Modeled Impacts of Economics and Policy on Historic Uranium Mining Operations in New Mexico

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Abstract

New Mexico was at the forefront of the nuclear age, producing more uranium (U) than any other state in the U.S. for more than three decades until the early 1980s. The state is also unique because these historic activities have been studied and quantified over during this time, providing a unique opportunity to identify how historic uranium mining operations were influenced by economics and policy. In order to quantify these relationships, this study used a system dynamics approach to determine how these factors affected mining industry decisions and how those impacts varied based on mine size. The results of this work found that as the industry evolved over time, the influence of these factors changed and that they did not impact all mining operations equally. Results indicate that price guarantees for U concentrate and subsidies for mining and milling in the early years (1948–1964) of U mining encouraged mines of all size, although smaller mines opened and closed more quickly in response to changes in price. The economic environment created by these policies encouraged exploration and production. However, the latter led to an excess in supplies and declining prices when these incentives lapsed in the mid-1960s, which negatively impacted small- and medium-sized mines, neither of which opened after 1964. The presence of larger mines had more impact on the closing of small mines than closing of medium mines, possibly as a result of economies of scale for the medium mines or their ability to access milling resources after 1964. Lastly, medium and large mines that produced both uranium and vanadium may have had a slight historic advantage over mines that produced only uranium, as evidenced by longer delays in closing response to a unit change in average price. Quantification of these relationships assists in an improved understanding of the factors that influenced historic mining operational decisions and illustrates the complexity of the roles played by economics and policies in the boom and bust cycle manifested in the uranium industry.

Introduction

The uranium industry in New Mexico experienced rapid growth following the advent of the nuclear age. Mines and mills in the state produced more uranium (U) than any other region in the United States and were, in the mid-60s, responsible for up to 35% of U concentrate (U_3O_8) produced globally (Roskill, 1991). Between 1947 and 2002, more than 200 recorded mines and 8 mills throughout the state produced more than 340 million pounds of U_3O_8 and generated \$4.7B in revenue (McLemore, 1983; McLemore et al., 2013; McLemore, in press). An integral part of uranium mining in New Mexico is the Grants uranium district. The region became known as the "Uranium Capital of the World" (Fitch, 2012) because the Grants mining district produced more than 99% of state-wide production between 1948 and 1982 (McLemore, 1983).

While the growth of the industry was rapid, it was also marked by a degree of randomness as a result of varying demand for U (used primarily for weapons by the Federal government and nuclear power generation by both the Federal government and commercial utility companies), discovery of new reserves and concerns of U scarcity, and evolving regulatory frameworks, all of which impacted both negotiated prices for long term contracts and U spot prices (Roskill, 1991). Spot price refers to an estimated value regarding transactions involving "significant quantities of natural uranium concentrates" (Roskill, 1991) that could be completed at a specific date; it is often considered to be the average price of negotiated large, long-term contracts and does not typically include smaller sales that would be included in an average price estimate (Roskill, 1991).

Roskill (1991) and Walker and Wellock (2010) describe the historic complexity of the U market. Of particular interest is how successive discoveries of new uranium reserves and uranium's practical uses increased public perception of the utilitarian value of this commodity. They also note how the rapid development of the nuclear power industry was encouraged by government subsidies and information-sharing (Walker and Wellock, 2010). "Probably the single most important difference is that the uranium industry [as compared to other mineral industries], born under a nuclear cloud, was the brainchild of the government" (Roskill, 1991).

Although the regional and national U industry thrived for nearly 30 years, it rapidly diminished in the early 1980s due to declines in prices, delays and cancellations of orders for new nuclear power plants (Roskill, 1991), and disasters, such as Three Mile Island, that altered the trajectory and credibility of the nuclear industry (Walker and Wellock, 2010). Uranium production in New Mexico ended in 2002 with the closure of the Quivira Mining Co. (formerly Kerr-McGee Corp.) mill, which at the end of its operation solely recovered U from mine water (McLemore and Chenoweth, 2003)

Nuclear energy currently supplies 19% of U.S. electric power, but nearly all of the U fuel supply is imported (US EIA, 2016). Increasing U prices and improvements in mining technologies, recognition that nuclear power is carbon free, as well as the desire for energy security and energy supply stability have resulted in renewed interest in U production in NM and elsewhere. While many factors influence mining operations, historic U.S. mining of U was driven by government-related markets, regulations, and subsidies enacted to encourage the development of the nuclear industry by ensuring a stable and reliable supply of uranium.

The objective of this study was to improve understanding of the roles that economics and policy played in the operation of U mines in New Mexico using a system dynamics modeling (SD) framework. Because New Mexico was at the forefront of the U boom, was a leading domestic producer for nearly three decades, and because a historic record of mine production exists, this area provides a unique opportunity for evaluating how these two factors influenced past mining operations. While numerous additional factors influence the development and operation of a U mine (e.g., geologic or geographic setting), understanding the dynamics of mine opening and closing through use of historical data may provide insight into historic U mining operational decisions and a useful tool in understanding and planning for future activities associated with extractive industries

Historical Background

Uranium is a radioactive element that had been used to color glass and ceramic products in the 19th and early 20th Centuries (Roskill, 1991). The 1910 discovery of the medical application of radium, a daughter product of uranium, increased the value of what had been previously considered a relatively useless element (Roskill, 1991). The following year, one gram of radium sold for between \$120,000 to \$160,000 (Roskill, 1991), approximately 11–15 million dollars per gram in current dollars. However, it was the discovery of nuclear fission in 1939 that would propel U from “an element of little value to one of the most sought after commodities in the world” (Ballard and Conkling, 1955; SJBRUS, 1980). This discovery and the development of the nuclear industry, including both weapons and power generation applications, would leave an indelible mark on both New Mexico and the world.

Uranium-vanadium deposits were discovered in the eastern Carrizo Mountains in the San Juan Basin in 1918 (Chenoweth, 1997). Initially, these deposits were primarily mined for vanadium, an economically important metal used both to strengthen steel and as a catalyst for sulfuric acid production (Hilliard, 1994). The Vanadium Company of America (VCA) produced more than ten thousand pounds of ore between 1942 and 1946 (McLemore, 1983) and more than half of the vanadium produced domestically came from this and other regions within the Colorado Plateau until the mid-1980s (Hilliard, 1994). Uranium became increasingly important during the second World War, when an estimated 44,000 lbs. of U_3O_8 were recovered from the VCA’s mill tailings for the Manhattan Project (McLemore, 1983; McLemore and Chenoweth, 2003).

