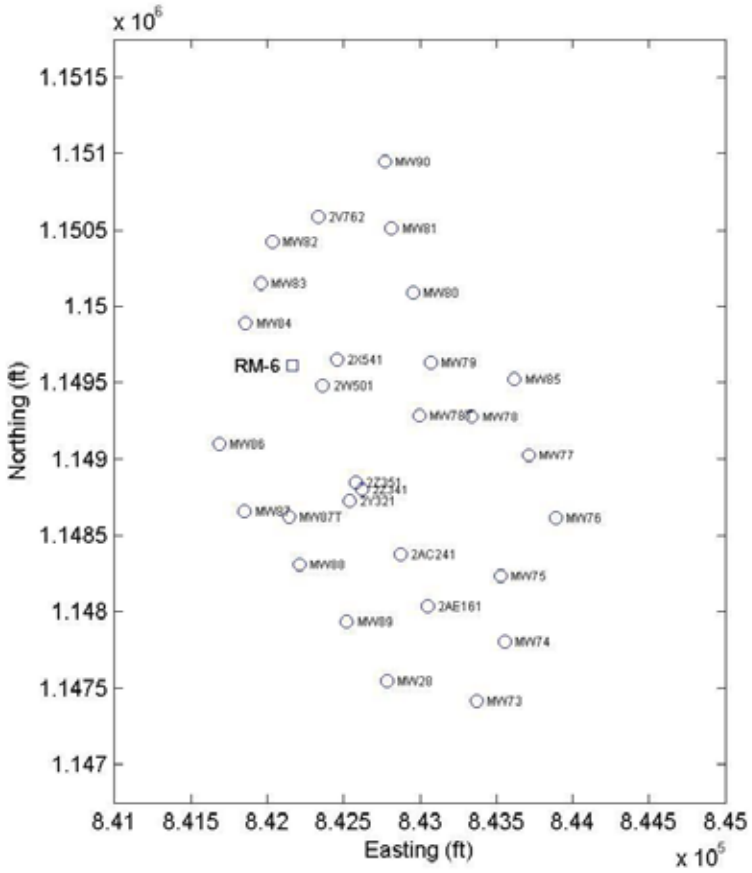


Figure 3. Location of the pumping and monitoring wells at Mine Unit 2 (circles). The square denotes the one regional sampling well (RM-6) within Mine Unit 2

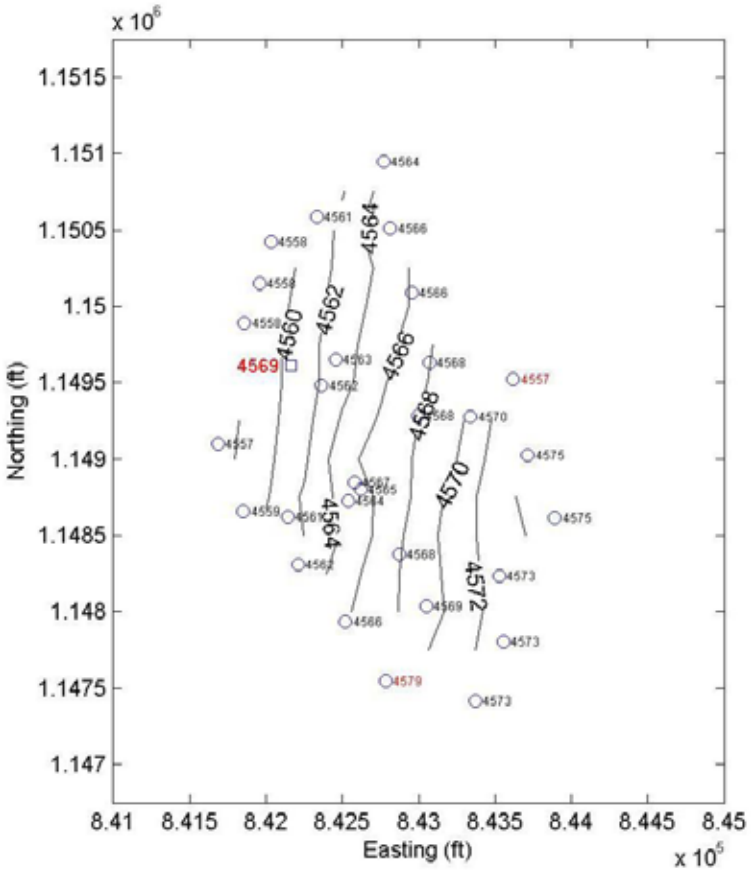


Figure 4. Measured head (in ft) at Mine Unit 2 with interpolated equipotential lines. The groundwater flow direction is approximately perpendicular to the equipotential lines, i.e., from the east to the west. The head measurement at RM-6, MW28, and MW85 (shown in red) are much different than the measurements in neighboring wells, so they were not included in the interpolation.

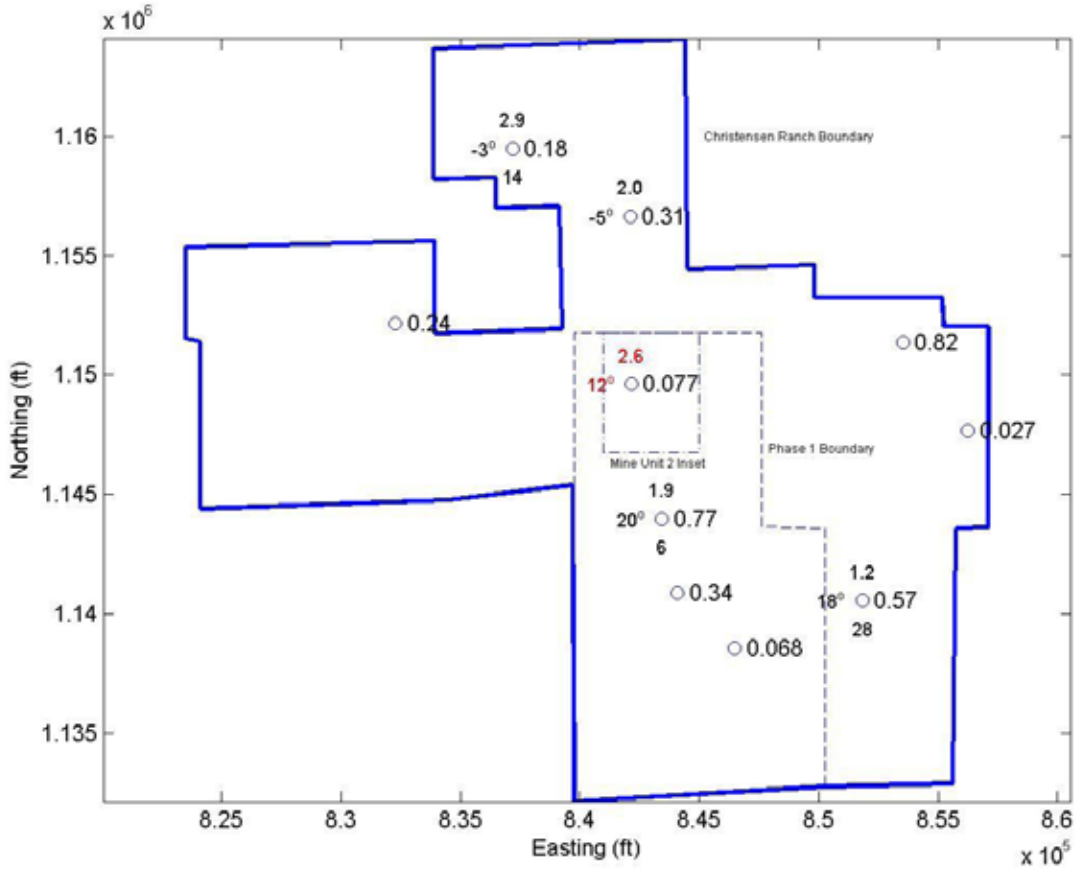


Figure 5. Regional monitoring well locations (circles). Values to the right of the circles are hydraulic conductivity values (in ft/d) measured with falling head permeameter tests. Values to left of the circles are direction of the maximum horizontal hydraulic conductivity, with 0^o due east, and values increasing in the counterclockwise direction. Values above the circles are the ratio of maximum to minimum horizontal hydraulic conductivities. Values below the circles are the ratio of horizontal to vertical hydraulic conductivity. All values are obtained from the permit application, except the direction of the maximum horizontal hydraulic conductivity at RM-6 and the ratio of maximum to minimum horizontal hydraulic conductivities at RM-6 (shown in red), which were obtained from the pumping test analysis.

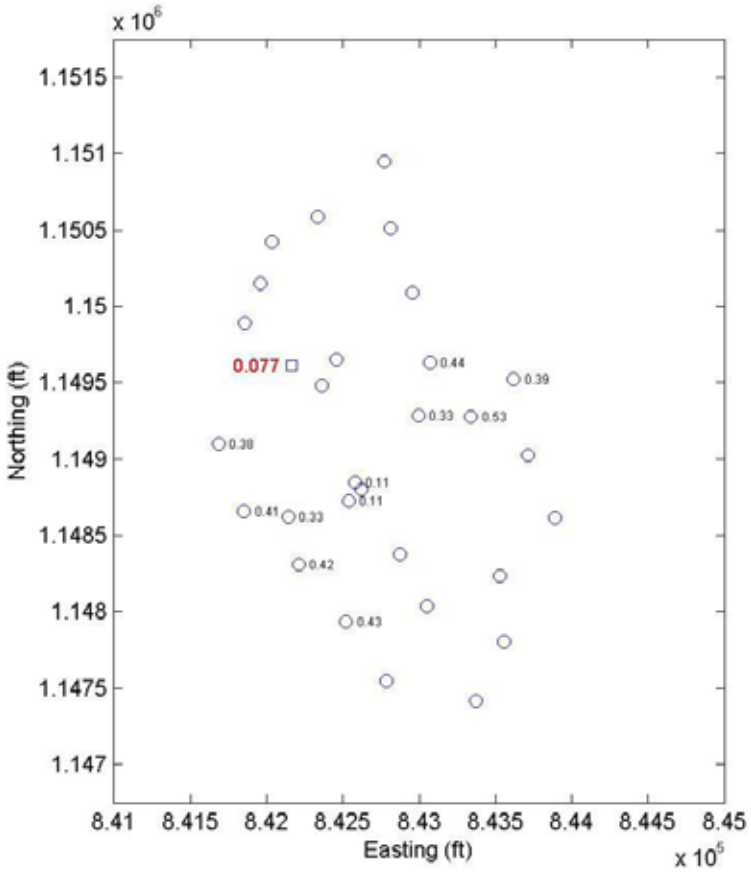


Figure 6. Hydraulic conductivity values (in ft/d) from pumping test at Mine Unit 2. Circles denote pumping and monitoring well locations; square denotes location of RM-6. The hydraulic conductivity at RM-6 was obtained from the permit application.

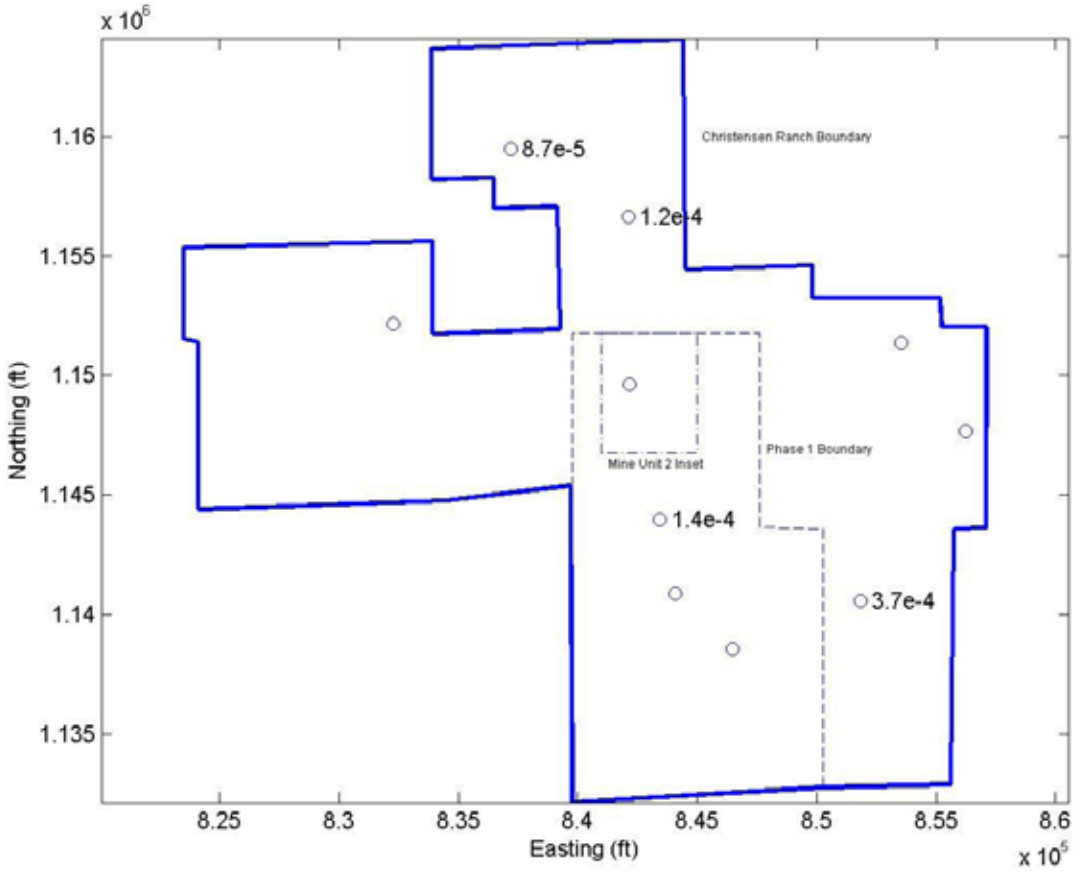


Figure 7. Storage coefficient values (dimensionless) at regional monitoring wells (circles).

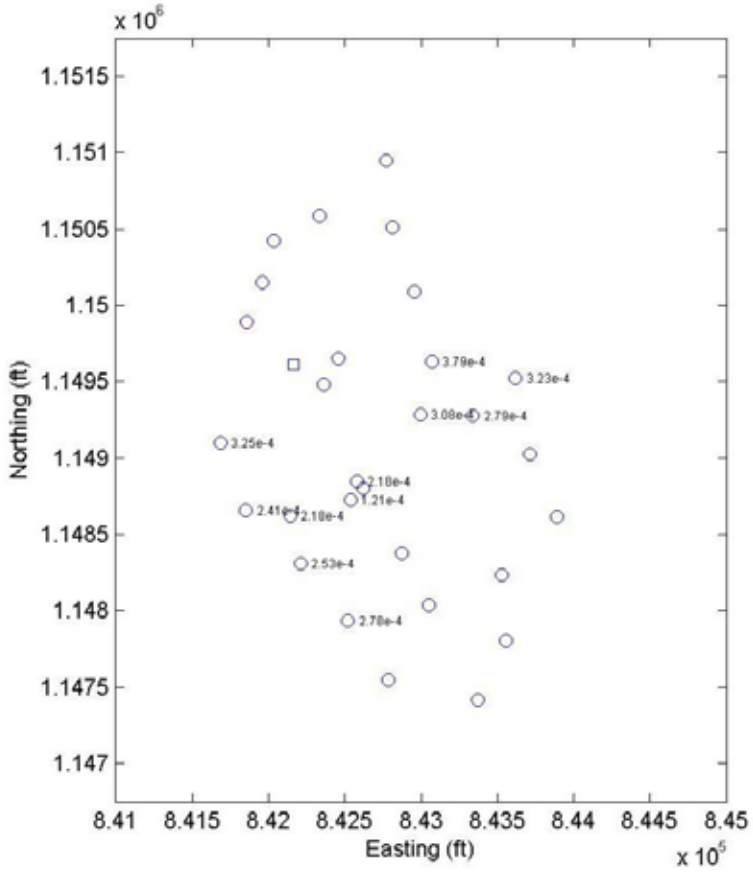


Figure 8. Storage coefficient values (dimensionless) from pumping test at Mine Unit 2. Circles denote pumping and monitoring well locations; square denotes location of RM-6.

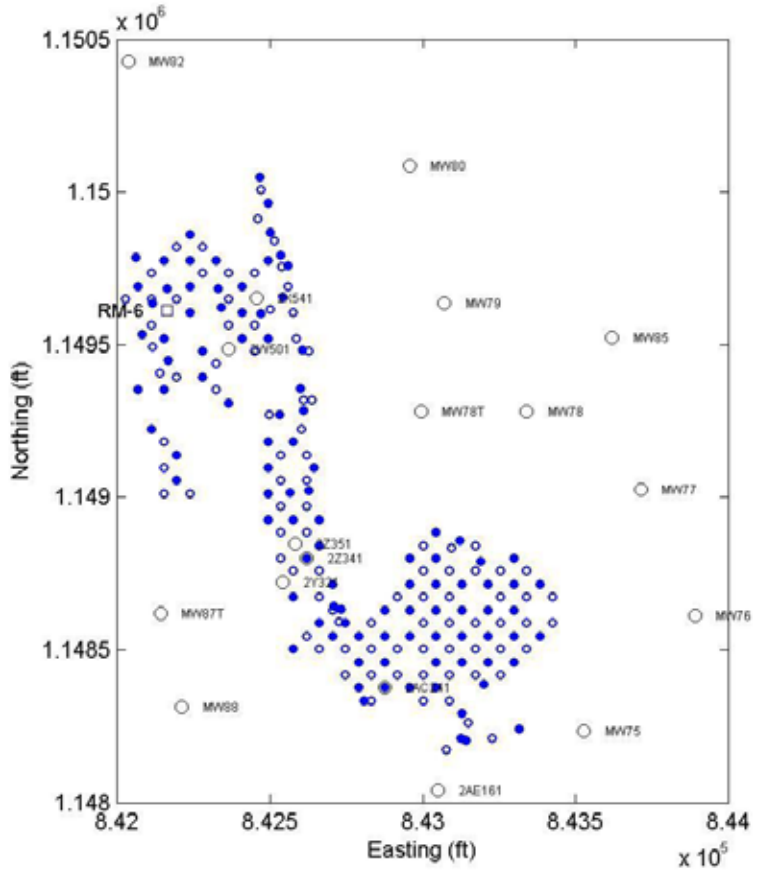


Figure 9. Assumed locations of injection (small open circles) and extraction (small filled circles) wells at Mine Unit 2. Large open circles denote pumping and monitoring well locations; square denotes location of RM-6.