The creation and evolution of policy and regulatory frameworks for U influenced the development of the nuclear industry and affected U mining in particular. In 1943, the Atomic Energy Act established the Atomic Energy Commission, which placed nuclear energy under the sole control of the US government and restricted its use to military applications (Walker and Wellock, 2010). In 1954, the Atomic Energy Act was revised to allow for commercial nuclear applications, encourage collaborative research and development between national laboratories and industry, and provide subsidies for energy and defense research as well as the U supply this research required (Walker and Wellock, 2010). Both Acts included specific provisions to ensure a stable supply of U: the Federal government guaranteed a minimum price (\$8/lb. U_3O_8) and offered additional subsidies towards exploration, mine engineering, ore transportation, and milling costs (Roskill, 1991). In 1955, large U deposits were discovered in what is now referred to as the Ambrosia Lake subdistrict of the Grants uranium district (Fig. 1). These events sparked the uranium boom that lasted for more than three decades (McLemore and Chenoweth, 2003).

Mining Techniques and Production

Uranium production in NM historically relied on both underground and surface mining techniques (McLemore et al., 2002). The grade (concentration of uranium in the ore) and geologic position of the U deposit are the most significant factors in selection and application of mining techniques. Of the more than 1,000 uranium occurrences in the New Mexico Mines database, production activities are reported for 216 mines from 1942 until 2002 (McLemore and Chenoweth, 2003; McLemore et al., 2002). Of these, 102 were underground mines, 75 were surface or open pit mines, and 39 were characterized as both surface/open pit and underground mines. During this period of production, the grade of recovered ore ranged from 0.02–0.63% in the state (or 1 lb. of U_3O_8 from approximately 5,000 to 160 lbs. of ore respectively) (McLemore et al., 2002). Ore grade also varied by mine and date of production. For example, the Church Rock Mine recovered U ore of 0.21% grade in 1960 and 0.16% grade in 1962 (McLemore et al, 2002). The geographic distribution of uranium mines in New Mexico and their associated average annual production are shown in Figure 1.

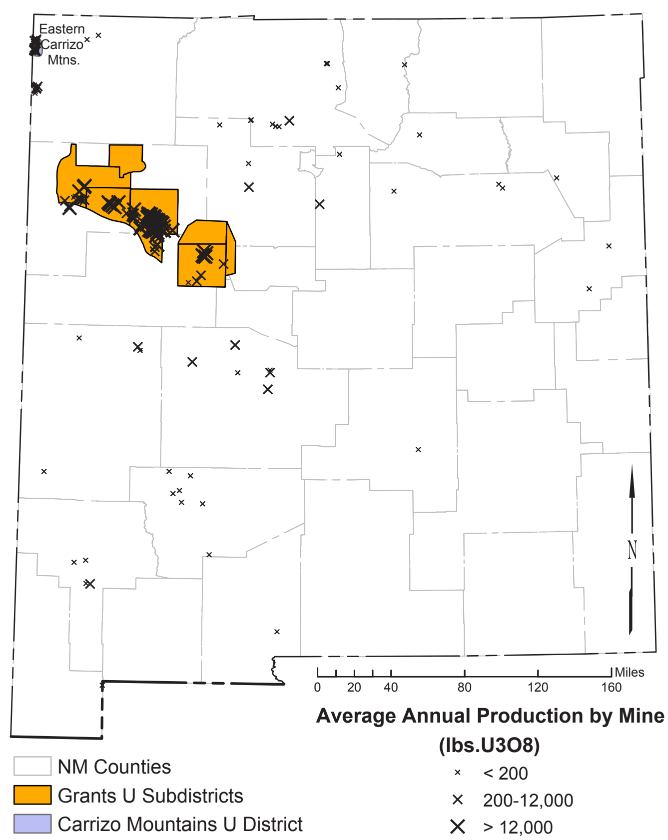

Figure 1. New Mexico uranium mines and their average annual production (1948–1985). Average production calculated as total U production divided by total operating years. Modified from McLemore et al. (2002).

Systems Dynamics Modeling

Model Approach and Development

Based on previous application to other mining operations (O'Regan and Moles, 2001, 2006), we propose that a system dynamics (SD) approach is well suited to understand and quantify the impacts of economics and changing regulatory environments on the opening and closure of historic U mines. This procedure quantifies the variability of mine openings or closings as a function of mine size, mining method, and the historic co-production of metals such as vanadium. In the context of this model, opening and closing represent the historic operational lifecycle of a mine (start and end of U production) rather than the legal and physical closing incorporated into a contemporary mine's lifecycle. This modeling technique allows for both the separation and interaction of these variables in order to understand how mine characteristics such as size and mining methods are affected by policy and economics over time. Our objective was to quantify the effect of each variable on historic mining operations. Note that the impact of these variables on one mine may have implications on other mines. The results of the model help to explain how and why mining companies decide to open a new mine or close an existing one.

This model assumes historic mining decisions were influenced by both market forces, particularly U price and competition, and government-related changes in nuclear policy. Although a poor proxy for the actual prices negotiated between producers and purchasers, we used the average price of U because no quantitative data exists for these individual transactions. In addition to market price, government policies towards the industry provided additional incentives to encourage development. For example, in 1954 the Atomic Energy Commission provided subsidies for transportation, processing facility construction, and mine engineering costs in addition to minimum price guarantees ($8/lb. U_3O_8) for U in order to ensure a steady supply for both weapons and the developing nuclear power industry (Roskill, 1991).

One might postulate that profitability was greatly enhanced, regardless of mine size, during early U mining due to a guaranteed market for U and subsidies for production costs (resulting in profits as high as a 40% return on investment (Roskill, 1991)). Conversely, in later years a lapse in subsidies may have reversed this trend in favor of larger mines. For example, the upfront capital costs and expertise required to recover ore from deeper deposits may not have been possible for smaller mines in the absence of government incentives. Economies of scale, the principal that an increase in the scale of production decreases the unit cost of production, suggests that the size of a mine may have been an important factor in its response to changing market forces and policy environments. Therefore, government stimulation and market price of U may have affected the response (i.e. opening or closing) of historic mines in the region differently as a function of their size.

The influence of government policies, which are often the most challenging aspect of a system to model quantitatively, were treated by delineating four time periods initiated by passage of specific legislation that are described in brackets: 1) 1948–1954 [the Atomic Energy Act of 1946, which stated that all U produced must be used in government applications, guaranteed a market for ore if it was above 0.2% U_3O_8, and provided subsidies for exploration, mine engineering, ore transportation, and milling costs; note we begin with the year 1948 because that is the beginning of the average domestic U sale price record], 2) 1954–1964 [the Atomic Energy Act of 1954, which reaffirmed the government's U markets and subsidies but allowed for collaborative research on nuclear technologies between the government and private industry, resulting in increased demand for U], 3) 1964–1974 [President Johnson's mandated 25% cutback in enriched U production in 1963 and the 1964 Private Ownership of Special Nuclear Materials Act, which decreased government demand for U, allowed guaranteed prices and subsidies for U to lapse, and wholly opened the nuclear industry to the public domain (both nationally and internationally)], and 4) 1974–1985 [passage of the Energy Reorganization Act 1974, which ended government stewardship over the domestic nuclear power program (Buck, 1983)]. We chose 1985 as our ending date because by then all but one mine in the state had closed (McLemore et al., 2002). Rather than including these periods of regulatory changes as variables, the four time periods were represented as four distinct simulations within model optimization. The differences in economics and policies as a function of modeled time periods is shown in Table 1. Early years were marked by government-supported minimum prices and subsidies. In later years these economic incentives lapsed and the sales market of U concentrate broadened.

TABLE 1: Comparison of economics and policy on U markets for the four modeled time periods.

Policy Time Periods	Government Price	Subsidies	Government Usage	Public Usage	International Sales
1948–1954	X	X	X		
1954–1964	X	X	X	X	
1964–1974			X	X	X
1974–1985			X	X	X

As in any model, a number of real-life complexities hinder this model's accuracy. One, average historic prices do not reflect the entire spectrum of U commerce dynamics. These dynamics were often dominated by long-term contracts between mines, mills, and energy companies (Roskill, 1991), the terms of which are not often reported. Given data limitations, it is difficult to assess the impact on the accuracy of the model due to exclusion of long-term contracts. Two, the co-production of other metals such as vanadium (V), the price of which has been lower but more stable compared to U historically, may have influenced the ability of a mine to weather low U price environments. Because V mining in the region was as a co- or by-product of U mining (Hilliard, 1994), we assume that trends in U prices were representative of both U and V commerce. Therefore, we ran our model first using mines that produced U only and then using mines that produced both U and V.

Our model is designed to evaluate three hypotheses that depend on several assumptions. The hypotheses are: 1) subsidies from the U.S. government for U mining both promoted and sustained smaller mines prior to 1964, 2) smaller mines responded more quickly to changes in price than did large mines, and 3) mines that produced both uranium and vanadium were more stable than mines that produced uranium only because of diversified production and the relatively stable historic price of vanadium. As mentioned earlier, we assume high U prices were a significant factor in a company's decision to open a new mine, whereas closing may have occurred as a result of low prices. We also assume mine openings and closings are a function of mine size, categorized as small, medium, or large and estimated based on total production averaged over the total duration of operation in years (see below). Economies of scale generally dictate that larger mines are able to produce a commodity at a lower per-unit cost than smaller ones, which make them more competitive in a dynamic economic environment than smaller mines. Therefore, we assume that an increase in the number of large mine operations may influence operational decisions (especially closing) for smaller mines. We describe this influence using a variable called the impact of larger mines coefficient. We believe this coefficient accounts for perceived scarcity and market flooding on competition between mines of varying sizes.

The ability of a mine to remain in operation in spite of low U prices may also have been a function of its ability to economically produce other commodities like vanadium. Of the 216 mines that produced U between 1948 and 1985, 68% also produced V. While the number of V producing mines was dominated by small and medium-sized mines (41 and 44%, respectively), large mines produced nearly three-quarters of total V produced during this period. Although historic V prices have consistently been a fraction of that for U, its price has been more stable. Between 1948 and 1980, average V price was 18% of U price with a standard deviation of 1 compared to U (SD = 8.9) (McLemore et al., 2003; USGS, 2013). Therefore, the number of openings and closings for U+V mines were compared to U-only mines in order to discern whether commodity diversity influenced operational decisions. Similar to U-only mines, real annual production data for either U or V are not available in U+V mines (instead, for both we divide total production over years of operation). Therefore, it was not possible to determine whether U+V mines were able to increase production of V in low U-price environments in order to maintain profitability or lengthen closing response time in down markets.

Model Description

In order to understand historic mine operations (i.e. opening vs. closing), mines were grouped by size and evaluated in terms of response time to changes in uranium price, policy changes, and other mining activity in the region. These were included in a Powersim Studio 9 (Powersim, 2016) optimization tool to determine the optimal value for each of these variables. This system dynamics software platform allows for rapid evaluation of dynamic interaction between multiple variables over time. The model is designed to run on an annual time step from the initial date of U price availability (1948) (McLemore and Chenoweth, 1989) until the year 1985, when all but one mine in the state had closed (McLemore et al, 2002). In order to evaluate the effects of changing policies, four time periods are included in the analysis (1948–1954, 1954–1964, 1964–1974, and 1974–1985) that reflect significant changes in policy regarding U commerce, as described in the previous section.

Optimization is a method commonly used in economic modeling to quantify the value of a series of variables that, when combined, most closely represents the real behavior of a system. The Powersim Optimization Tool uses an evolutionary search algorithm in which values of model decision variables change over time. During the optimization process, the model simulation is run many times where the best results from one simulation are used as inputs into the next simulation until a minimum difference between the number of actual and modeled mine openings and closings are achieved for each of the four policy-defined time periods. The four decision variables that potentially impact the decision to open or close a mine in the model are: 1) a coefficient response to price, 2) moving average price, 3) price time delay, and 4) impact of larger mines on smaller mine closings.

Figure 2 illustrates the conceptual process of the model and flow paths by which the decision variables (boxed) are determined from the input of real price data. Simulations are conducted separately for small, medium, and large mines. The various decision variables are defined as follows. The price coefficient indicates the number of mines that opened or closed due to a unit change in average real price of uranium, and the moving average price is the window of time over which the price is averaged. A large 'moving

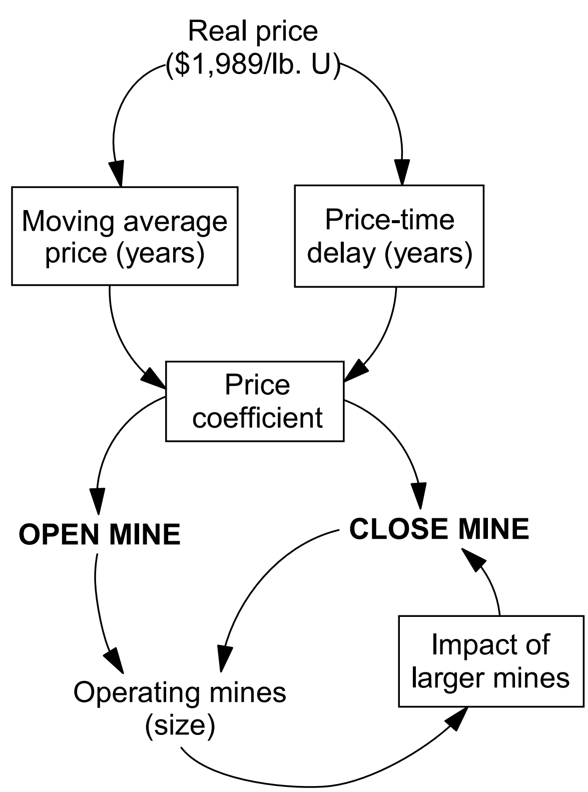

Figure 2. Conceptual model and system dynamics flow paths used in this study.

average price' implies that decisions on whether to open or close a mine depend on prices averaged over a longer term and not simply in response to short term market fluctuations. The price time delay is the length of time that passes before opening or closing occurs in response to a unit change in average price. Factors that delay construction or closing of a mine, such as the time needed to arrange for financing or evaluating trends in the market, are incorporated in the 'price time delay' variable. A large value for 'price time delay' indicates that decisions regarding mine operation are not an immediate response to changes in price. Optimal values for the moving average price and price time delay are computed directly from the real price input data using the Optimization Tool. Lastly, the impact of larger mines is a coefficient that describes the effect of larger mines on small mine closing, where a large coefficient indicates that a greater number of smaller mines closed in response to an increase in the number of larger mines operating in the region. This coefficient is also determined by iterative optimization. This coefficient was applied to the number of large mines operating during a designated time period when evaluating their impact on medium mines, and to both large and medium mines when evaluating their impact on small mines.