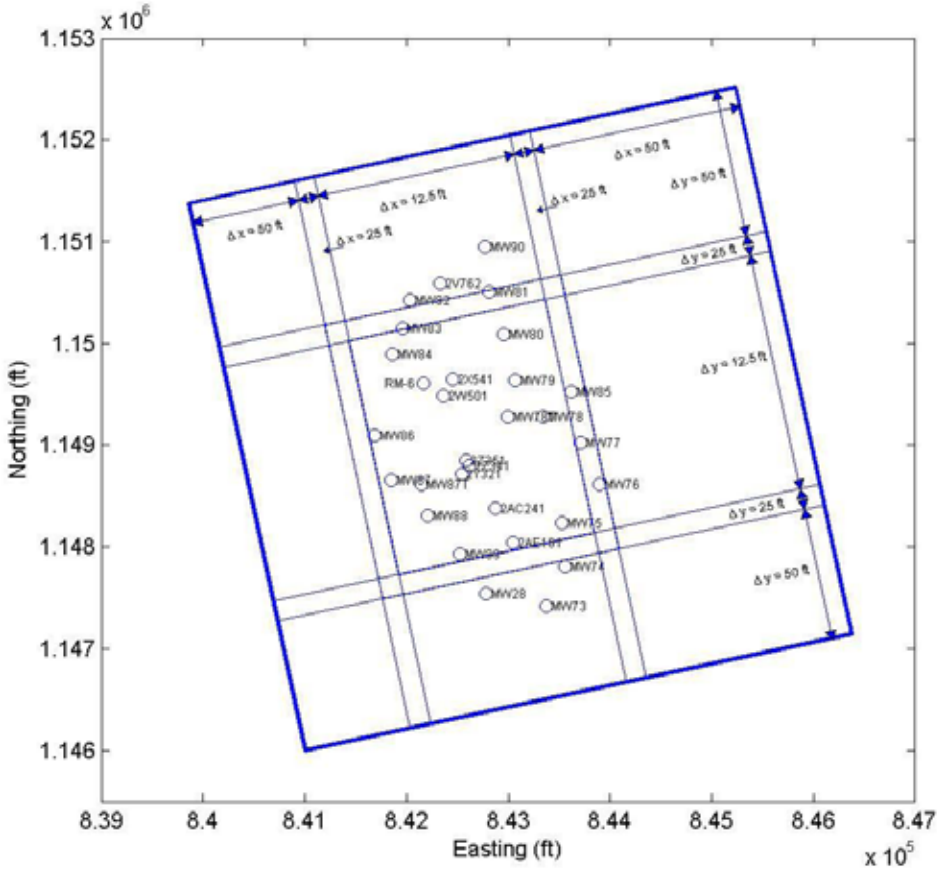


Figure 10. Model domain (thick blue line). Thin blue lines are boundaries between regions with different grid block spacing, as labeled.

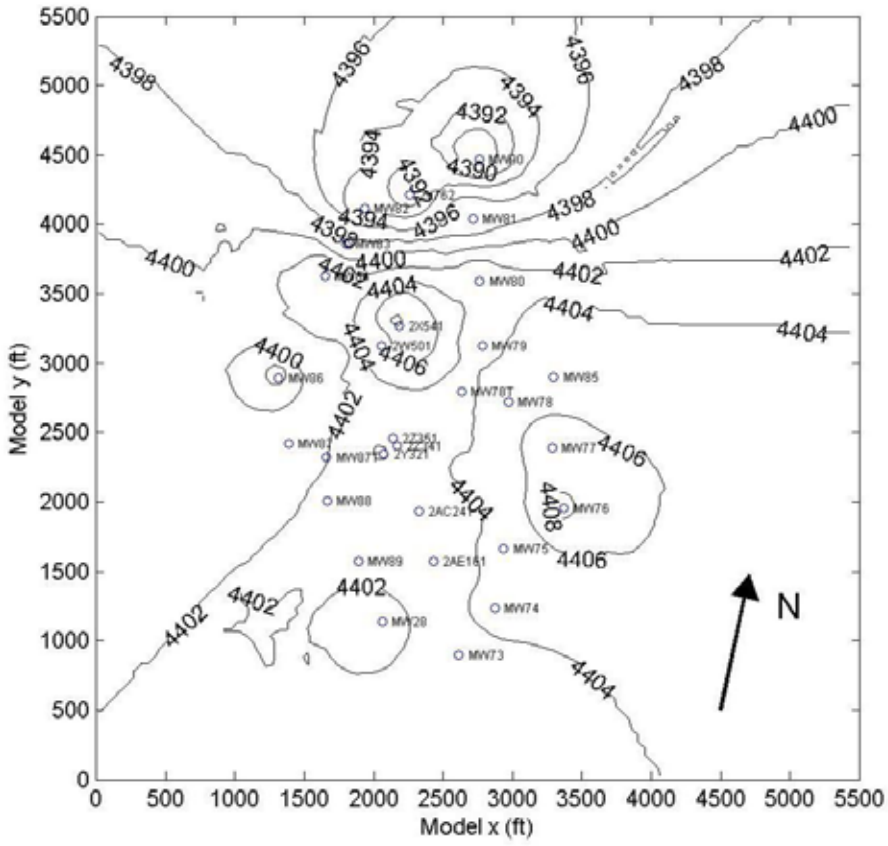


Figure 11. Top elevation (ft) of Unit K. Monitoring well and pumping well locations are shown as circles. Note that the plot domain is the model domain in model coordinates.

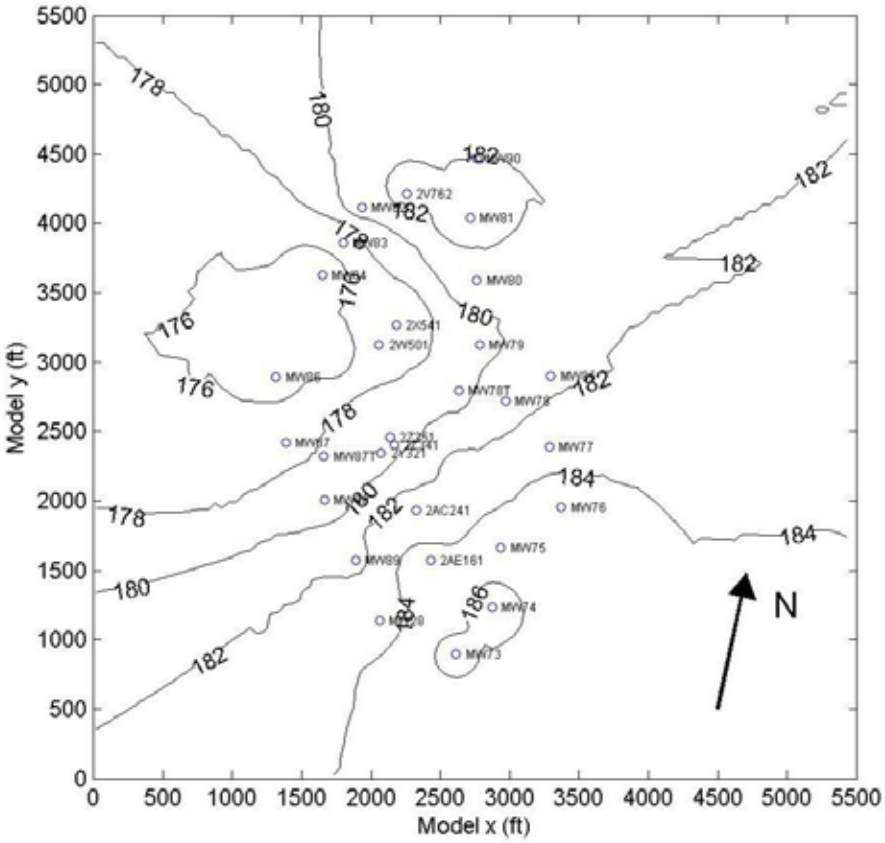


Figure 12. Thickness (ft) of Unit K. Monitoring well and pumping well locations are shown as circles. Note that the plot domain is the model domain in model coordinates.

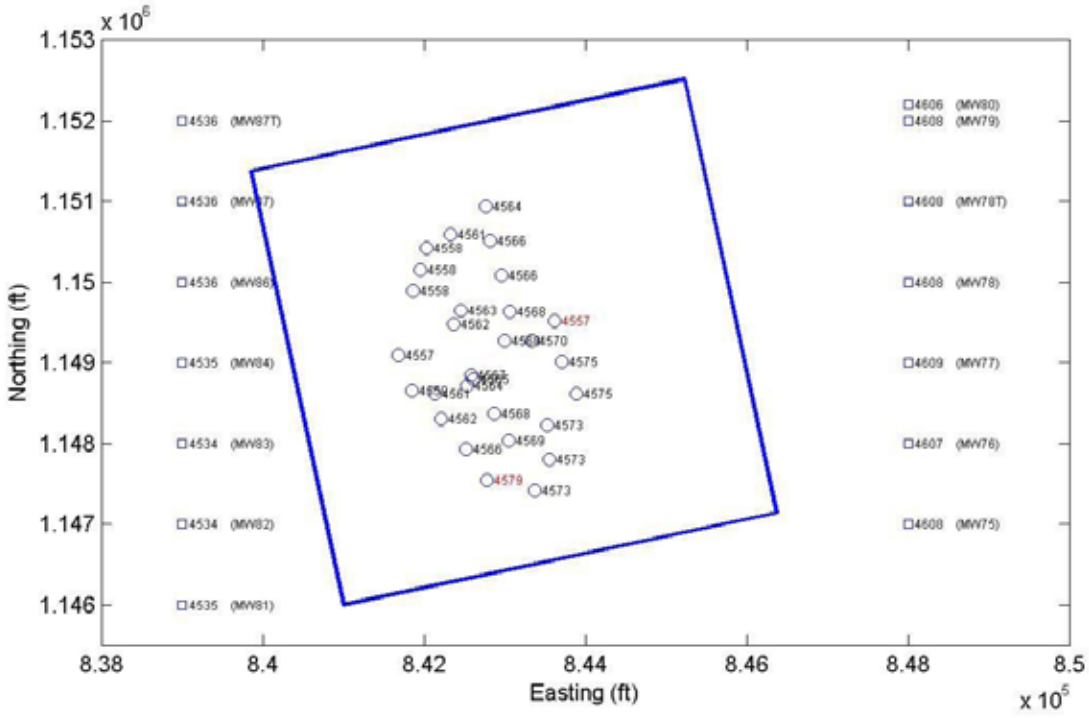


Figure 13. Locations (squares) of pseudopoints. Numerical value to the right of the square is the head at the pseudopoint, and the text identifies the monitoring well whose head was used to interpolate the head at the pseudopoint. The model domain (thick line) and pumping and monitoring well locations and heads are shown for reference.

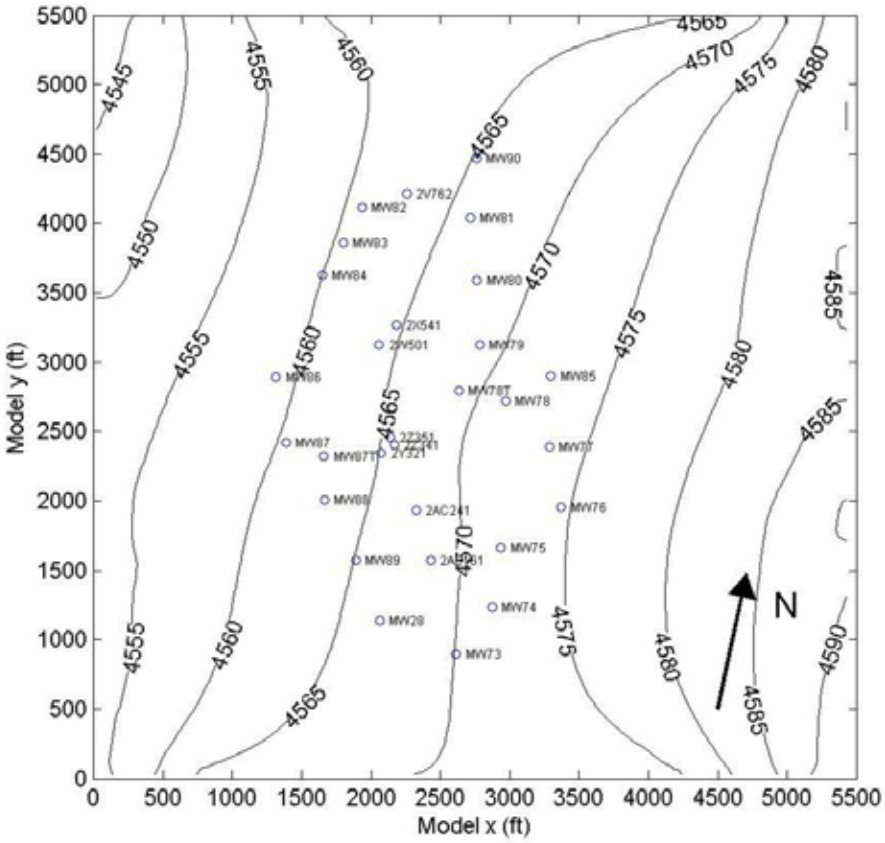


Figure 14. Initial head (ft) for the simulation. Heads along the domain boundary are the boundary heads. Monitoring well and pumping well locations are shown as circles. Note that the plot domain is the model domain in model coordinates.

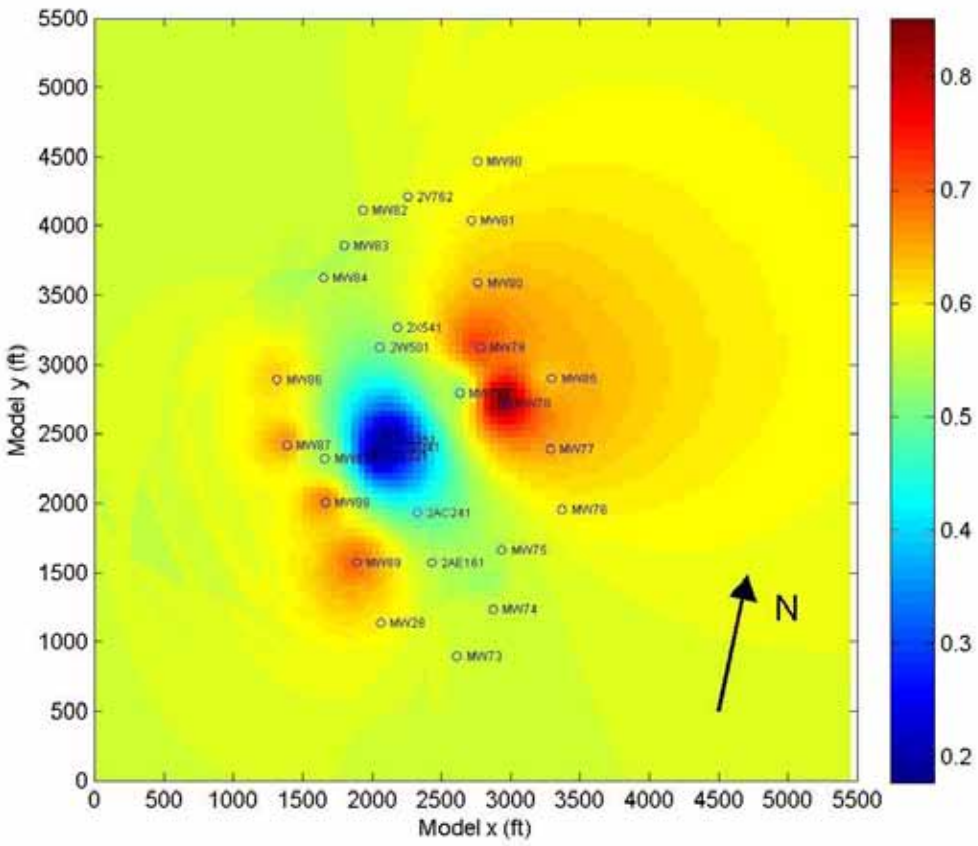


Figure 15. Hydraulic conductivity (ft/d) in Unit K. Monitoring well and pumping well locations are shown as circles. Note that the plot domain is the model domain in model coordinates.