The first tier of optimization produces a value for the price coefficient from the moving average price and the price time delay. Using the price coefficient and the impact of larger mines coefficient, the model then predicts in a second tier of optimization how many mines open and close in a given policy-related time period from which the number of operating mines can be determined. In each iteration, the predicted number of operating mines of a given size are then compared to the actual number, and variable values are then adjusted until the difference between predicted and actual are minimized.

This process is summarized by the objective function, which shows: 1) how optimized decision variables are used to predict the number of opening (a) and closing (b) of mines, and 2) how the minimum difference between the predicted values and the actual values are calculated for each time period and then summed over the four time periods. For opening and closing, the objective of each optimization is to achieve the minimum difference between actual historic mines and modeled mines of each size for each time period (n).

Equation 1: Objective function describing the modeled opening (a) and closing (b) of historic U mines of a given size class (small, medium, large)

Where: MIN = minimum

ABS = absolute value

n = four policy-related time periods,

t_D = price time delay

t_A = moving average price

β_1= price coefficient

β_2 = impact of larger mines coefficient

It is assumed that changes in coefficients (β) and time delays (t) over the four policy-related time periods (n) will quantitatively describe the effects of changing policy and economic environments and support evaluation of the three proposed hypotheses.

$$a)\ f(n)_{MIN} = \sum_{n=1}^{4} \left(\text{Historic Mines} - (\beta_1[t_D(t_A(\text{PRICE}))])\right)$$

$$b)\ f(n)_{MIN} = \sum_{n=1}^{4} \left(\text{Historic Mines} - (\beta_1[t_D(t_A(\text{PRICE}))] + \beta_2[\text{LARGER MINES}])\right)$$

Model Input

Historic mine operations data were obtained from the New Mexico Mines Database (McLemore et al., 2002), which lists the operation and total U recovered for each mine from 1942 to 1989. More than half (128) of these mines showed a date range of production only, nearly 40% reported either a single year of production (64) or production amounts for every year in the production period (19), and five mines reported a combination of a range and annual production values (McLemore et al., 2002). Because of the disparate time scales for which production data was available, total production was divided by the time period of operation to determine estimated annual production. This value was used to classify mines as small (<200 lb/yr), medium (200–12,000 lb/yr), or large (>12,000 lb/yr). Mines were also characterized by type (surface, underground, combined) from McLemore et al. (2002) and as either U or U+V producing mines.

The real price of U (per year) is the primary economic input into the model. It is obtained by adjusting the nominal price for inflation into 1989 dollars. This adjustment allows comparison over time of real changes in value per pound of U (Figure 3). Although, there are several sources of nominal price data for uranium and vanadium (Figure 3), Roskill (1991) was used because U prices were represented in both nominal and real (1989) dollars adjusted for inflation, whereas other sources listed only nominal values.

Roskill (1991) reported U prices from two data sources: US Atomic Energy Commission (USAEC) prices (1948–1971) and the Nuclear Exchange Commission (NUEXCO) prices (1968–1990). Figure 3 also shows that vanadium prices (USGS, 2013) have historically been both lower and more stable that U prices. Comparison of nominal and real prices shows how the guaranteed minimum price for U during 1948–1964 did not result in a steady market value of U, which steadily declined between 1953 and the early 1970s. This price decrease could be due to increasing supplies of U resulting from government subsidization of the early U market or to government surpluses of U due to bans on wepons testing that decreased government demand for U.

Once historic and economic inputs were incorporated into the model and prior to optimization, a range of potential values was assigned to each variable. Price ('price coefficient') and 'impact of larger mines' each have a starting coefficient ranging from -1 to 1, with a starting value of 0.1. This allows for modeling of potentially counterintuitive results, such as increasing prices resulting in a negative response from mines. Both time variables, 'moving average price' and 'price time delay' were given a range of values from 0 to 5 with a starting value of 2.5. Using these starting values and allowed ranges, the Optimization Tool obtains temporary values for each variable during a given iteration, and then reintroduces these values as inputs until the optimal value is achieved for opening and closing mines in each size category over the four specified time periods.

Results

Historic Mining Operations Model

Data gathered from the New Mexico Mines database (McLemore et al., 2002) indicate that uranium mining in New Mexico was dominated by small and medium-sized mines from the late 1940s to the late 1950s, when the number of these types of mines peaked (Fig. 4). Large mines began operations in the early 1950s. The number of large mines subsequently overtook the number of smaller mines and peaked in the mid-1960s concomitant with closing of smaller mines (Fig. 4).

The optimal values chosen for the decision variables minimized the differences in the number of operating mines between historical data and modeled predictions (Fig. 4). When compared to historic data, the variables included in the model accounted for 81.6% of the variability in large mine operations, 93.8% for medium mines, and 89.0% for small mines based on R-squared values (Table 2). Furthermore, the F-test reveals that these results are significant (Table 2). Generally, an F-test greater than 0.01

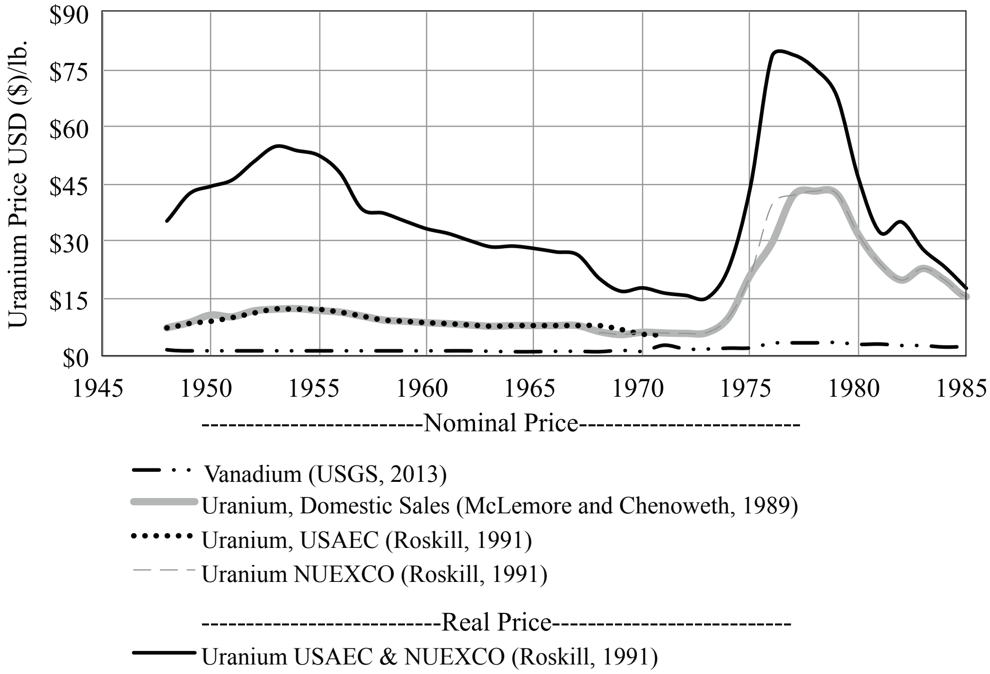

Figure 3. Comparison of reported nominal and real prices for V and U.

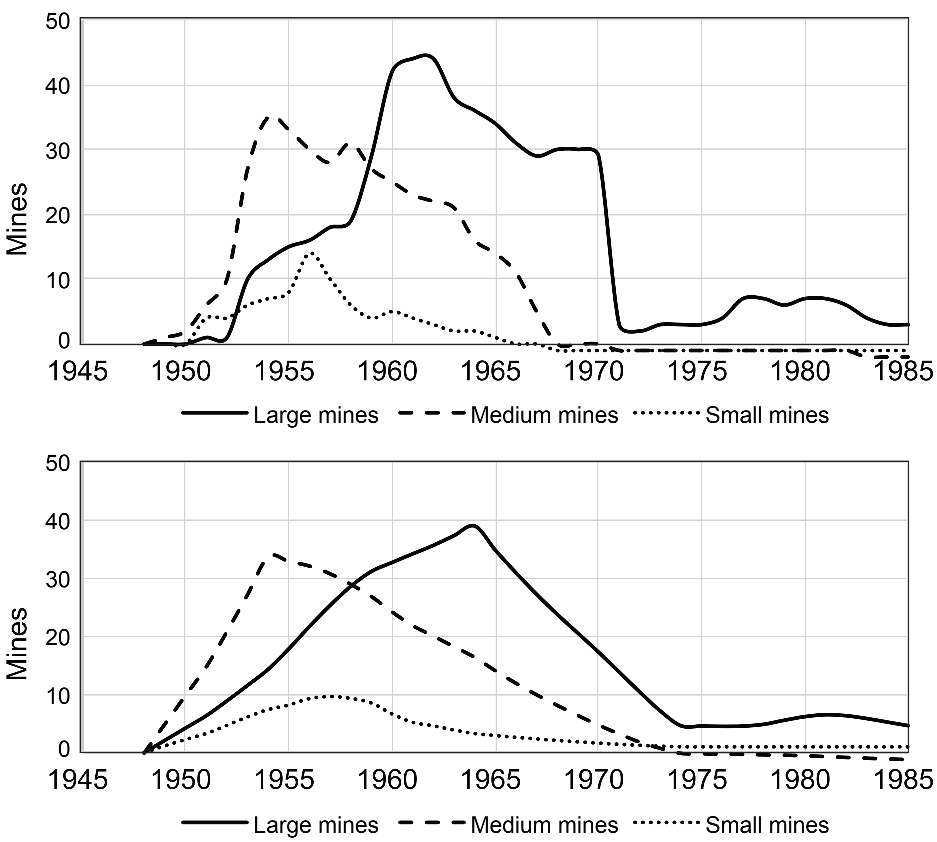

Figure 4. Number of historic mine operations (top) compared to those predicted by the model (bottom). X axis is in years.

TABLE 2: Statistical comparison of actual versus modeled mining operations.

Statistic	Mine Size		
	Small	Medium	Large
R-square	0.863	0.940	0.874
F-statistic	3.94E-17	1.40E-23	8.77E-18

indicates that results are not significant and the smaller the F-statistic in a regression output, the greater the probability modeled results are not due to chance. Model results are summarized in Tables 3a–3c. For the opening and closing of mines in each size class, optimized values for the decision variables are listed for the policy-relevant time frames. Below, we discuss the economic and policy implications that can be inferred by the modeled optimal values.

Economic Variables

The economic variables included in the model are intended to reflect how changes in price over time affected the opening and closing of mines of a given size. The decision to open or close a mine is influenced by numerous factors that include both price and competition; therefore, both the 'price time delay' and 'moving average price' are intended to capture how company decision making responded to short-term fluctuations in price stability over time.

Price coefficient

A key gauge of sensitivity to price (of a given mine type or size) is the price coefficient, which indicates the number of mines that opened or closed due to a unit change in average real price of U.

This coefficient could not be calculated for time periods when mines of a given size were not in operation (e.g., small mines in 1974–1985). Note the steady decrease in the opening price coefficient for large mines through 1948–1985, where the price coefficient decreased by more than two-thirds between 1954–1964 and 1964–1974. Such a decrease was not obvious during 1948–1964 for smaller to medium mines, except for a slight decrease in the closing price coefficient. Upon comparing small- and medium-sized U vs. U+V mines (Tables 3b and 3c), price coefficients are commonly an order of magnitude higher for U+V mines. This difference in price coefficient indicate that small to medium mines producing both U and V were more responsive (larger coefficient) to change in U price (Table 3c) than were small to medium mines that produced only U (Table 3b).

Price time delay

Figure 5 depicts the price time delay for mine opening and closing as a function of mine size. With the exception of mine closing during 1948–1954, small mines opened and closed rapidly (≤1 year). Openings for medium sized mines took ~1 year and large mines ~2 years throughout the four modeled time frames. Closing of medium to large mines took slightly longer in earlier years (4–5 years) compared to later years (3–4 years for large mines; 1.5–2.5 years for medium mines, per the model).

When mines producing U+V were compared to U-producing mines, the most noticeable difference in model results was in their price time delays. When compared to mines producing only U, medium and large U+V producing mines closed more slowly between 1954–1974 based on their higher price time delay values. Small mines producing U+V had similar price time delays for opening and closing as those producing only U.

Trends in Mine Openings and Closings

In general, there were more openings and closings of all U mines (U and U+V) in the first two periods than the last two periods (Fig. 6) and large mines dominate openings and closings after 1964, reflective of the total number of historic operating mines as a function of size (Fig. 4). Mines producing both U and V opened in greater numbers in the first two policy-related time periods as compared to U-only, but closed in much greater numbers between 1954–1964 (Fig. 7). However, U+V mines were predominantly small- and medium-sized mines, so these results could be more indicative of the role mine size played in operational (opening and closing) decisions. Between 1964 and 1985, fewer U+V mines closed as compared to U-only mines and these mines were medium or large; no U+V mines opened during this time (Fig. 7).

Discussion

Model results indicate that responses to changes in price and competition from larger mines influenced opening and closing and varied in response to national policies.