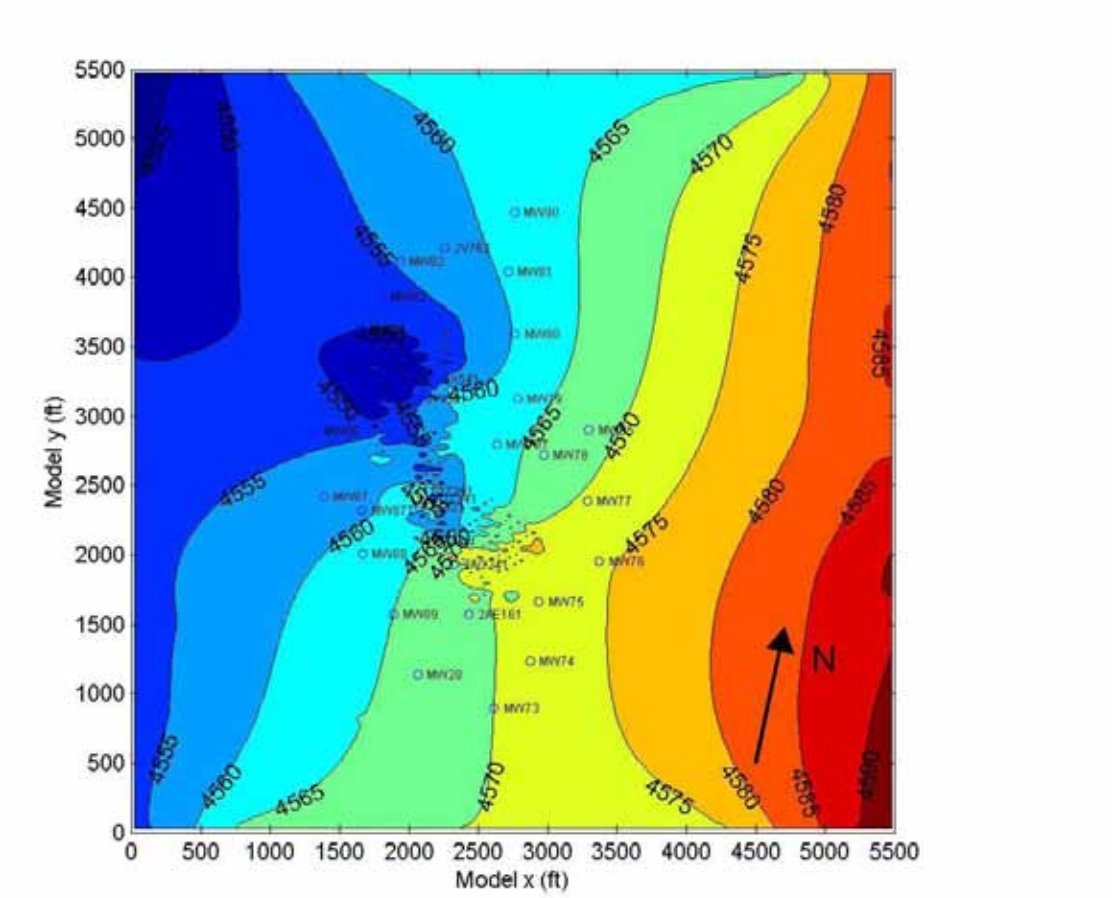


Figure 16. Simulated head (ft) at the end of the 50-month ISL mine operation.

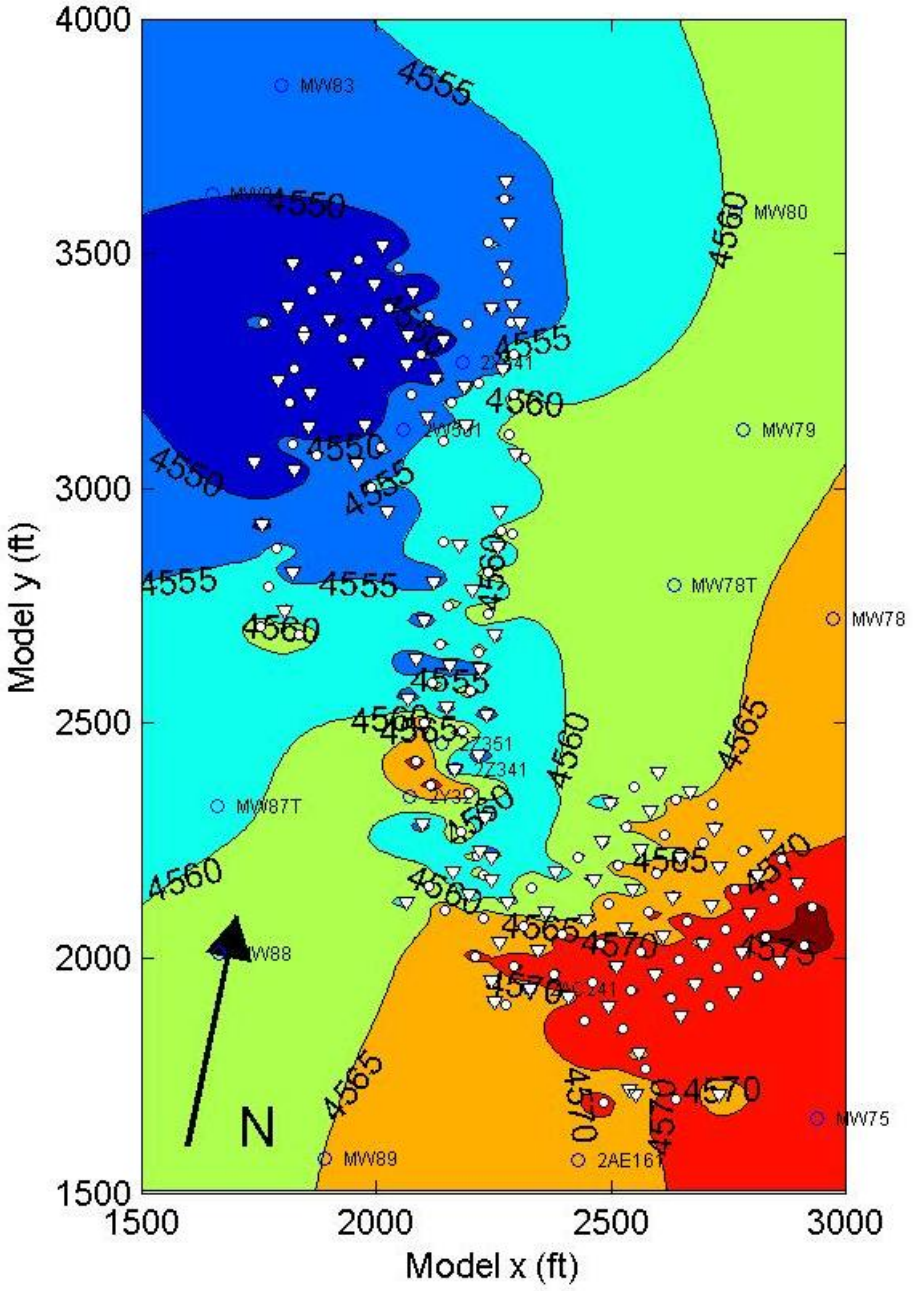


Figure 17. Simulated head (ft) at the end of the 50-month ISL mine operation. Injection wells are shown as white circles; extraction wells are shown as white triangles.

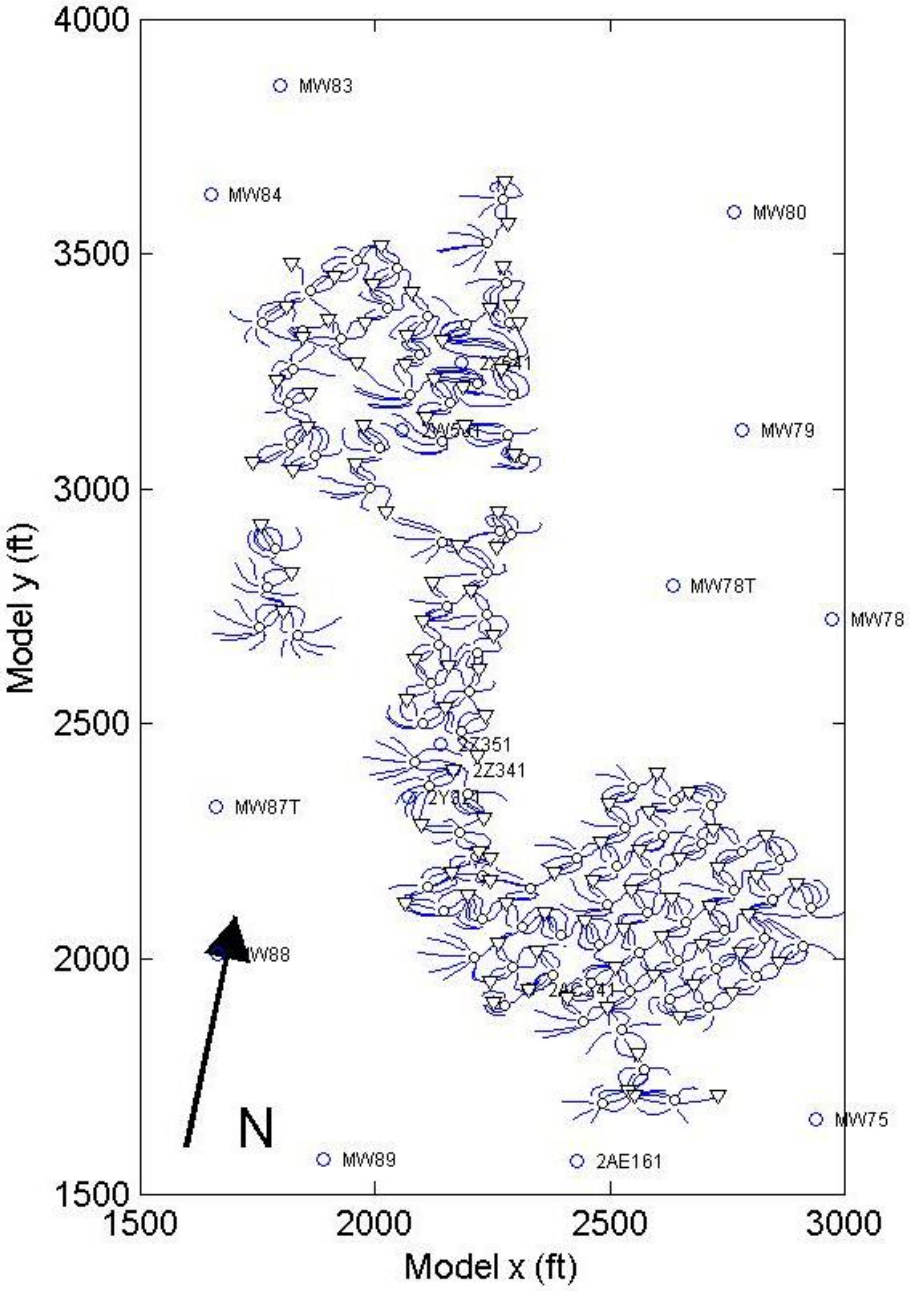


Figure 18. Paths of injected particles during 50-month ISL operations. Injection wells are shown as white circles; extraction wells are shown as white triangles.

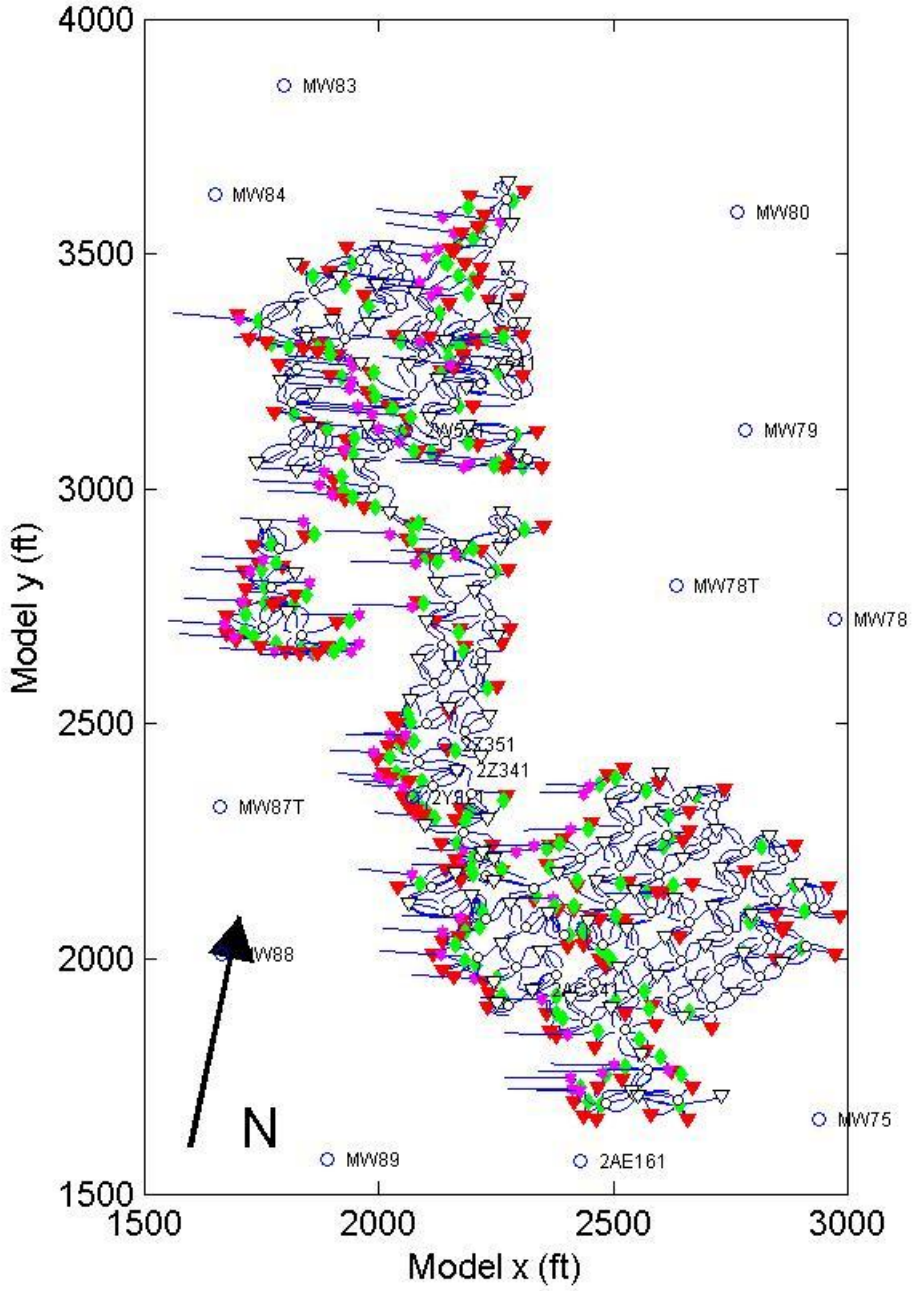


Figure 19. Paths of injected particles during the ISL mining operations, restoration operations, and an additional 20 years after restoration is completed. Injection wells are shown as white circles; extraction wells are shown as white triangles. Red triangles represent the particle position at the end of the ISL mining period; green diamonds represent the particle position at the end of the groundwater sweep; and magenta hexagons represent the particle position at the end of the restoration period. The particles were released at the start of the ISL mining operations. Injection wells are shown as white circles; extraction wells are shown as white triangles.

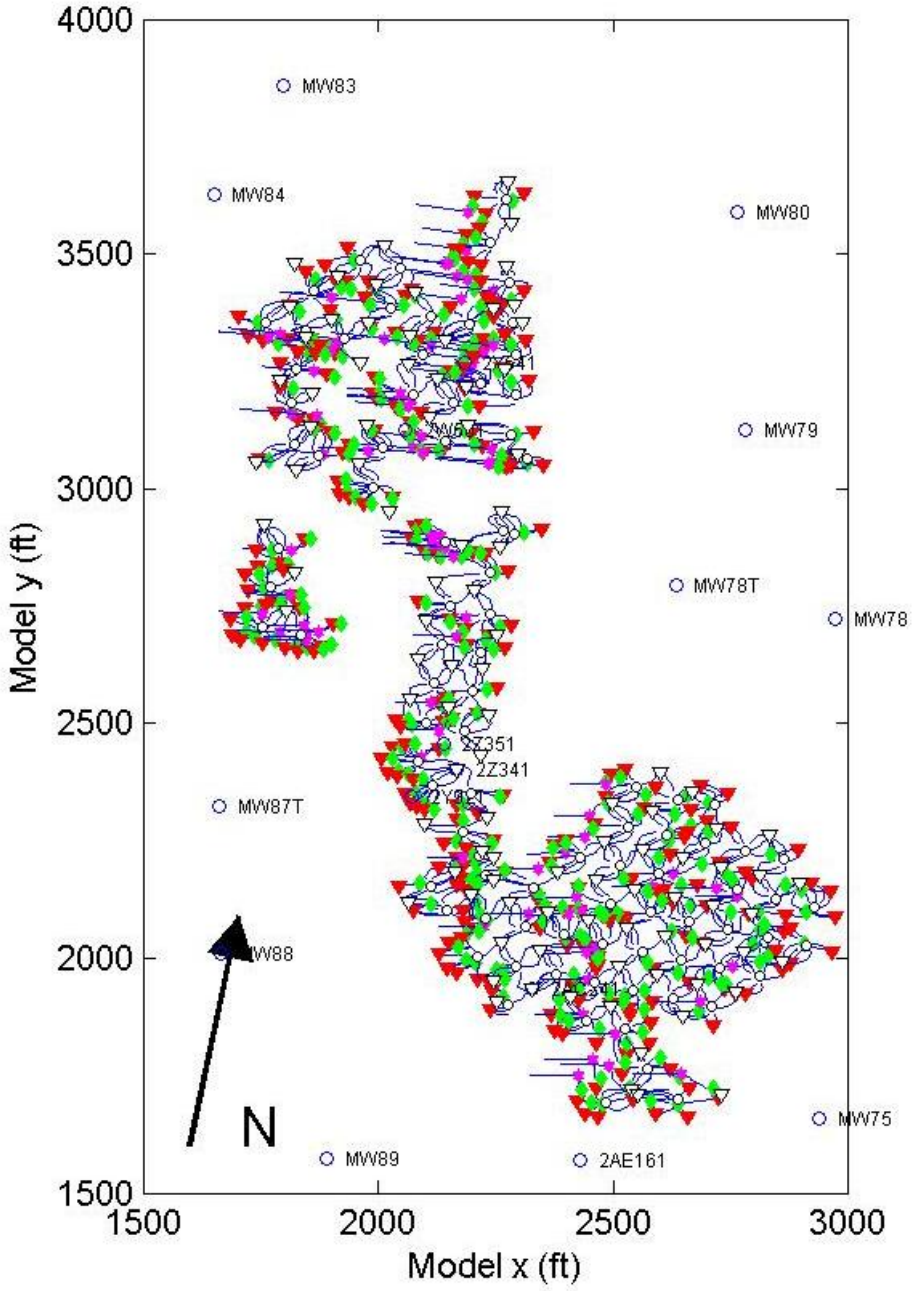


Figure 20. Paths of injected particles during the ISL mining operations, restoration operations, and an additional 20 years after restoration is completed. Injection wells are shown as white circles; extraction wells are shown as white triangles. Red triangles represent the particle position at the end of the ISL mining period; green diamonds represent the particle position at the end of the groundwater sweep; and magenta hexagons represent the particle position at the end of the restoration period. The particles were released midway (760 days) into the ISL mining operations.