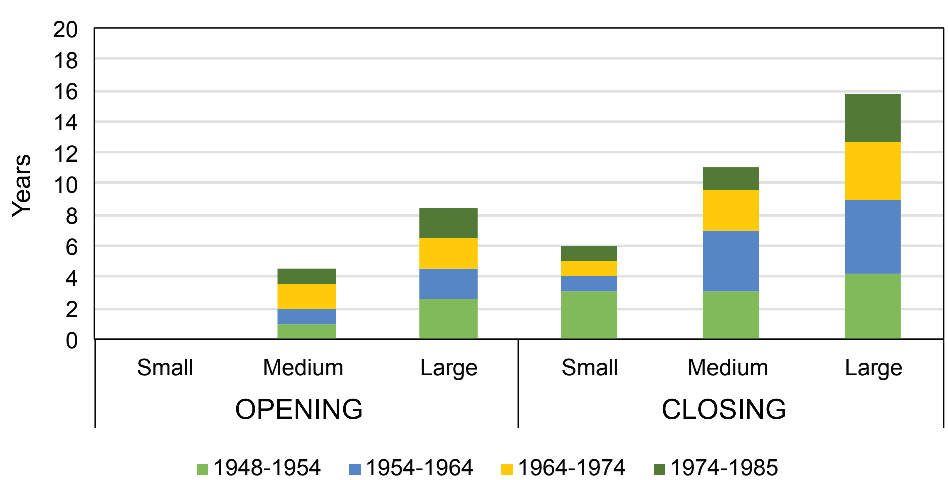

Figure 5. Comparison of modeled time delays for mine opening and closing (from Table 3a).

TABLE 3a. All Mines. Modeled regression results, includes regression results from all mines regardless of the type of commodity produced. Data are categorized according to policy-relevant time periods (in years).

Mine Size	Operation	Variable	1948–1954	1954–1964	1964–1974	1974–1985
Small Mines	**Open**	Price Coefficient	3.00E-02	3.00E-02	0.00E+00	N/A
		Moving Average Price	1.00 yr	1.00 yr	2.60 yr	N/A
		Price Time Delay	0.00 yr	0.00 yr	0.00 yr	N/A
	Close	Price Coefficient	3.00E-02	2.00E-02	1.90E-03	N/A
		Moving Average Price	2.00 yr	2.00 yr	1.00 yr	N/A
		Price Time Delay	3.00 yr	1.00 yr	1.00 yr	N/A
		Impact of Larger Mines	1.00E-02	1.00E-02	3.00E-03	N/A
Medium Mines	**Open**	Price Coefficient	1.50E-01	2.00E-02	0.00E+00	N/A
		Moving Average Price	3.00 yr	3.00 yr	1.60 yr	N/A
		Price Time Delay	1.00 yr	1.00 yr	1.60 yr	N/A
	Close	Price Coefficient	4.00E-02	3.00E-02	1.00E-02	N/A
		Moving Average Price	2.00 yr	1.00 yr	1.00 yr	N/A
		Price Time Delay	3.00 yr	4.00 yr	2.50 yr	N/A
		Impact of Larger Mines	5.00E-03	6.00E-03	8.50E-03	N/A
Large Mines	**Open**	Price Coefficient	5.00E-02	3.00E-02	1.00E-02	9.50E-03
		Moving Average Price	1.00 yr	1.00 yr	1.00 yr	2.00 yr
		Price Time Delay	2.50 yr	2.00 yr	2.00 yr	2.00 yr
	Close	Price Coefficient	0.00E+00	1.00E-02	6.00E-02	9.00E-03
		Moving Average Price	1.20 yr	1.117 yr	1.00 yr	3.00 yr
		Price Time Delay	4.15 yr	4.81 yr	3.70 yr	3.05 yr
		Impact of Larger Mines	N/A	N/A	N/A	N/A

TABLE 3b. U Mines only. Modeled regression results, includes results for U-producing mines only. Data are categorized according to policy-relevant time periods (in years).

Mine Size	Operation	Variable	1948–1954	1954–1964	1964–1974	1974–1985
Small Mines	**Open**	Price Coefficient	4.00E-03	9.80E-03	0.00E+00	N/A
		Moving Average Price	1.00 yr	1.00 yr	1.00 yr	N/A
		Price Time Delay	0.00 yr	0.00 yr	0.00 yr	N/A
	Close	Price Coefficient	7.50E-04	4.80E-03	1.00E-03	N/A
		Moving Average Price	1.00 yr	1.00 yr	1.00 yr	N/A
		Price Time Delay	1.00 yr	1.00 yr	0.00 yr	N/A
		Impact of Larger Mines	1.00E-02	1.00E-02	3.00E-03	N/A
Medium Mines	**Open**	Price Coefficient	1.00E-02	9.10E-03	1.00E-02	N/A
		Moving Average Price	1.00 yr	1.00 yr	1.00 yr	N/A
		Price Time Delay	1.00 yr	1.00 yr	1.20 yr	N/A
	Close	Price Coefficient	9.00E-04	1.00E-03	3.90E-03	N/A
		Moving Average Price	1.00 yr	1.00 yr	1.00 yr	N/A
		Price Time Delay	2.50 yr	1.60 yr	1.50 yr	N/A
		Impact of Larger Mines	5.00E-04	3.00E-02	3.00E-02	N/A
Large Mines	**Open**	Price Coefficient	6.50E-03	9.00E-02	4.00E-02	9.00E-03
		Moving Average Price	1.50 yr	1.50 yr	1.00 yr	0.90 yr
		Price Time Delay	1.00 yr	1.00 yr	0.73 yr	0.65 yr
	Close	Price Coefficient	1.00E-04	3.00E-02	1.30E-01	9.00E-03
		Moving Average Price	1.00 yr	0.70 yr	1.00 yr	1.32 yr
		Price Time Delay	3.20 yr	3.10 yr	2.60 yr	1.80 yr
		Impact of Larger Mines	N/A	N/A	N/A	N/A

TABLE 3c. U & V Mines. Modeled regression results, includes results from mines producing both U and V. Data are categorized according to policy-relevant time periods (in years).

Mine Size	Operation	Variable	1948–1954	1954–1964	1964–1974	1974–1985
Small Mines	**Open**	Price Coefficient	6.00E-02	1.10E-01	0.00E+00	N/A
		Moving Average Price	1.00 yr	1.00 yr	1.00 yr	N/A
		Price Time Delay	0.00 yr	0.00 yr	0.00 yr	N/A
	Close	Price Coefficient	3.00E-02	1.10E-02	5.00E-03	N/A
		Moving Average Price	1.00 yr	1.00 yr	1.00 yr	N/A
		Price Time Delay	1.00 yr	1.00 yr	0.00 yr	N/A
		Impact of Larger Mines	1.00E-02	1.00E-02	3.00E-03	N/A
Medium Mines	**Open**	Price Coefficient	1.60E-01	6.00E-02	0.00E+00	N/A
		Moving Average Price	1.0 yr	1.00 yr	1.00 yr	N/A
		Price Time Delay	1.00 yr	1.00 yr	1.20 yr	N/A
	Close	Price Coefficient	2.00E-02	9.00E-02	5.00E-02	N/A
		Moving Average Price	1.00 yr	1.00 yr	1.00 yr	N/A
		Price Time Delay	3.50 yr	3.00 yr	2.50 yr	N/A
		Impact of Larger Mines	5.00E-04	3.00E-02	3.00E-02	N/A
Large Mines	**Open**	Price Coefficient	5.00E-02	2.00E-02	0.00E+00	0.00E+00
		Moving Average Price	1.50 yr	1.50 yr	1.00 yr	0.90 yr
		Price Time Delay	1.00 yr	1.00 yr	0.73 yr	0.65 yr
	Close	Price Coefficient	0.00E+00	3.00E-02	3.00E-02	9.00E-04
		Moving Average Price	1.00 yr	0.70 yr	1.00 yr	1.32 yr
		Price Time Delay	4.15 yr	3.20 yr	3.00 yr	2.00 yr
		Impact of Larger Mines	N/A	N/A	N/A	N/A