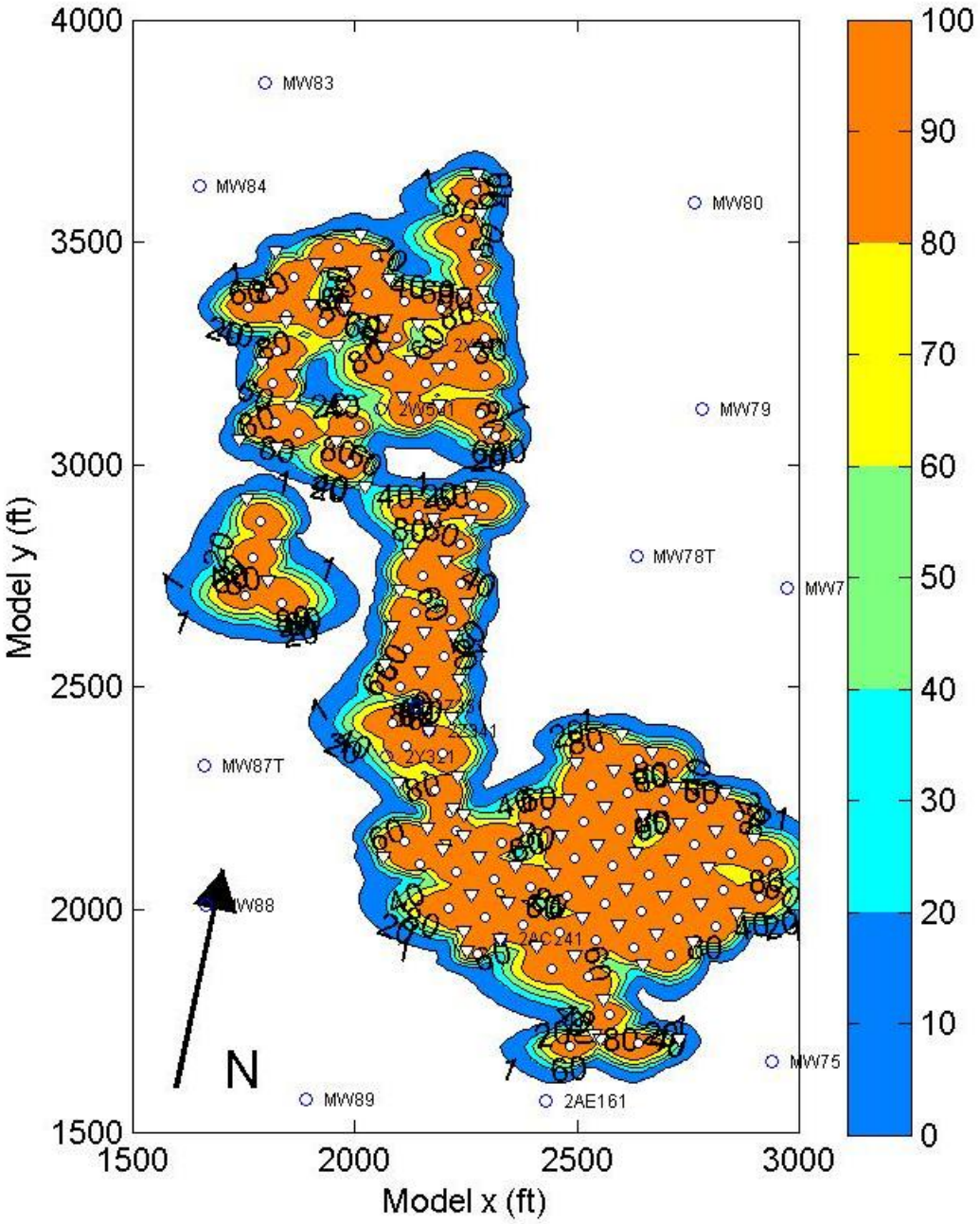


Figure 21. Percentage of lixiviant at each position at the end of the ISL mine operations. Contour intervals are 1%, 20%, 40%, 60%, and 80%. Injection wells are shown as white circles; extraction wells are shown as white triangles.

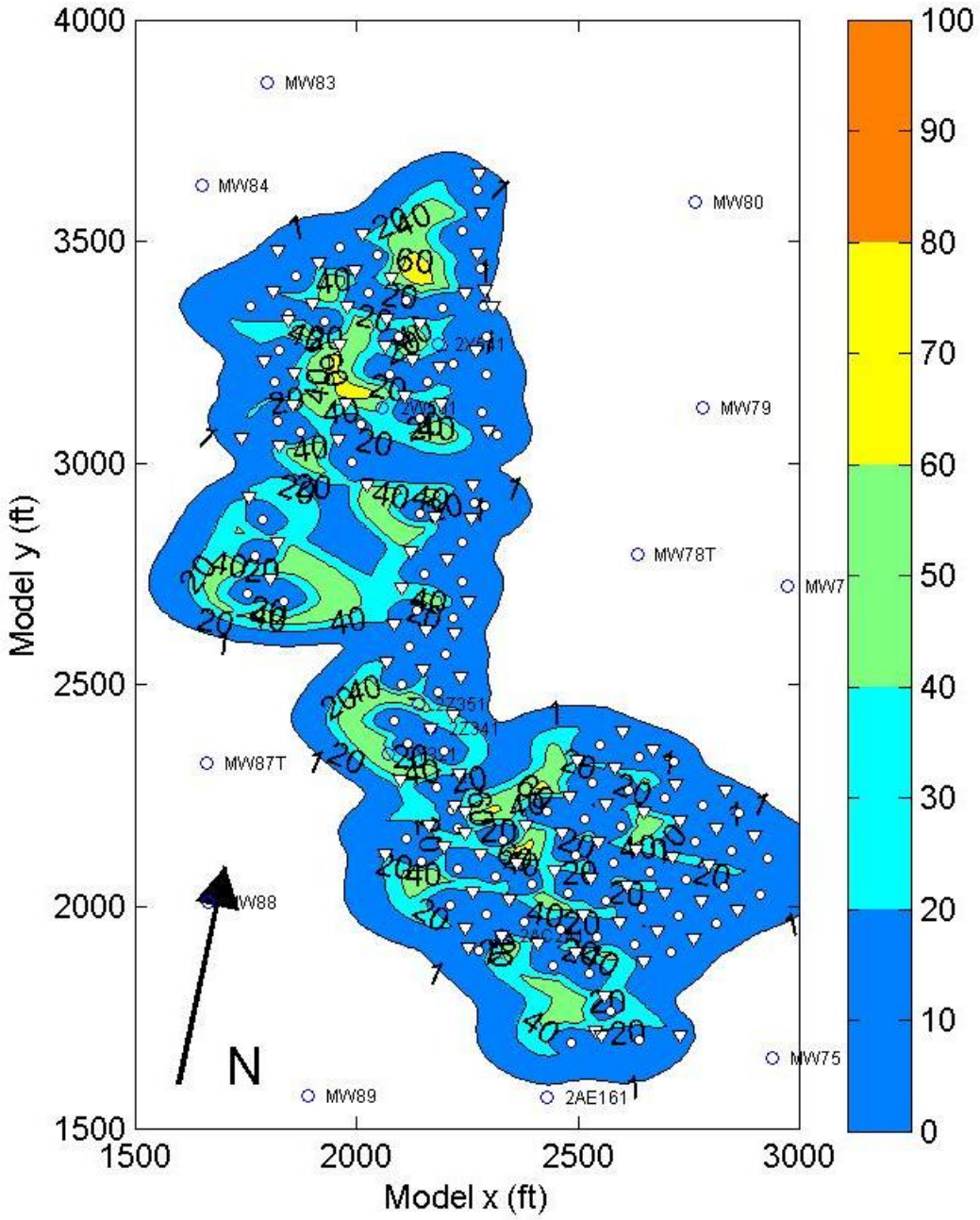


Figure 22. Percentage of lixiviant at each position at the end of the restoration operations. Contour intervals are 1%, 20%, 40%, 60%, and 80%. Injection wells are shown as white circles; extraction wells are shown as white triangles.

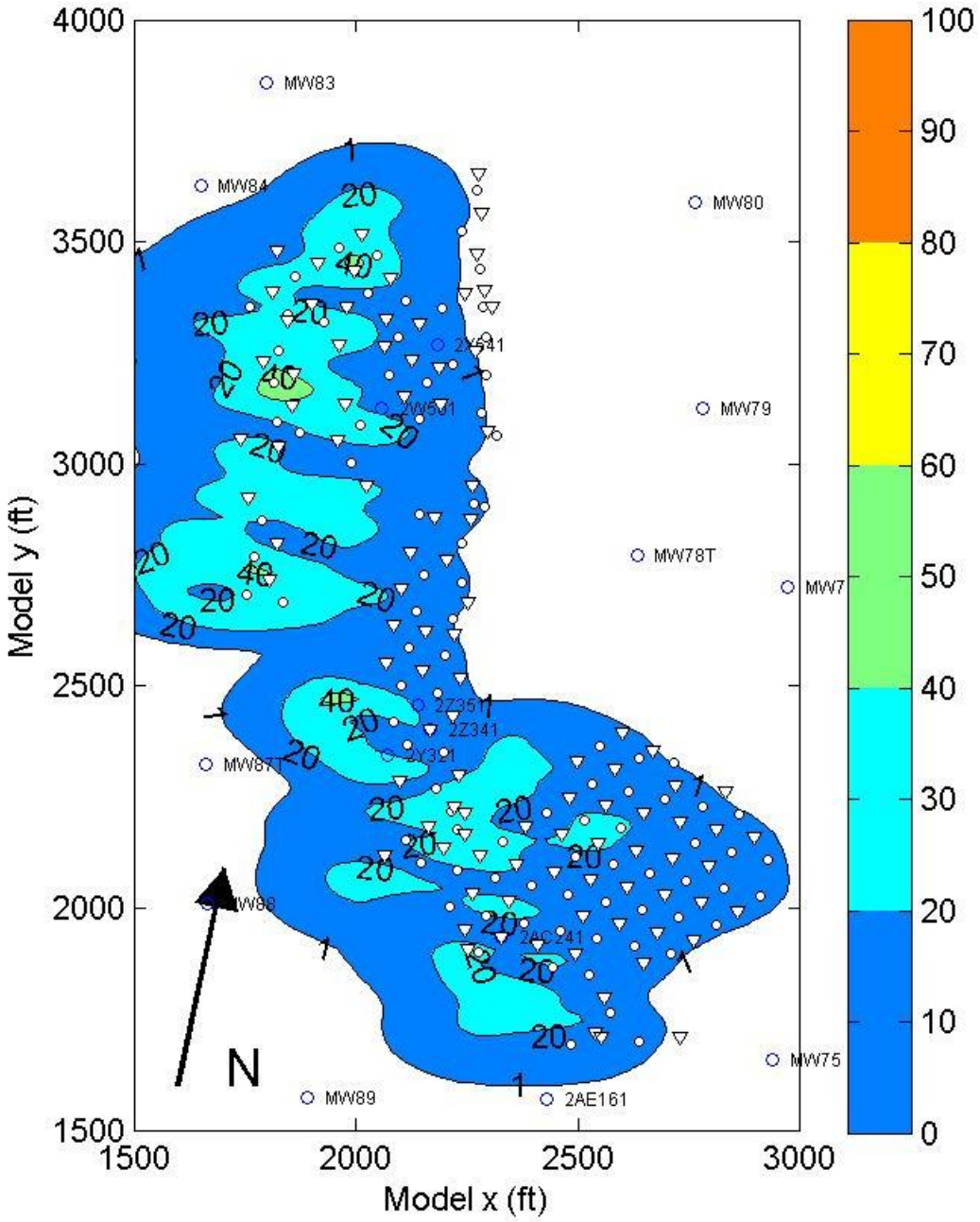


Figure 23. Percentage of lixiviant at each position 20 years after restoration was completed. Contour intervals are 1%, 20%, 40%, 60%, and 80%. Injection wells are shown as white circles; extraction wells are shown as white triangles.

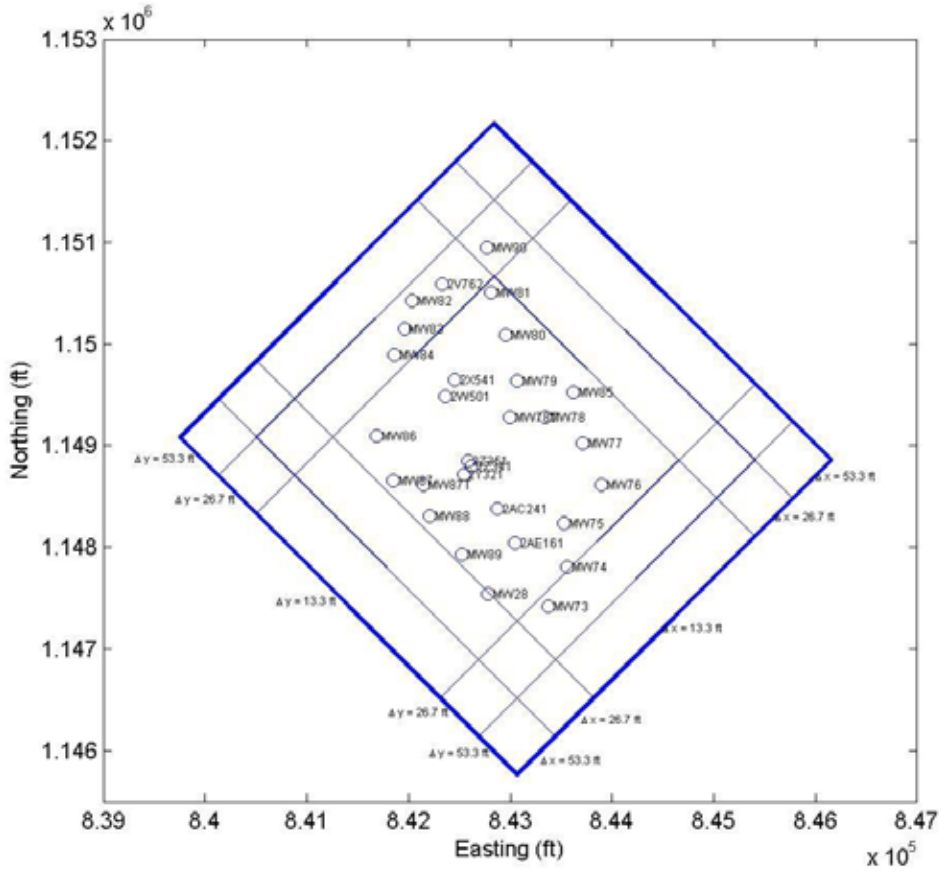


Figure 24. Model domain for alternative model (thick blue line). Thin blue lines are boundaries between regions with different grid block spacing, as labeled.

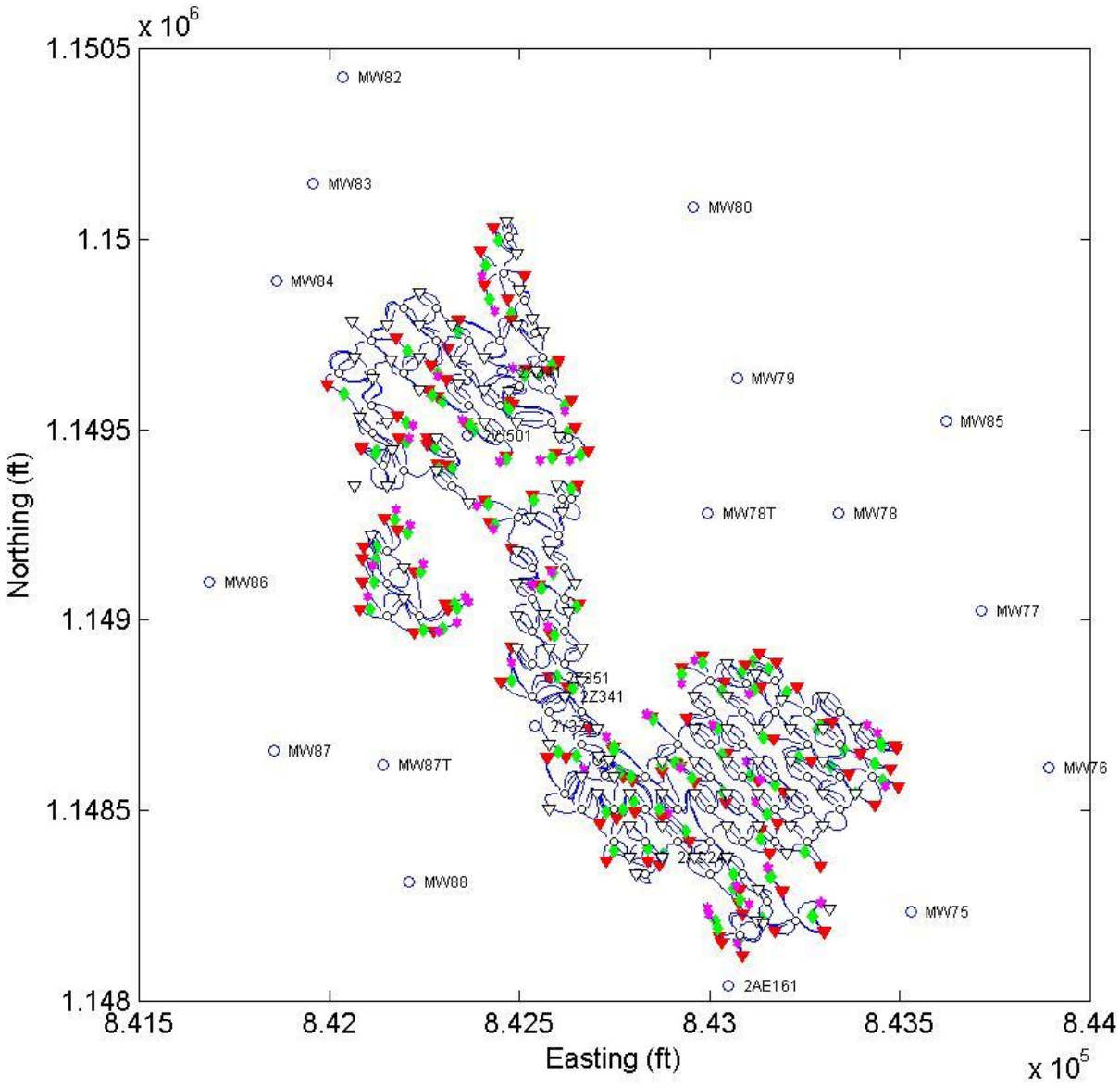


Figure 25. Paths of injected particles, based on the alternative flow model, during the ISL mining operations, restoration operations, and an additional 20 years after restoration is completed. Injection wells are shown as white circles; extraction wells are shown as white triangles. Red triangles represent the particle position at the end of the ISL mining period; green diamonds represent the particle position at the end of the groundwater sweep; and magenta hexagons represent the particle position at the end of the restoration period. The particles were released at the start of the ISL mining operations. Injection wells are shown as white circles; extraction wells are shown as white triangles.

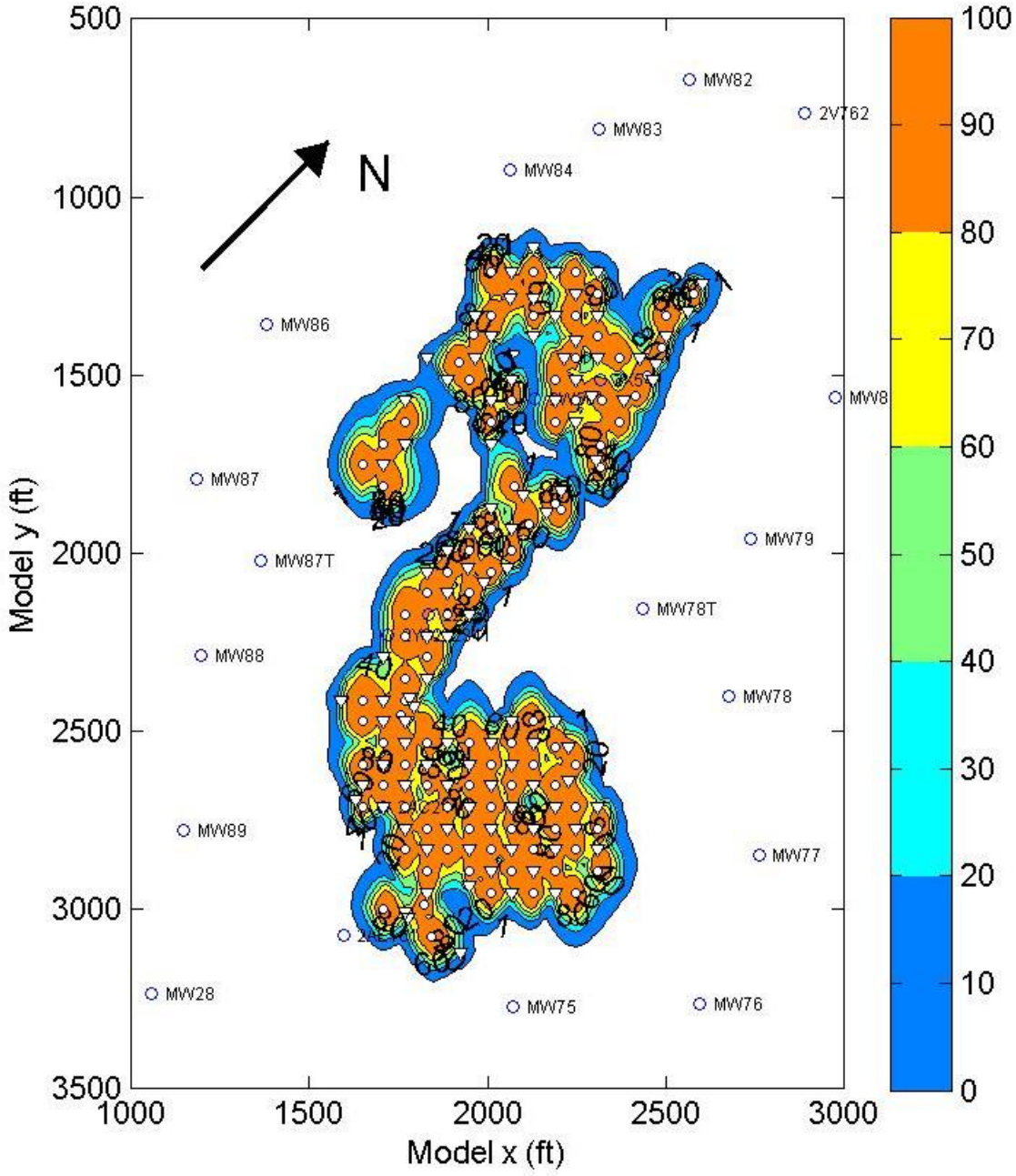


Figure 26. Percentage of lixiviant at each position at the end of the ISL mine operations simulated using the alternative model. Contour intervals are 1%, 20%, 40%, 60%, and 80%. Injection wells are shown as white circles; extraction wells are shown as white triangles.

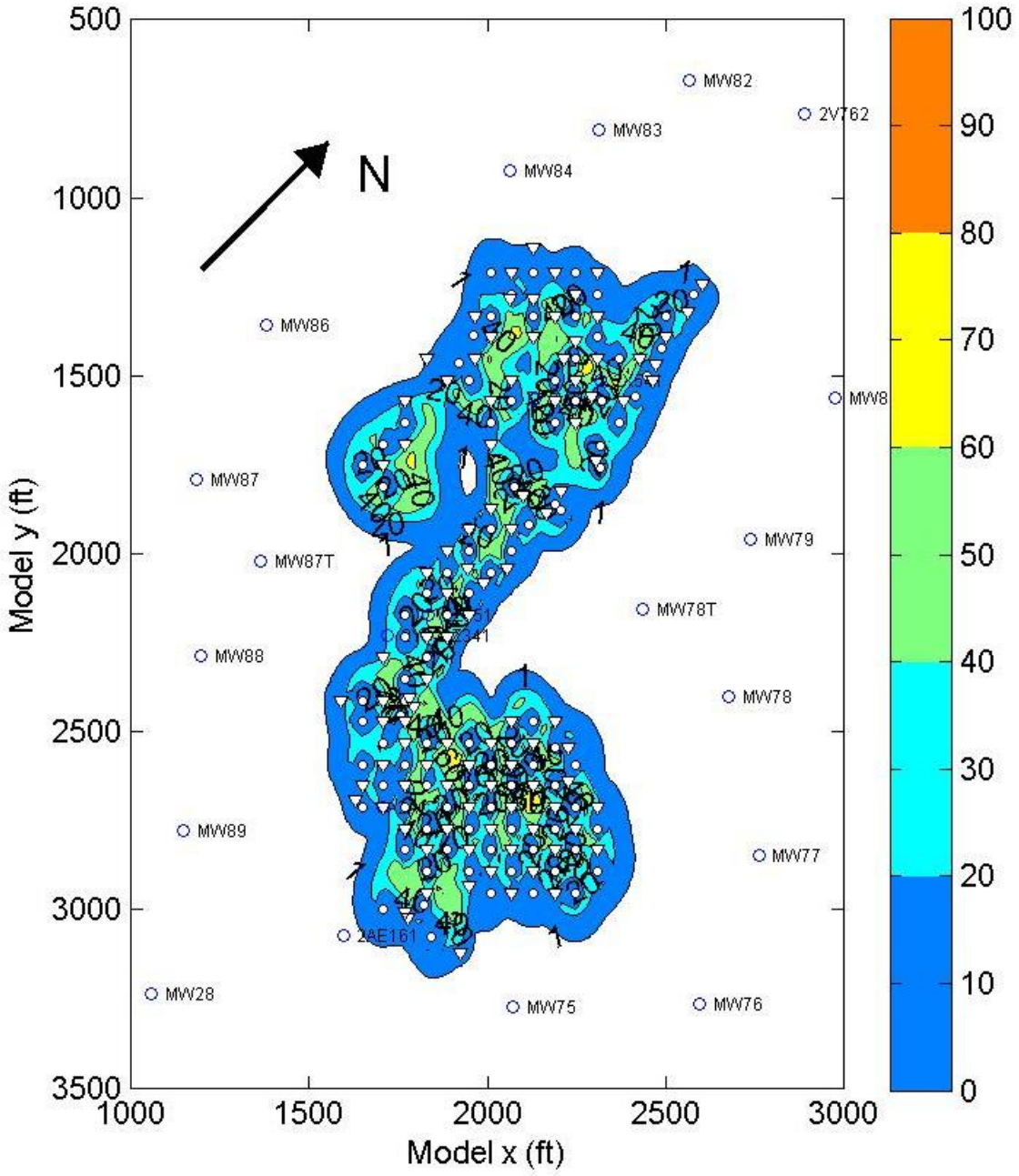


Figure 27. Percentage of lixiviant at each position at the end of the restoration operations simulated using the alternative model. Contour intervals are 1%, 20%, 40%, 60%, and 80%. Injection wells are shown as white circles; extraction wells are shown as white triangles.

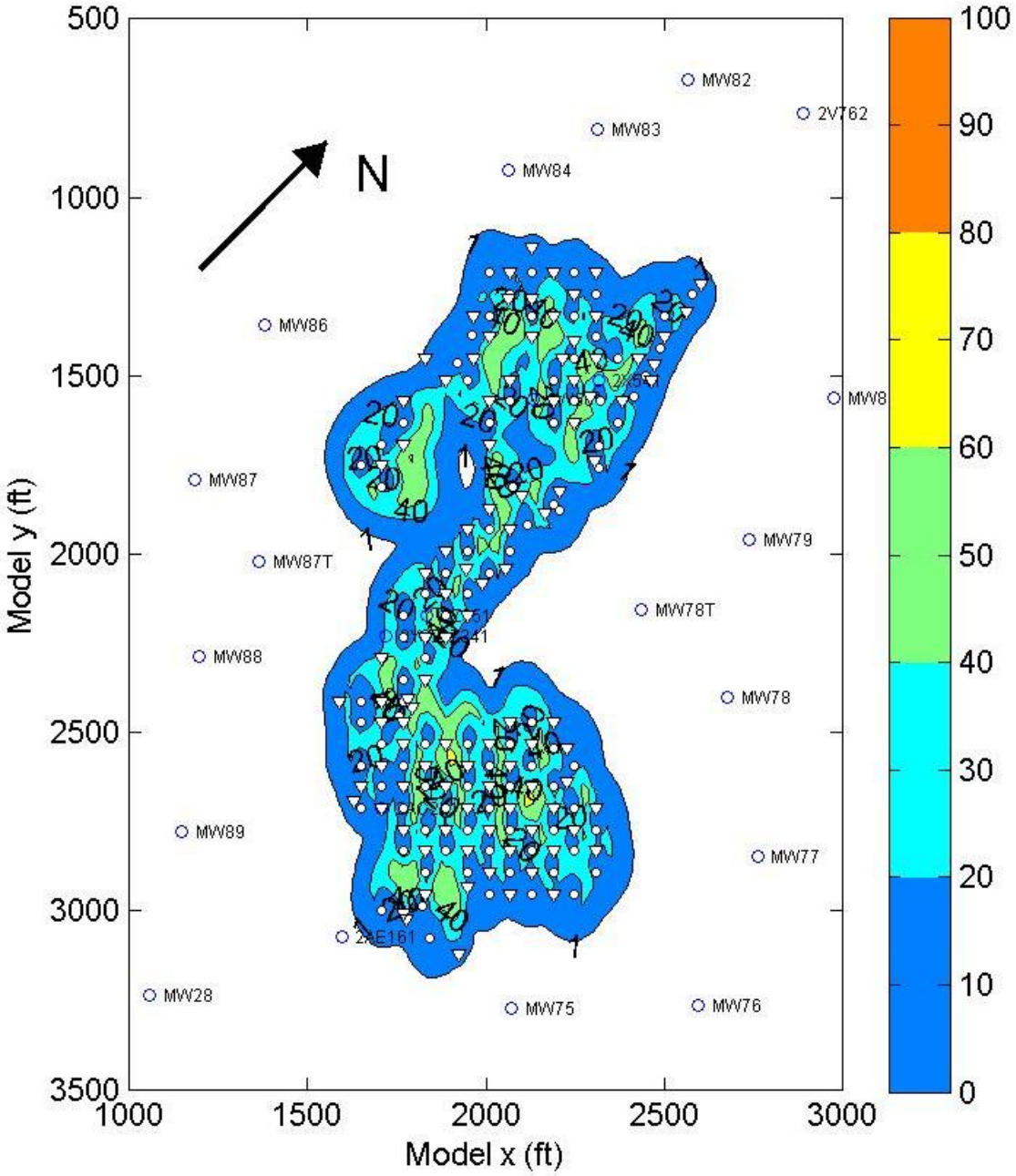


Figure 28. Percentage of lixiviant at each position 20 years after completion of the restoration phase simulated using the alternative model. Contour intervals are 1%, 20%, 40%, 60%, and 80%. Injection wells are shown as white circles; extraction wells are shown as white triangles.

Endnotes

1 *See* "In Situ Mining Research," Proceedings of the Bureau of Mines, Technology Transfer Seminar, Denver, Colo., August 5, 1981, mines.az.gov/DigitalLibrary/usbm_ic/USBMIC8852InSituMining.pdf. Accessed August 25, 2011. *See also* BuMines IC8777, "Uranium In-Situ Mining in the United States," 1978, babel.hathitrust.org/cgi/pt?id=mdp.39015078453639. Accessed August 25, 2011. For industry perspective, *see* Wyoming Mining Association, "In-Situ Recovery," WMA website, wma-minelife.com/uranium/uranium.html. Accessed August 25, 2011. The WMA's full description of ISL mining is that it is "a noninvasive, environmentally friendly mining process involving minimal surface disturbance which extracts uranium from porous sandstone aquifers by reversing the natural processes which deposited the uranium." *See also* Bill Boberg, "Uranium Mining by In-Situ Recovery (ISR) Technology," Ur-Energy, Inc., 2006, nma.org/pdf/uranium/060409_in_situ.pdf. Accessed August 25, 2011.

2 U.S. Environmental Protection AgencyEPA, Review of 40 CFR 192, May 27, 2010 , epa.gov/rpdweb00/tenorm/REVIEW40CFR192.htm. Accessed August 25, 2011.

3 EPA has stated in public meetings that it does not expect to issue even a draft until early 2012.

4 For the Colorado rules, *see* Colorado Mined Land Reclamation Board, Mineral Rules and Regulations of the Colorado Mined Land Reclamation Board for Hard Rock, Metal, and Designated Mining Operations, State of Colorado, Effective September 30, 2010, mining.state.co.us/rulesregs/HardRockRulesAdoptedAug122010EffSep30.pdf. Accessed August 25, 2011. The issue of states' adopting improved mining laws for regulating conventional uranium recovery is a matter that is not addressed in detail in this paper. As an example, both New Mexico (in 1994) and Colorado (in 2008) improved the legal and regulatory framework of uranium recovery in their respective states. It should be noted that Colorado's mining rules have been challenged by industry. *See* "Powertech Challenges State's Uranium Mining Rules," *North Colorado Business Report,* November 11, 2010, ncbr.com/article.asp?id=54553. Accessed August 25, 2011.

5 U.S. Government, Abandoned Mined Lands Portal, a federal partnership of several agencies with cross-cutting jurisdiction, abandonedmines.gov/p.html. Accessed August 25, 2011. With respect to the scale of the cleanup necessary for uranium mines, the U.S. government states: "The uranium mining industry began in the U.S. in the 1940s primarily to produce uranium for weapons and later for nuclear fuel. Although there are about 4,000 mines with documented production, the EPA—with information provided by other federal, state, and tribal agencies—has identified 15,000 mine locations with uranium occurrence in 14 western states. Most of those locations are found in Colorado, Utah, New Mexico, Arizona, and Wyoming, with about 75 percent of those on federal and tribal lands. The majority of these sites were conventional (open-pit and underground) mines." Abandoned Mined Lands Portal, "Abandoned Uranium Mines," abandonedmines.gov/wbd_um.html. Accessed August 25, 2011.