We expound on these topics below, but perhaps more significant than the results of the model was the development of a modeling framework for understanding the relationships between price and policy on U mining operations that has been discussed previously (Buck, 1983; Roskill, 1991; Peach and Popp, 2008) but never quantified. This approach has utility for other commodities (such as oil and gas) in understanding the dynamic relationships between natural resource development and economics subjected to changing policy and regulatory environments.

There are several important limitations of this model. Although a production record exists of New Mexican U mines, annual production data is available for less than half of these. Furthermore, our annual production data is really an estimate using an average of total production of each mine divided by the mine's total years of operation (for both U and V) because most mines do not have year-by-year data. This introduces error and limits the number of data points available for the model. The second limitation is that the average price of U does not reflect long-term contract prices negotiated between U producers and consumers. Lastly, the role of profitability as a function of profit and fixed and variable costs are not included in this model. Although it likely influenced operational decisions, annual cost and profit data was not available for every mine or year of production. An exploration of the dynamics between actual annual production volumes of U-only mines vs. U+V mines over time as a function of changing prices warrants further study.

Trends in historic mining operations

Small and medium sized mines thrived in the state until the late 1950s (in terms of their overall number), but then declined coincidently with an increase in the number of large mines (Fig. 4). The peak in small- to medium-sized historic mining operations during 1952–1958 coincided with high real uranium prices (Figs. 3 and 4). Small- to medium-sized operations declined in conjunction with falling prices between 1958 and ~1970. Note that the number of large operations peaked in 1960–1962, after the 1952–1958 peak in price, consistent with their higher price time delay values for opening.

A possible explanation for these trends is that in early years (1948–1964) guaranteed purchase by the Federal government, regardless of quantity, encouraged production by mines of all size. In later years, (1964–1985) after the lapse of Federal purchase guarantees and subsidies which largely benefited smaller operations (Roskill, 1991), larger mines were able to produce U at lower cost due to economies of scale, where increasing production capacity generally decreases the per-unit cost of production. Below, we use our model results to explore this possibility.

Another explanation for the increase in the proportion of large mines vs. medium-small mines after 1964 may relate to mill capacity and mill contracts. Although one-quarter of total U.S. domestic mills and more than half of domestic milling capacity operated in New Mexico during this time, many of these mills were either already nearing capacity (Peach and Popp, 2008) or ore-processing suitability to mill the ore produced in the region. In the absence of government subsidies for transportation, the added cost of moving ore from mines to mills at increasing distances would have directly impacted the profitability of existing mines. The Marquez mill was constructed in 1980 to provide additional milling capacity, but the mill owner (Bokum Resources) declared bankruptcy in 1981 and the mill was never operational (McLemore and Chenoweth, 2003). As such, larger mines may have been able to wield more market power than smaller operations, negotiating longer-term contracts at lower prices with both mills and U purchasers.

Influence of price versus governmental policies

Four policy situations were included in the model: the Atomic Energy Acts of 1946 and 1954, the Private Ownership of Special Nuclear Materials Act (1964), and the Energy Reorganization Act (1974) (Buck, 1983; Walker and Wellock, 2010). Mine openings and closings were modeled for each time period bracketed by these policy situations to understand how operational responses to changes in price varied as a result of regulatory changes. From 1948–1954, mines of all sizes opened rapidly while few mines closed (Fig. 6). The passage of the Atomic Energy Act of 1954 might have caused rapid growth of uranium mining in the second time period (reflected by mine openings), but closing rates also increased for both small and medium sized mines (Fig. 6). Declining real prices after 1954 were likely an important factor for the increase in these closing rates, perhaps influenced by the sluggish development of nuclear energy technologies (Peach and Popp, 2008). In addition, the moratorium on weapons testing signed by President Eisenhower in 1958 (Buck, 1983), combined with ample existing military stockpiles, dampened demand by the federal government for nuclear weapons.

The peak for small and medium mine closings occurred between 1954–1964 compared to the larger proportion of large mine closings which occurred in the following time period (1964–1974). The latter period coincided with a decline in domestic mining activity in general. This decline was likely due to withdrawal of the US Government's role as steward for the uranium and nuclear industries in 1974 (Buck, 1983) as well as increasing foreign U production (from South Africa, France, and Canada, which collectively surpassed US production by the early 1980s) (Roskill, 1991).

Coupled with other data, trends in price coefficients help to elucidate how government policies impact mine sensitivity. As a hypothetical example, assume that U prices were stable over two time periods of comparison, the first containing notable government subsidies and the second having no government subsidies. However, during these two time periods there was a decreasing trend in the opening price coefficient. One could interpret this scenario as indicating earlier government policies positively impacted mining operations, since fewer mines opened in the second time period. An increase in the closing price coefficients across the two hypothetical time periods would imply greater sensitivity to changes in price in the second time period, which might be due to the lack of stability provided by government subsidies provided in the earlier time period.

We argue that government subsidies affected mines of all sizes, but price change trends complicate whether smaller mines were disproportionally influenced. The high number of historic mining operations for all mine sizes during the early years (1948–1964) suggests that government subsidies for transportation, exploration, engineering, and milling costs impacted all mines. However, this comparison may also be due to relatively

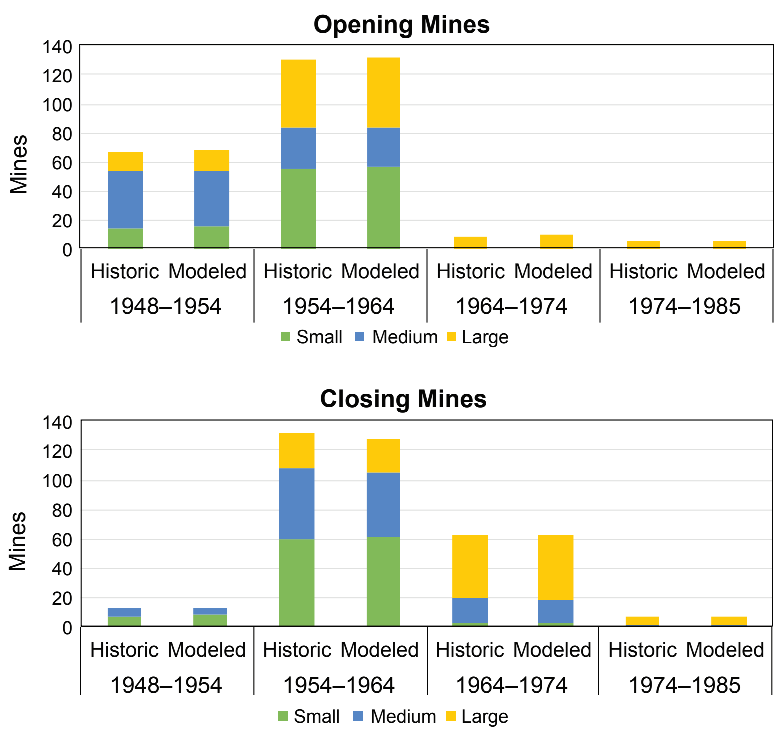

Figure 6. Total number of opening mines (left) and closing mines (right) across the four modeled time periods.