6 EPA has stated in public meetings that it does not expect to issue even a draft until early 2012.

7 U.S. Government, Abandoned Mined Lands Portal, a federal partnership of several agencies with cross-cutting jurisdiction, abandonedmines.gov/p.html. Accessed August 25, 2011. With respect to the scale of the cleanup necessary for uranium mines, the U.S. government states: "The uranium mining industry began in the U.S. in the 1940s primarily to produce uranium for weapons and later for nuclear fuel. Although there are about 4,000 mines with documented production, the EPA—with information provided by other federal, state, and tribal agencies—has identified 15,000 mine locations with uranium occurrence in 14 western states. Most of those locations are found in Colorado, Utah, New Mexico, Arizona, and Wyoming, with about 75 percent of those on federal and tribal lands. The majority of these sites were conventional (open-pit and underground) mines." Abandoned Mined Lands Portal, "Abandoned Uranium Mines," accessed August 25, 2011, abandonedmines.gov/wbd_um.html.

8 The Uranium Mill Tailings Radiation Control Act (UMTRCA), discussed *infra* at 14, and 68-69, directs EPA to set standards for protection of the environment and public health for uranium recovery, which are found at 40 CFR 192. Those regulations have not been fully updated for two decades.

9 U.S. Energy Information Administration, Uranium Marketing Annual Report, May 31, 2011, eia.gov/uranium/marketing.

10 For the Colorado rules, *see* Colorado Mined Land Reclamation Board, Mineral Rules and Regulations of the Colorado Mined Land Reclamation Board for Hard Rock, Metal, and Designated Mining Operations, State of Colorado, Effective September 30, 2010, mining.state.co.us/rulesregs/HardRockRulesAdoptedAug122010EffSep30.pdf. Accessed August 25, 2011. The issue of states' adopting improved mining laws for regulating conventional uranium recovery is a matter that is not addressed in detail in this paper. As an example, both New Mexico (in 1994) and Colorado (in 2008) improved the legal and regulatory framework of uranium recovery in their respective states. It should be noted that Colorado's mining rules have been challenged by industry. *See* "Powertech Challenges State's Uranium Mining Rules," *North Colorado Business Report,* November 11, 2010, ncbr.com/article.asp?id=54553. Accessed August 25, 2011.

11 *See* U.S. Government, Abandoned Mined Lands Portal, "Abandoned Uranium Mines."

12 William L. Chenoweth, "Historical Review of Uranium Production from the Todilto Limestone, Cibola and McKinley Counties, New Mexico," *New Mexico Geology* 7 (November 1985): 82-83, geoinfo.nmt.edu/publications/periodicals/nmg/downloads/7/n4/nmg_v7_n4_p80.pdf. Accessed August 25, 2011.

13 U.S. Department of Energy/EIA, Uranium Industry Annual 1994 (July 1995): viii., ftp://ftp.eia.doe.gov/nuclear/047894.pdf. Accessed August 25, 2011.

14 Id., p. ix.

15 42 U.S.C. § 2011, et seq., law.cornell.edu/uscode/42/usc_sec_42_00002011----000-.html. According to the NRC, "In general terms, 'source material' means either the element thorium or the element uranium, provided that the uranium has not been enriched in the isotope uranium-235. Source material also includes any combination of thorium and uranium, in any physical or chemical form, or ores that contain by weight one-twentieth of one percent (0.05 percent) or more of uranium, thorium, or any combination thereof. Depleted uranium (left over from uranium enrichment) is considered source material." nrc.gov/materials/srcmaterial.html. Accessed August 25, 2011.

16 42 U.S.C. § 2092, law.cornell.edu/uscode/42/2092.html. Accessed August 25, 2011.

17 63 NRC 510, 512-13 (2006).

18 *See* Train v. Colorado Public Interest Research Group, 426 U.S. 1, 1976, supreme.justia.com/us/426/1/case.html. Accessed August 25, 2011. The real-world effect of this patchwork of laws has engendered dismay. In describing the actions of the Interior Department, George Arthur, Chairman of the Resources Committee of the Navajo Nation Council, testified: "The Department of the Interior has been in the pocket of the uranium industry, favoring its interests and breaching its trust duties to Navajo mineral owners." Testimony of the Honorable George Arthur, Chair of the Navajo Tribal Council Resources Committee, before Oversight and Government Reform Committee of the United States House of Representatives, October 23, 2007, oversight-archive.waxman.house.gov/documents/20071127163605.pdf. Accessed August 22, 2011. *See also* Chairman Arthur's testimony, 2, citing McClanahan v. Hodel, No. Civ. 83-161-M, 14 Indian L. Rep. 3113 (D.N.M. 1978), appeals dismissed, vac. as moot, nos. 87-1186 and 87-1234 (10th Cir. 1988). This case invalidated fraudulently obtained uranium leases approved by the Bureau of Indian Affairs (BIA) and observed *who observed?* that "the BIA and Interior generally seem to have been more concerned throughout the leasing processing with their relationship with Mobil [the uranium lessee] than their relationship with the Indian owners."

19 Atomic Energy Act of 1954, as Amended (hereinafter "AEA"), found in Nuclear Regulatory Legislation, NUREG-0980, Vol.

1, No. 9, 111th Cong., 2nd Sess., January 2011, 7-233, nrc.gov/reading-rm/doc-collections/nuregs/staff/sr0980/v1/sr0980v1.pdf#pagemode=bookmarks&page=5. Accessed August 25, 2011.

20 *See* EPA, "Technologically-Enhanced, Naturally-Occurring Radioactive Materials From Uranium Mining" (hereinafter "TENORM Report"), 2-1. April 2008. Volume 1 can be found at epa.gov/rpdweb00/docs/tenorm/402-r-08-005-voli/402-r-08-005-v1.pdf and Volume 2 at epa.gov/radiation/docs/tenorm/402-r-08-005-volii/402-r-08-005-v2.pdf. Accessed August 25, 2011.

21 A comprehensive treatment of the types of wastes found at the conventional mining and milling sites would significantly extend the length of this report. Therefore we refer the reader to an excellent summary of the volume and characteristics of uranium mining and milling waste. *See* EPA, TENORM Report, 3-1–3-31. April 2008.

22 The EPA describes "tailings" as follows: "Wastes produced by the extraction or concentration of uranium or thorium from any ore processed primarily for its source material content is defined by Section 11e.(2) of the Atomic Energy Act as byproduct material. That material is not considered to be TENORM in the U.S., and is regulated by the NRC or its Agreement States. Under UMTRCA, the NRC must utilize EPA environmental protection standards to develop its regulations for active and inactive uranium milling and extraction facilities. The NRC does not have regulatory authority over conventional type uranium mine wastes." Id., Appendix IV, AVI-5.

23 For a thorough treatment of federal responsibility for the uranium mill tailings cleanup, see Paul Robinson, "Uranium Mill Tailings Remediation Performed by the U.S. DOE: An Overview." Southwest Research & Information Center, May 18, 2004, sric.org/U_Mill_Tailing_Remediation_05182004.pdf. Accessed August 25, 2011.

24 For the full text of this law, see *Nuclear* Regulatory Legislation, 111th Congress, 2nd Session, NUREG-0980, Vol. 1, No. 9, January 2011, 503-526, nrc.gov/reading-rm/doc-collections/nuregs/staff/sr0980/v1/sr0980v1.pdf. Accessed August 25, 2011.

25 *See* U.S. Department of Energy/EIA, "U.S. Uranium Production Facilities: Operating History and Remediation Cost Under Uranium Mill Tailings Remedial Action Project as of 2000," January 11, 2005, eia.doe.gov/cneaf/nuclear/page/umtra/title1map.html. Accessed August 25, 2011. *See also* EPA, TENORM Report, Vol. 1, 4-15–4-18. We have not yet identified an entirely comprehensive assessment of uranium mining and milling's legacy costs, but this EPA report, which relies on the report from the U.S. Department of Energy, Energy Information Agency (hereinafter "DOE/EIA"), is one of the few efforts we have discovered that make an attempt at a comprehensive tally of some of the costs.

26 EPA, TENORM Report, Vol. 1, 4-15–4-20. Here the EPA presents some cost data for reclaiming uranium mines and milling facilities. Costs can vary dramatically from site to site and will be dependent on a host of factors.

27 James H. Clarke and Frank L. Parker, Vanderbilt University, "Uranium Recovery and Remediation of Uranium Mill Tailings: Russian and U.S. Experience," from *Cleaning Up Sites Contaminated With Radioactive Materials*, International Workshop Proceedings, Glenn E. Schweitzer, Frank L. Parker, and Kelly Robbins, editors, Committee on Cleaning Up of Radioactive Contamination: Russian Challenges and U.S. Experience, Office for Central Europe and Eurasia Development, Security, and Cooperation, Policy and Global Affairs, National Research Council of the National Academies, in cooperation with the Russian Academy of Sciences, the National Academies Press, Washington, D.C., nap.edu/openbook.php?record_id=12505&page=69; at 73. Accessed August 25, 2011.

28 Francie Diep, "An 'Overwhelming Problem' in the Navajo Nation," *Scienceline,* December 30, 2010, scienceline.org/2010/12/an-%E2%80%9Coverwhelming-problem%E2%80%9D-in-the-navajo-nation/. Accessed August 25, 2011. Here an EPA official states that just assessing the uranium mines in the Navajo Nation costs the EPA about $12 million every year, and that remediation would cost "in the hundreds of millions." Another reference source for ongoing cleanup information that is frequently updated is the World Information Service on Energy (hereinafter "WISE") Uranium Project website. For the basic home page, *see* wise-uranium.org/indexu.html#UMMCI. Accessed August 25, 2011. For more extensive treatments of decommissioning sites in the United States, regardless of the regulator and usefully presented by state, *see* "Decommissioning Projects—USA" (last updated December 21, 2010), wise-uranium.org/udusa.html. Accessed August 25, 2011. And for uranium Superfund sites, *see* EPA, *earlier references attribute this to "U.S. Government"* Abandoned Mined Lands Portal, epa.gov/aml/index.htm. Accessed August 25, 2011. Administered by the EPA, Superfund is the government's program to clean up uncontrolled hazardous waste sites.

29 By 1990, mine production of uranium had dropped to 5.9 million pounds of U_3O_8; production continued throughout the 1990s and early 2000s at even lower levels. With the exception of larger declines in the early 1990s (in 1992, mines produced 1 million pounds) and early 2000s (in 2003, mines produced 2.2 million pounds), uranium production from mines has stayed at around 4 million pounds of U_3O_8 a year for the past two decades. DOE/EIA, "Uranium Industry Annual 1992," 60, tonto.eia.doe.gov/FTPROOT/nuclear/047892.pdf. Accessed August 25, 2011. *See also* DOE/EIA, "Summary Production Statistics of the U.S. Uranium Industry," July 15, 2010, eia.doe.gov/cneaf/nuclear/dupr/usummary.html. Accessed August 4, 2011.

30 Environmental Working Group, U.S. Mining Database, 2007, ewg.org/sites/mining_google/US/analysis.php. Accessed August 22, 2011.

31 uxc.com/data/uxc_AboutUraniumPrices.aspx. Accessed August 4, 2011. *incomplete info.*

32 "Fast Breeder Reactor Programs: History and Status," Research Report 8, International Panel on Fissile Materials, February 2010, p. 6, ipfmlibrary.org/rr08.pdf. Accessed August 25, 2011.

33 Ux Consulting Company, "UxC Nuclear Fuel Price Indicators (delayed)," uxc.com/review/uxc_Prices.aspx. Accessed August 4, 2011.

34 *See*, for example, the carefully worded statement of the International Atomic Energy Agency on the subject: "As we look to the future, presently known resources fall short of demand. However, if significant and timely exploration is conducted and sufficient resources are discovered, there could be an adequate supply of lower cost uranium to satisfy demand. Nevertheless, if the exploration effort is insufficient, or is not implemented in a timely manner, it will become necessary to rely on very high cost conventional or unconventional resources to meet demand as the lower cost known resources are exhausted. Therefore, to ensure maximum utilization of newly discovered resources, exploration must begin relatively soon." International Atomic Energy Agency, 2001, "Analysis of Uranium Supply to 2050," www-pub.iaea.org/MTCD/publications/PDF/Pub1104_scr.pdf, at 5. Accessed August 25, 2011.

35 I.A. Matthews and M.J. Driscoll, "A Probabilistic Projection of Longterm Uranium Resource Costs," Center for Advanced Nuclear Energy Systems, Massachusetts Institute of Technology, June 2010, p. 25, web.mit.edu/mitei/docs/spotlights/nuclear-fuel-cycle-nfc-119.pdf. *accessed when?*

36 DOE/EIA, "Summary Production Statistics of the U.S. Uranium Industry," July 15, 2010.

37 DOE/EIA, "Annual Energy Review 2009," p. 279, Table 9.3, "Uranium Overview, Selected Years, 1949-2008," eia.doe.gov/emeu/aer/pdf/pages/sec9_7.pdf. Accessed August 25, 2011. *See also* DOE/EIA, "Uranium Industry Annual 1992," October 1993, p. 38, Table 17, "Uranium Concentrate Production by State, 1947-1992," tonto.eia.doe.gov/FTPROOT/nuclear/047892.pdf, *and* DOE/EIA, "Total Production of Uranium Concentrate in the United States, 1996-3rd Quarter 2010," November 9, 2010, eia.doe.gov/cneaf/nuclear/dupr/qupd_tbl1.html. Accessed August 25, 2011.

38 "World Uranium Mining" (updated April 2011), world-nuclear.org/info/inf23.html.

39 DOE/EIA, "Domestic Uranium Production Report," July 15, 2010, eia.gov/cneaf/nuclear/dupr/dupr.html. Accessed August 25, 2011.

40 EPA, "Uranium Location Database Compilation," August 2006, epa.gov/rpdweb00/docs/tenorm/402-r-05-009.pdf. *accessed when?*

41 *See* Manuel Quinones, "Uranium: Va. Becomes Ground Zero for Mining Efforts," *E&E Daily*, May 27, 2011, eenews.net/Greenwire/2011/05/27/2 (subscription required).

42 Natural Resources Defense Council, "Uranium ISL Mine Database," Table 2, 20-27.

43 DOE/EIA, "Uranium Purchased by Owners and Operators of U.S. Civilian Nuclear Power Reactors by Origin Country and Delivery Year," Table 3, August 18, 2010. eia.doe.gov/cneaf/nuclear/umar/table3.html. Accessed August 25, 2011.

44 Southwest Research and Information Center, "Is There a Need for New Uranium Mines in the U.S.?" *Voices From the Earth* 10 (Spring 2009): 5, sric.org/voices/2009/v10n1/Need%20for%20New%20U%20Mines.pdf. Accessed August 25, 2011.

45 WNA, "World Uranium Mining," April 2011, world-nuclear.org/info/inf23.html. Accessed August 25, 2011.

46 Korea Electric Power Corp. (Kepco) may invest up to $45 million in exchange for a 40 percent interest in a Canadian company's Gas Hills uranium properties in Wyoming. Under a binding agreement with Vancouver-based Strathmore Minerals Corp. announced on August 5, 2011, the companies set the terms for a possible joint venture for the exploration and development of the Gas Hills Beaver Rim area and for a pre-feasibility study for the entire Gas Hills project, activities that constitute Phase I of the project. Kepco would invest at least $10 million during Phase I. Upon Phase I's completion, Kepco would have the option to invest up to another $35 million in Phase II in exchange for 40 percent ownership of the entire Gas Hills project. *Platts Nuclear News Flashes*, August 8, 2011 (subscription required).

47 eia.gov/forecasts/aeo/source_nuclear.cfm.

48 *See* Table 2 for NRC listing of active and proposed uranium recovery operations that will be licensed and regulated by the NRC.

49 Southwest Research and Information Center, "Uranium Mining & Milling: A Primer," *The Workbook* 1, *orig. document says "Vol. IV"* Nos. 6 and 7 (Nov./Dec. 1979): 225-226, sric.org/uranium/1979_SRIC_URANIUM_PRIMER.pdf. Accessed August 25, 2011.

50 DOE/EIA, "Decommissioning of U.S. Uranium Production Facilities," 1995, 11-14. atomictraveler.com/MillDecommissioningData.pdf. Accessed August 25, 2011. *See also infra* Figure 2 on 12.

51 For more information on conversion, enrichment, and fabrication processes as they relate to the weapons production program, *see* DOE, Office of Environmental Management, "Nuclear Weapons Production Processes and History," Chapter 2 in *Linking Legacies*, January 1997, em.doe.gov/Publications/linklegacy.aspx. Accessed August 25, 2011.The topic of restoration of uranium mills is not discussed in any depth in this report.

52 Institute for Energy and Environmental Research (hereinafter "IEER"), "Uranium: Its Uses and Hazards," July 2005, ieer.org/fctsheet/uranium.html. Accessed August 25, 2011.

53 For a thorough treatment of mine wastes, *see* EPA, TENORM Report, Vol. 1, Chapter 3, "Volume and Characteristics of Uranium Mine Wastes." We also briefly discuss some of the environmental harms associated with conventional uranium recovery, *infra* in Chapter 2.

54 Peter Diehl, "Uranium Mining and Milling Wastes: An Introduction," WISE Uranium Project, August 15, 2004, wise-uranium.org/uwai.html#TAILCHAR. Accessed August 25, 2011. The tailings at conventional mines and their radioactive and toxic characteristics are also described in detail in the EPA TENORM Report, Vol. 1, 3-29: "Wastes are primarily disposed of in the form of a slurry composed of tailings, gangue (defined as the valueless minerals in an ore; that part of an ore that is not economically desirable but cannot be avoided in mining. It is separated from the ore minerals during concentration) (including dissolved base metals), spent beneficiation solutions, and process water bearing carbonate complexes (alkaline leaching) and sulfuric acid (acid leaching), sodium, manganese, and iron. The characteristics of this waste vary greatly, depending on the ore, the beneficiation procedure, and the source of the water (fresh or recycled). The liquid component is usually decanted and re-circulated to the crushing/grinding or leaching circuit. Tailings typically consist of two fractions, sands and slimes. The sand and slimes may be combined and deposited directly in the impoundment or may be distributed through a cyclone such that the sand fraction is directed toward the dam while the slimes are directed to the interior of the pond (Merritt 1971). The fate of radionuclides is of special interest in uranium mill tailings. Radium-226 and thorium-230 are the principal constituents of concern and are associated with the slime fraction of the tailings. Radon-222 (gas) is also a tailings constituent. The concentrations of radionuclides in the tails *tailings?* will vary depending on the leach method used (thorium is more soluble in acid than alkaline leaches). Typically, tailings will contain between 50 and 86 percent of the original radioactivity of the ores depending on the proportion of radon lost during the operation. Other tailings constituents (including metals, sulfates, carbonates, nitrates, and organic solvents) would also be present in the tailings impoundment depending on the type of ore, beneficiation methods, and waste management techniques."

55 EPA, "Uranium Location Database Compilation," August 2006, p. 6, Table 2.

56 SRIC, "Church Rock Spill: 30 Years Later," *Voices From the Earth* 10 (Summer 2009): 6, sric.org/voices/2009/v10n3/voices_10_3_churchrock_spill_30yrs.pdf. Accessed August 25, 2011.

57 EPA, "Addressing Uranium Contamination in the Navajo Nation," epa.gov/region9/superfund/navajo-nation/index.html. Accessed November 8, 2011.

58 DOI, EPA, NRC, DOE, and Indian Health Services, "Health and Environmental Impacts of Uranium Contamination in the Navajo Nation," a report requested by the House Committee on Oversight and Government Reform, June 9, 2008, 4-12, epa.gov/region9/superfund/navajo-nation/pdf/NN-5-Year-Plan-June-12.pdf. Accessed August 25, 2011.

59 *See* note 17 for discussion of 2008 House Oversight Committee Hearings and Navajo testimony.

60 Robert G. McSwain, testimony on the health and environmental impact of uranium mining on the Navajo Nation before the House Committee on Government Oversight and Reform, October 23, 2007, hhs.gov/asl/testify/2007/10/t20071023e.html. Accessed August 25, 2011.

61 F.D. Gilliland et al., "Uranium Mining and Lung Cancer Among Navajo Men in New Mexico and Arizona, 1969 to 1993," *Journal of Occupational and Environmental Medicine* 42 (March 2000): 278-283, journals.lww.com/joem/Abstract/2000/03000/Uranium_Mining_and_Lung_Cancer_Among_Navajo_Men_in.8.aspx (subscription required). Accessed August 25, 2011. *See also* Arjun Makhijani et al., *Nuclear Wastelands: A Guide to Nuclear Weapons Production and Its Health and Environmental Effects*, MIT Press, 1995. serc.carleton.edu/research_education/nativelands/navajo/humanhealth.html. Accessed August 25, 2011.

62 "Resolution of the 20th Navajo Nation Council—Third Year, 2005: Relating to Resources and Diné Fundamental Law; Enacting the Diné Natural Resources Protection Act of 2005; Amending Title 18 of the Navajo Nation Code," sric.org/uranium/DNRPA.pdf. *August 25, 2011*

63 Testimony of the Honorable George Arthur, Chair of the Navajo Tribal Council Resources Committee, before the Oversight and Government Reform Committee of the United States House of Representatives, October 23, 2007, oversight-archive.waxman.house.gov/documents/20071127163605.pdf. Accessed August 25, 2011.

64 EPA, Superfund web portal, updated January 3, 2011, epa.gov/superfund/. Accessed August 25, 2011.

65 F2, Inc., "Five-Year Review Report: Fourth Five-Year Review Report for Uravan Uranium Project (Union Carbide Corp.)," September 2010, p. 19, epa.gov/superfund/sites/fiveyear/f2010080003616.pdf. Accessed August 25, 2011.

66 *See* original EPA placement of Uravan on the National Priorities List, 51 Fed. Reg. 21054, 21063 (June 10, 1986) *and* State of Colorado oversight of the project at cdphe.state.co.us/hm/rpuravan.htm. Accessed August 22, 2011.

67 *See* babel.hathitrust.org/cgi/pt?id=mdp.39015078453639. Accessed August 25, 2011.

68 *See* Figure 2 for a visual representation of the extent to which domestic ISL recovery has supplanted domestic conventional mining for the production of U.S. uranium.

69 DOE/EIA, "U.S. Uranium Mine Production and Number of Mines and Sources," July 15, 2010, eia.doe.gov/cneaf/nuclear/dupr/umine.html. "Domestic Uranium Production Report—Quarterly (3rd Quarter)," November 9, 2010, eia.doe.gov/cneaf/nuclear/dupr/qupd.html. World Nuclear Association (hereinafter "WNA"), "World Uranium Mining," updated May 2010, world-nuclear.org/info/inf23.html. Accessed August 25, 2011.

70 *See Appendix B.* Rosanna M. Neupauer, "Degradation of Groundwater Quality From Uranium In-Situ Leach Mining," May 1, 2009. *where can this paper be accessed? Was it published? See also* Edgar B. Heylmun, "Roll Front Deposits," *International California Mining Journal's Prospecting and Mining Journal* 73 (October 2003), icmj2.com/03Oct/03OctFeature.htm. Accessed August 25, 2011.

71 *See Appendix A.*

72 EPA TENORM Report, Vol. 1, 2-9.

73 Heylmun, "Roll Front Deposits."

74 State of Texas, "Nuclear Energy," window.state.tx.us/specialrpt/energy/nonrenewable/nuke.php. Accessed August 22, 2011.

75 Molly Mechtenberg-Berrigan, "Radioactive Danger in Drinking Water," Nukewatch *Pathfinder,* Fall 2005, p. 9, nukewatchinfo.org/Quarterly/20053fall/page9.pdf.

76 EPA, TENORM Report, Vol. 1, 3-10.

77 Dustin Bleizeffer, "Water, Spill, Traffic Top Citizens' Concerns," *Wyoming Star-Tribune,* September 30, 2010, trib.com/business/energy/article_764aae9c-f584-5bce-8fa4-de2de1dc3568.html. Accessed August 25, 2011.

78 EPA, TENORM Report, AV, 11-17.

79 OECD Nuclear Energy Agency and IAEA, *Environmental Remediation of Uranium Production Facilities,* OECD Publishing, February 27, 2002, 277.

80 *See* 10 CFR 51.45 for the general requirements for an applicant's Environmental Report, nrc.gov/reading-rm/doc-collections/cfr/part051/part051-0045.html. *See* 10 CFR 51.60 for the requirements for Environmental Reports–Materials Licenses, nrc.gov/reading-rm/doc-collections/cfr/part051/part051-0060.html. Accessed August 25, 2011.

81 *See* "Contention 8 of the Petition to Intervene and Request for Hearing of the Oglala Sioux Tribe," before the United States Nuclear Regulatory Commission, Atomic Safety and Licensing Board, at 34. Filed April 6, 2010, wba.nrc.gov:8080/ves/view_contents.jsp.

82 That is, if a prescient member of the public (1) filed original contentions at the earliest possible moment of the licensing process and essentially put in "placeholder" NEPA contentions years in advance, (2) amended those contentions almost immediately once the draft EIS was issued, and (3) amended the contentions for a potential third time if the final EIS addressed positions not previously identifiable from the draft. *See* 10 CFR 2.323(a), nrc.gov/reading-rm/doc-collections/cfr/part002/part002-0323.html. Accessed August 25, 2011. This is an onerous and expensive process in the extreme for public interest groups. For a full discussion, *see* Anthony Z. Roisman, "Regulating Nuclear Power in the New Millennium (The Role of the Public)," *Pace Environmental Law Review* 26 (Summer 2009): 342, digitalcommons.pace.edu/cgi/viewcontent.cgi?article=1556&context=envlaw. Accessed August 25, 2011.

83 Id., 342.

84 NRC, Final GEIS, nrc.gov/materials/uranium-recovery/geis.html. Accessed August 25, 2011.

85 Draft GEIS, July 2008, xxxiii. The draft GEIS is available on the NRC ADAMS website at nrc.gov/reading-rm/adams.html; search the database with the accession number ML082030186.

86 NRC, GEIS, xxxv-xxxvi.

87 *See* NRDC Comments on Lost Creek, Moore Ranch, and Nichols Ranch Supplemental EISs, discussion at 4-7, pbadupws.nrc.gov/docs/ML1008/ML100850378.pdf. Accessed August 25, 2011.

88 *See Appendix A.*

89 Id., 1.

90 Id., 16.

91 *See Appendix A.*

92 *See* NRC, "Standard Review Plan for In Situ Leach Uranium Extraction License Applications, Final Report," June 2003, NUREG-1569 (hereinafter "SRP'), 6-9: "The primary goal of a restoration program is to return the water quality within the exploited production zone and any affected aquifers to pre-operational (baseline) water quality conditions. Recognizing that in situ leach operations fundamentally alter ground-water geochemistry, restoration activities *are not likely to return ground-water quality* to exact water quality that existed at every location prior to in situ leach operations" (emphasis added), nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1569/sr1569.pdf. Accessed August 25, 2011.

93 Neupauer, "Degradation of Groundwater Quality from Uranium In-Situ Leach Mining," May 1, 2009.

94 *See Appendix A.* The ability to produce reducing conditions, or "redox" potential, is key to understanding how heavy metals in aquifers behave. A reduction potential is a measure of the tendency of a chemical species to acquire electrons and thereby be reduced.

95 A.J. Thompson et al., "Generic Environmental Report in Support of the Nuclear Regulatory Commission's Generic Environmental Impact Statement for In Situ Leach Uranium Recovery Facilities," National Mining Association, November 30, 2007, nma.org/Attach/NMA%20Generic%20Enviromental%20Report%20on%20In%20Situ%20Ur%20Recovery.pdf.

96 Mark Moxley, Land Quality Division, Wyoming Department of Environmental Quality, "Report of Investigation: Power Resources, Inc., Smith Ranch–Highland Uranium Project," November 21, 2007, 4. EPA has also detailed significant problems. *See* EPA's TENORM Report, Vol. II, at AIII-8: "In the United States, excursions have been frequently detected by the monitoring wells located around the well field. One of the more infamous and environmentally problematic ISL operations was located at Irigaray, Wyoming. This facility was plagued by persistent environmental excursions which began in mid-March of 1979, and were not brought under control until early July of that same year. The Wyoming Department of Environmental Quality reported that these excursions were a result of the neglect of injection pressure monitoring as well as testing the integrity of the well casings."

97 *See* NRC, Final GEIS, G-128 for this exchange. Agreement States are those states that assume NRC regulatory authority under the Atomic Energy Act of 1954. *See* NRC, "Agreement State Program," nrc.gov/about-nrc/state-tribal/agreement-states.html. Accessed August 25, 2011. We disagreed with the NRC's response that such information was outside the scope of the NRC's review. While the Agreement States have assumed the NRC's regulatory responsibility for licensing ISL uranium mines, the NRC's legal obligations are not over. Specifically, Section 274j of the AEA (42 U.S.C. § 2021(j)) allows for the NRC, after reasonable notice and opportunity for hearing, to terminate or suspend all or part of its agreement with the state and reassert its licensing and regulatory authority if the agency finds it necessary for the protection of public health and safety, or if the state failed to comply with specific requirements. Additionally, the NRC is periodically required to review Agreement States to assure compliance with the law. As one example, the Texas Commission on Environmental Quality (TCEQ) regulations in Title 30, Texas Administrative Code, Chapters 37 and 336, are reviewed yearly by the NRC for equivalency with the NRC rules in 10 C.F.R. § 40. *See, e.g.,* NRC, "Compatibility Comment on Texas Final Regulations," May 13, 2009, nrc-stp.ornl.gov/special/regs/txregs090513.pdf. *See also* NRC, "Integrated Materials Performance Evaluation Program: Review of the Texas Agreement State Program, Final Report," February 22-26, 2010, nrc-stp.ornl.gov/reviews/10tx_imp.pdf. Accessed August 25, 2011. The NRC has yet to exercise its authority to terminate a state's agreement status on account of mismanagement of materials licensing.

98 NRC, SRP, 5-37, nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1569/sr1569.pdf. Accessed August 25, 2011.

99 Id., 5-38. While we understand that the industry attempts to respond to horizontal excursions by adjusting the flow rates of the injection and extraction wells, the NRC itself acknowledged that vertical excursions are more difficult to correct; some persist for years. Yet the NRC still refused to comprehensively analyze the past history of leaks. *See also* Final GEIS at 2-48.

100 NRC, Draft GEIS, July 2008, xxxiii.

101 NRC, GEIS, Sections 2.13, 2.4.1.2, and 4.5-12–4.5-14.

102 Id., 4.5-17.

103 EPA TENORM Report, 4-12. The EPA explains "groundwater sweep" as the process "initiated when the uranium concentration in the production fluid has dropped to a level where recovery is no longer feasible. During groundwater sweep, the lixiviant (sodium

bicarbonate) is discontinued, but the water is still pumped through the recovery wells, displacing contaminated water from the aquifer. As the aquifer is diluted in the concentration of the lixiviant, groundwater sweep becomes less useful."

104 Id., 4.2-26

105 Id., 4.5-18.

106 Robert Moran, cited in Oglala Sioux Tribe, "Petition to Intervene and Request for Hearing of the Oglala Sioux, Docket Number 40-9075-MLA" (April 6, 2010), 26-27, powertechexposed.com/2010.04.06%20PETITION%20TO%20INTERVENE%20AND%20REQUEST%20FOR%20HEARING.pdf. Accessed August 25, 2011.

107 Id.

108 Mark T. Anderson and Lloyd H. Woosley. "Water Availability for the Western United States—Key Scientific Challenges," USGS (2005), p. 6, pubs.usgs.gov/circ/2005/circ1261/pdf/C1261.pdf. Accessed August 25, 2011.

109 Id., 17.

110 Kathleen Miller and David Yates, "Climate Change and Water Resources: A Primer for Municipal Water Providers," AWWA Research Foundation and the University Corporation for Atmospheric Research (2005).

111 Natural Resources Defense Council, "In Hot Water: Water Management Strategies to Weather the Effects of Global Warming" (July 2007), p. vi., nrdc.org/globalWarming/hotwater/hotwater.pdf. Accessed August 25, 2011.

112 Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, "Climate Change 2007: The Physical Science Basis: Summary for Policymakers," February 2007, 4-7, pnud.cl/recientes/IPCC-Report.pdf. Accessed August 25, 2011.

113 Tetra Tech Inc., "Climate Change, Water, and Risk: Current Water Demands Are Not Sustainable," Natural Resources Defense Council, July 2010, nrdc.org/globalwarming/watersustainability/. Accessed August 25, 2011. For an overview of the Tetra Tech study, and for a more detailed description of methodology, *see*: Tetra Tech., Inc., "Evaluating Sustainability of Projected Water Demands Under Future Climate Change Scenarios," July 2010, rd.tetratech.com/climatechange/projects/nrdc_climate.asp. Accessed August 25, 2011.

114 Id., 11. Tetra Tech defined summer water deficit as the amount by which water withdrawal exceeds available precipitation in June, July, and August—typically the three warmest months of the year, when there is increased municipal, thermoelectric cooling, and irrigation demand.

115 Texas Comptroller of Public Accounts, "Liquid Assets: The State of Texas' Water Resources," January 2009, 1, window.state.tx.us/specialrpt/water/PDF/96-1360-LiquidAssets.pdf. Accessed August 25, 2011.

116 Id., 6.

117 NRC, Final GEIS, Table 2-6.1, 2-32.

118 Id., Table 2.7-3, 2-36.

119 We look forward to the forthcoming EPA rulemaking on 40 CFR 192, discussed 35, in hopes that the agency can rectify the issue of available data on ISL uranium mining impacts.

120 EPA, TENORM Report, Vol. 1, 3-9.

121 Stephen H. Brown, "Radiological Aspects of Uranium-Solution Mining," *Uranium* 1 (1982): 37-52.

122 EPA TENORM Report, Vol. 1, 3-10.

123 Pedro Ramirez, Jr., and Brad Rogers, "Selenium in a Wyoming Grassland Community Receiving Wastewater From an In Situ Uranium Mine," U.S. Fish and Wildlife Service, September 2000, p. 1, fws.gov/mountain-prairie/contaminants/papers/r6715c00.pdf. Accessed August 25, 2011.

124 Id., 1.

125 As noted by a state regulator, "Some of the spills may have little impact individually, but cumulatively they might have a significant impact on soils and/or groundwater." Moxley, 4.

126 *See* the NRC memorandum for Chairman Jaczko, Commissioner Klein, and Commissioner Svinicki, "Staff Assessment of Groundwater Impacts From Previously Licensed In-Situ Uranium Recovery Facilities," July 10, 2009, nrc.gov/reading-rm/adams.html, public accession number ML091770187. In practice, all regulators—the NRC or Agreement States—have allowed relaxation to weaker standards or "alternative concentration limits" rather than restoration of all parameters to pre-mining water-quality levels, or even to secondary standards such as EPA's Safe Drinking Water Standards.

127 NRC, Final GEIS, G-89.

128 *See* Memorandum for Chairman Jaczko, Commissioner Klein, and Commissioner Svinicki, "Staff Assessment of Groundwater Impacts From Previously Licensed In-Situ Uranium Recovery Facilities," July 10, 2009.

129 Powertech Inc., Applicant Powertech (USA) Inc.'s Response to Petitioner Oglala Sioux Tribe's Request for a Hearing/Petition for Intervention, Docket No. 40-9075-MLA, May 3, 2010, 17, powertechexposed.com/2010.05.03%20Powertech%20Response%20to%20Motion%20to%20Intervene.pdf. Accessed August 25, 2011.

130 The NRC has produced little on the topic beyond the memorandum cited in Note 105. *Can't be right; Note 105 is NRC's GEIS*

131 Reply letter from Joseph F. Thiel, Director of the Division of Environmental Programs, Texas Department of Health, to Texas Water Commission, Re: Modification to URI Longoria Restoration Table for Uranium to 3.0 mg/l, May 29, 1987, 62, pbadupws.nrc.gov/docs/ML0115/ML011550450.pdf. This letter was submitted as Attachment C-10 with Dr. Richard J. Abitz: Written Testimony of Richard J. Abitz in Support of Intervenors' Reply to HRI's and NRC Staffs' January 22, 2001, Responses to Intervenors' Presentation on HRI's Restoration Action Plan and Cost Estimates, Docket No. 40-8968-ML, May 23, 2001, available in its entirety at the URL given above. It should be noted that in 1987 there was no federal drinking water standard for uranium. The EPA promulgated a final uranium drinking water standard in 1999; it is 0.030 mg/l, far below the values allowed in this instance.

132 States can assume the NRC's role and act in lieu of the agency by assuming Agreement State status under Title II of UMTRCA. States that have licensed ISL mines, for example, include Texas and Wyoming. As an Agreement State, a state can assume regulation of uranium mill tailings and can enact rules equivalent to or more stringent than those required by the NRC and the EPA. *See* 10 C.F.R. § 150.31, requiring state compliance with any standards promulgated by NRC or EPA under UMTRCA. Specifically, Title II of UMTRCA focuses on uranium milling facilities operating after 1978 and established the framework for NRC and Agreement States to regulate mill tailings and other wastes at uranium and thorium mills licensed by the NRC at the time of UMTRCA's passage, and to adopt subsequent standards set by the EPA. edocket.access.gpo.gov/cfr_2008/janqtr/pdf/10cfr150.31.pdf. Accessed August 25, 2011. 42 USC 2092 et seq., and 42 USC 2111 et seq.

133 Crow Butte Resources, Inc., "Additional Stability Monitoring Data for Mine Unit 1 Groundwater Restoration Crow Butte Uranium Project," submitted to NRC October 11, 2002, 2-6; Crow Butte Resources, Inc., "Mine Unit 1 Groundwater Restoration, Crow Butte Uranium Project," submitted to NRC January 10, 2000, 36. Also, for radium-226 ***the limit*** *for radium-226?* was set at 229.7 pCi/L. These documents can be obtained via an advanced web-based ADAMS search by typing "Crow Butte," "groundwater," and "restoration" into the document content section at wba.nrc.gov:8080/ves/.

134 Letter from Daniel M. Gillen, Chief of the Fuel Cycle Facilities Branch, Division of Fuel Cycle Safety and Safeguards, Office of Nuclear Material Safety and Safeguards, to Michael L. Griffin, Manager of Environmental and Regulatory Affairs, Crow Butte Resources, Inc., Re: License Amendment 15, Crow Butte Resources In Situ Leach Facility License No. SUA-1534, Wellfield #1 Restoration Acceptance (TAC NO. L52491), February 12, 2003. These documents can be obtained via an advanced web-based ADAMS search by typing relevant search terms into the document content section at wba.nrc.gov:8080/ves/.

135 Power Resources, Inc., "Ground Water Restoration Report for the Smith Ranch–Highland Uranium Project," 13. *this isn't exactly how it was rendered in first ref (note #100)*

136 NRC, "Technical Evaluation Report: Review of Power Resources, Inc.'s A-Wellfield Groundwater Restoration Report for the Smith Ranch-Highland Project." *incomplete info?*

137 Letter to COGEMA: "Review of COGEMA Mining, Inc., Irigaray Mine Restoration Report, Production Units 1 through 9, Source Materials License SUA-1341 (TAC LU0137)."

138 NRC, "Technical Evaluation Report: Review of COGEMA Mining, Inc., Irigaray Mine Restoration Report, Production Units 1 Through 9, Source Materials License SUA-1341 (TAC LU0137)."

139 COGEMA Mining, Inc., "Wellfield Restoration Report, Christensen Ranch Project, Wyoming," March 5, 2008, 1-1 and 1-2, powertechexposed.com/Wellfield_Restoration_Report_Christensen_Ranch_Mar_5_2008.pdf. Accessed August 25, 2011.

140 Memorandum for Chairman Jaczko, Commissioner Klein, and Commissioner Svincki, "Staff Assessment of Groundwater Impacts From Previously Licensed In-Situ Uranium Recovery Facilities" (July 10, 2009).

141 Susan Hall, "Groundwater Restoration at Uranium In-Situ Recovery Mines, South Texas Coastal Plain," USGS, 2009, 6, pubs.usgs.gov/of/2009/1143/pdf/OF09-1143.pdf. Accessed August 22, 2011.

142 Id., 7; Southwest Groundwater Consulting LLC, "Report on Findings Related to the Restoration of Groundwater at In-Situ Uranium Mines in South Texas," September 28, 2008, 1 (stating data are "unorganized and difficult to navigate"), uraniuminfo.org/files/BK_Darling%20Report_Complete_Sept_30.pdf. Accessed August 25, 2011.

143 Hall, "Groundwater Restoration at Uranium In-Situ Recovery Mines, South Texas Coastal Plain," 6.

144 Id., 30.

145 Id., 21.

146 Id., 8.

147 Id., 7.

148 Id., 9.

149 Id., 10.

150 Southwest Groundwater Consulting LLC, "Report on Findings Related to the Restoration of Groundwater at In-Situ Uranium Mines in South Texas," September 28, 2008, 3 and Attachment A.

151 Id., 2.

152 Id, 4-5.

153 Id. 5-6 (based on data from all of the listed mines except O'Hern).

154 See note 2, *supra*.

155 If one searches online in the NRC database or visits state offices, significant amounts of paper exist, but little of it is compiled in a coherent and publicly accessible fashion. Note that when we use the word *paper* we literally mean "paper." Almost no usable state data are online and publicly accessible; for access one must visits relevant state offices and pay for copying said paper. Obtaining material online from the NRC was complicated further by the less-than-user-friendly ADAMS database that has only recently been updated. For example, one can go to the NRC website and find under "nuclear materials" and "uranium recovery" a link to an NRC page briefly describing the Smith Ranch–Highlands ISL operation or the Crow Butte ISL operation. The ADAMS database may contain detailed information about an ISL mining site's multiple contamination excursion notices, documents about failures or acceptance of weakened groundwater restoration standards, or discussion of the adequacy of financial assurance documents. However, to find any document, one needs an "accession number" that identifies the individual document. Such a process ensures that a reader will have to search repeatedly through potentially hundreds of documents. Industry and the federal government have available resources and staff to plow through such a process. But few organizations—including under-resourced state regulators—have the financial wherewithal to conduct similar efforts. Obtaining materials from relevant state agencies was equally difficult, and not set up for public accessibility. First, most states lack funds and therefore do not have the resources or staff to place a great deal of regulatory information online. Second, while our interactions with individual state staffers were uniformly excellent, particularly in Wyoming, regulating operations as complex as large ISL sites strains limited state budgets. this is so delicately worded, it seems like a non-sequitur in relation to first half of sentence. Was something cut? It was considerably easier to actually send representatives from SRIC and NRDC to offices in Wyoming to locate requested information. Unfortunately, when we did find the relevant files, the information was less than comprehensive.

156 Discussed *supra* at 66-67, *check* the USGS performed a limited survey of ISL aquifer restoration in Texas and had similar experiences in terms of locating useful regulatory data.

157 As simple proof of the regulatory mess, DOE authority to perform remedial action at these sites—a job that is not yet done—expired in 1998, except for the authority to perform groundwater restoration activities.

158 *See* note 132 for discussion of Agreement State status and assumption of NRC authority. *See also* 10 C.F.R. § 150.31, requiring state compliance with any standards promulgated by the NRC or the EPA under UMTRCA, nrc.gov/reading-rm/doc-collections/cfr/part150/part150-0031.html. Accessed August 25, 2011.

159 *See* 10 C.F.R. § 40. *See also* Section 11(z) of the AEA, which states that "the term 'source material' means (1) uranium, thorium, or any other material which is determined by the Commission pursuant to the provisions of section 61 to be source material; or (2) ores containing one or more of the foregoing materials, in such concentration as the Commission may by regulation determine from time to time," 42 USC 2014(z). *See also* Section 11(e) of the AEA , which states that "the term 'byproduct material' means (1) any radioactive material (except special nuclear material) yielded in or made radioactive by exposure to the radiation incident to the process of producing or utilizing special nuclear material, and (2) the tailings or wastes produced by the extraction or concentration of uranium or thorium from any ore processed primarily for its source material content," 42 USC 2014(e).

160 The EPA has developed guidance—but not regulations—for use in cleanup of radioactively contaminated soils and groundwater primarily for the Superfund program in "Risk Assessment Guidance for Superfund Vol. I: Human Health Evaluation Manual (Part A)," EPA/540/1-89/002, epa.gov/oswer/riskassessment/ragsa/pdf/rags-vol1-pta_complete.pdf. Accessed August 25, 2011. The soil standards are based on radiation standards developed for the UMTRCA program for uranium mills (US EPA 1998, 199c), while cleanup standards for groundwater use the EPA's maximum contaminant levels established under the SDWA. The radionuclide soil cleanup standard for combined radium-226, radium-228, and thorium-232 is 5pCi/g. For groundwater cleanup and protection, the EPA drinking water standards for uranium, 30 ug/L and 5pCi/L, are the targets.

161 EPA TENORM Report, p. A VI-3. ISL uranium mining commonly occurs in U.S. drinking waters. (*See* EPA, "Underground Injection Controls," water.epa.gov/type/groundwater/uic/wells_class3.cfm. Accessed August 25, 2011.) It is therefore subject to the limitations established under the UIC program. However, the regulations also provide an exemption for some aquifers, 40 C.F.R. §144.7, ecfr.gpoaccess.gov/cgi/t/text/text-idx?type=simple;c=ecfr;cc=ecfr;rgn=div5;idno=40;q1=144.7;sid=570ece3e13fd69281543eb220711e662;view=text;node=40%3A22.0.1.1.6#40:22.0.1.1.6.1.42.7. Accessed August 25, 2011. The EPA has established the following criteria for determining whether an injection well qualifies for that exemption. To qualify for an exemption, an aquifer cannot "currently serve as a source of drinking water," and it "cannot now and will not in the future serve as a source of drinking water" because: (1) considering the amount of minerals or hydrocarbons, the location is "expected to be commercially producible"; (2) it is located at depth or location such that recovery of the water is "economically or technologically impractical"; (3) "it is so contaminated that it would be economically or technologically impractical to render that water fit for human consumption"; or (4) "it is located over a Class III well mining area subject to subsidence or catastrophic collapse," Id., § 146.4(a) – (b).

162 Letter from Brian J. Walsh, Hydrology Specialist, Ground Water Quality Program, State of South Dakota Department of Environment and Natural Resources, re: Deficiency of Revised Permit Application for Dewey-Burdock, April 19, 2010, p. 1, powertechexposed.com/SD%20DENR%20Class%20III%20UIC%20Permit.htm. Accessed August 25, 2011.

163 *See* Associated Press, March 15, 2011, "Daugaard Signs Bill Easing Uranium Regulations," posted March 15, 2011, *Rapid City Journal* online, rapidcityjournal.com/news/local/article_d3ef1dde-4f50-11e0-8b6d-001cc4c002e0.html. Accessed August 25, 2011.

164 *See* NRC, SRP, "Standard Review Plan for In Situ Leach Uranium Extraction License Applications, Final Report," June 2003, nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1569/sr1569.pdf. Accessed August 25, 2011.

165 10 C.F.R. § § 40.42(h)-(k); 10 C.F.R. § 40, Appendix A.

166 In its guidance on the subject (not rules), the NRC candidly acknowledges the likelihood of contamination as it recites its primary restoration standards: "The primary goal of a restoration program is to return the water quality within the exploited production zone and any affected aquifers to pre-operational (baseline) water quality conditions. Recognizing that in situ leach operations fundamentally alter ground-water quality geochemistry, restoration activities *are not likely to return ground-water quality to exact water quality that existed at every location prior to in situ leach operations*. Still, as a primary restoration goal, licensees are required to attempt to return the concentrations of the monitored water quality indicator constituents to within the baseline range of statistical variability for each constituent." SRP, 6-9 (emphasis added).

167 In its description of the secondary restoration standards in its guidance, the NRC continues with its relatively candid assessment of damage to aquifers, but deviates into a point of significant controversy by asserting that restoration to class of use is an appropriate fallback option. The SRP states: "Secondary Restoration Standards—In situ operations may cause permanent changes in water quality within the exploited production zone, because the in situ leach extraction process relies on changing the chemistry in the production zone to remove the uranium. The applicant may therefore *propose returning water quality to its pre-operational class of use* (e.g., drinking water, livestock, agricultural, or limited use) as a secondary restoration standard." SRP, 6-9 (emphasis added). Finally, the SRP addresses what has become the default decision for ISL uranium mines, restoration to "alternative concentration limits." The NRC states: "If a constituent cannot technically or economically be restored to its secondary standard within the exploited production zone, an applicant must demonstrate that leaving the constituent at the higher concentration would not be a threat to public health and safety or the environment or produce an unacceptable degradation to the water use of adjacent ground-water resources. SRP, 6-9.

168 *See* endnote 132 for a discussion of Agreement State roles and NRC responsibilities.

169 Jeffrey S. Merrifield, memorandum for Chairman Diaz, Commissioner McGaffigan, Commissioner Jaczko, and Commissioner Lyons from Commissioner Merrifield, "Regulation of Groundwater Protection at In Situ Leach Uranium Extraction Facilities," January 17, 2006, 1 nrc.gov/reading-rm/doc-collections/commission/comm-secy/2006/2006-0001comjsm.pdf. Accessed August 25, 2011.

170 Id.

171 Memorandum for Chairman Klein, Commissioner McGaffigan, Commissioner Merrifield, Commissioner Jaczko, and Commissioner Lyons, "Path Forward for Rulemaking on Groundwater Protection at In Situ Leach Uranium Extraction Facilities," April 30, 2009, 1.

172 Id., 2. It should be noted that NRDC was not contacted by the NRC to reach a consensus on rulemaking strategies, nor, to our knowledge, were any other environmental groups contacted.

173 NRC, "Briefing on Uranium Recovery," March 2, 2010, transcript, 9, nrc.gov/reading-rm/doc-collections/commission/tr/2010/20100302.pdf. Accessed August 25, 2011.

174 Id., 9.

175 NRC Rulemaking Working Groups, 10 CFR Part 40, In Situ Leach Working Group, nrc-stp.ornl.gov/rulemakingwgrps.html. Accessed January 25, 2011.

176 NRC, "Environmental Impact Statement for the Lost Creek ISR Project; Supplement to the Generic Environmental Impact Statement for In-Situ Leach Uranium Milling Facilities," NUREG-1910 Supplement 3, draft report for comment, November 2009, 5-1–5-13, nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1910/s3/sr1910s3.pdf. Accessed August 25, 2011.

177 NRC, "Environmental Impact Statement for the Moore Ranch ISR Project; Supplement to the Generic Environmental Impact Statement for In-Situ Leach Uranium Milling Facilities," NUREG-1910 Supplement 1, final report, August 2010. 5-7, nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1910/s1/sr1910s1.pdf. Accessed August 25, 2011.

178 NRC, "Environmental Review Guidance for Licensing Actions Associated With NMSS Programs," final report (NUREG-1748), nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1748/sr1748.pdf, 4-1 to 4-14, August 2003. Accessed August 25, 2011.

179 *See* Nichols Ranch SEIS, 5-1–5-3.

180 Dustin Bleizeffer, "State Seeks Action in Illegal CBM Spill," *Wyoming Star-Tribune,* February 25, 2010, trib.com/news/state-and-regional/article_55d3d7d5-dba6-50eb-a3d9-4433dde8c10b.html. Accessed August 25, 2011.

181 Natural Resources Defense Council, "Drilling Down: Protecting Western Communities From the Health and Environmental Effects of Oil and Gas Production," (2007), 5, nrdc.org/land/use/down/down.pdf. Accessed August 25, 2011.

182 Id.

183 *See* 34-32-112.5. Designated mining operation—rules, powertechexposed.com/1161_rerevised_May_2_2008.pdf. Accessed November 8, 2011.

184 The issue of states' adopting improved mining laws for regulating conventional uranium recovery is not addressed in detail in this paper. As examples, both New Mexico (in 1994) and Colorado (in 2008) have substantially improved the legal and regulatory framework of uranium recovery within their borders.

185 Rep. John Kefalas, Colorado House of Representatives, et al., "Session Law Chapter 252: An Act Concerning an Increase in the Regulatory Authority of the Mined Land Reclamation Board Over Mining, and, in Connection Therewith, Ensuring the Protection of Ground Water and Public Health, and Making an Appropriation," approved May 20, 2008, state.co.us/gov_dir/leg_dir/olls/sl2008a/sl_252.pdf. Accessed August 25, 2011.