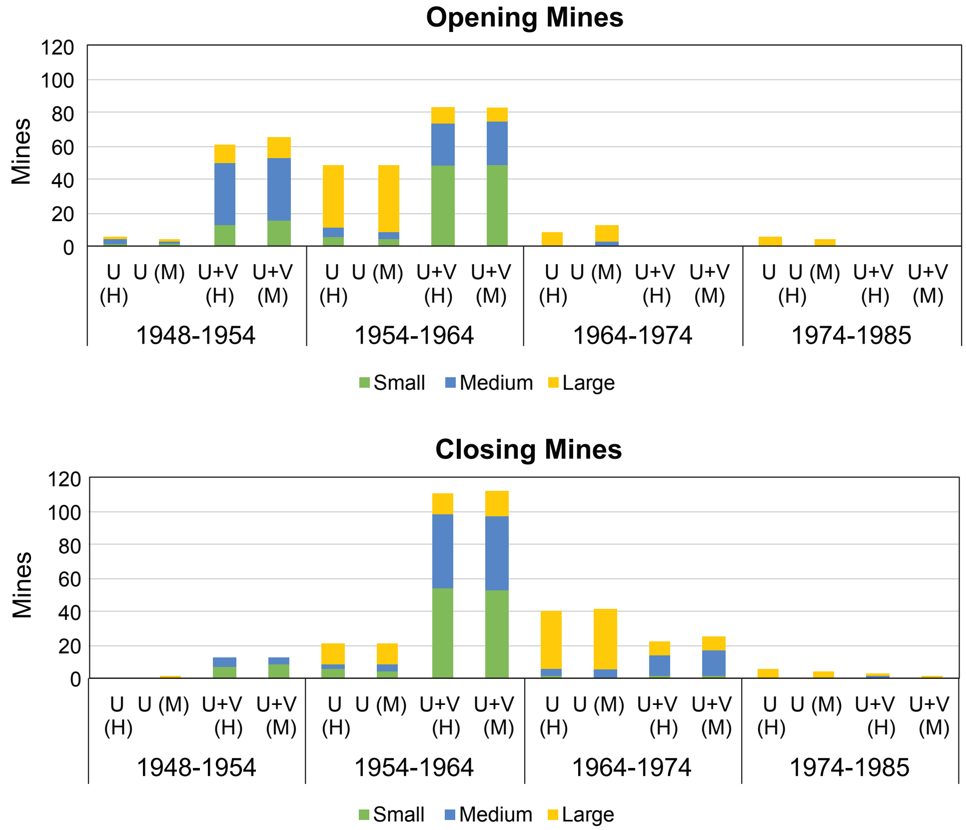

Figure 7. Comparison of the number of openings and closings for U-only mines versus U+V mines. H = historic mines and M = model-predicted mines. Data are shown for each of the four policy-related time periods.

high U prices. Mine size was the most significant indicator of whether a mine would open or close in response to price in the years following these subsidies (1964–1985). In contrast to large mines, no small or medium mines opened after 1964. Also, opening-related price coefficients for all mine sizes were greatest in earlier periods (1948–1954 and 1954–1964) and declined in later periods (Table 3a), which implies that the combination of high prices and subsidies for development encouraged mine openings prior to 1964. Although the same decreasing trend is seen for closing-related price coefficients for small and medium mines through the 1964–1974 policy time period (suggesting less sensitivity to price changes with time, even after subsidies ended), the values of closing price coefficients are greater than coeval opening price coefficients. This indicates that a decision to close rather than a decision to open had greater sensitivity to price changes following the lapse in government subsidies. Both the price coefficients and the historical data suggest that government policies prior to 1964 stimulated and sustained small and medium sized mines. Furthermore, the greatly reduced number of small- and medium-sized mines after 1964 supports our hypothesis that the loss of government subsidies, combined with the decreasing price of U, had a disproportionate impact on these size classes compared to larger mines. No clear trend is evident in the opening and closing price coefficients for large mines. Lastly, it is noteworthy that relatively few mines opened in 1974–1985 despite a large increase in real price in the early half of 1974–1985, which was actually higher than in 1952–1956 (Figs. 3–6). This paucity of openings could be attributed to the lack of government subsidies or the lack of a guaranteed market and purchaser by the government (these being more amenable to small mine operators than larger mine operators, the latter being able to better negotiate complex contracts with non-government purchasers). In summary, analysis of our data indicates that government subsidies likely impacted mines of all sizes; but due to complications posed by declining prices between 1958 and ~1970, we cannot conclusively determine that these subsidies preferentially promoted and sustained smaller mines prior to 1964.

Response times

For all four time periods, the smaller values of the price time delay coefficient for smaller and medium mines compared to larger mines supports our second hypothesis: that smaller mines respond more quickly to changes in price than large mines. The discrepancy in values suggest that the greater initial investment and fixed costs associated with larger mines may have tempered their response to changes in price (which was likely due to economies of scale for larger mines as well as higher operating costs and higher costs associated with opening and closing). On the other hand, the smaller initial investment and fixed costs associated with medium and smaller sized mines allowed them to open and close more rapidly in response to fluctuations in U prices. Grouping the time periods into 1948–1964 and 1964–1985, there is a general trend of a decrease in price time delay for a given mine size. This could be interpreted that decisions to open or close a mine occurred more quickly in the absence of subsidies.

Co-production of vanadium

We hypothesized that mines producing both U and V may have had a slight advantage, both in the speed and magnitude at which they responded to changes in price, over mines that produced U only. Because V is a co- or by-product of U production and because its price was consistently less than that of U, its production was subsidized by U production (Hilliard, 1994). Across all time periods, our modeling results showed generally higher closing and opening price coefficients for small and medium U+V mines compared to U-only mines, indicating that the U+V mines were more sensitive to changes in price which argues against our hypothesis. However, the closing price coefficients were slightly larger for U-only large mines, consistent with our hypothesis. No difference was seen in the price time delays for small mines between U-only and U+V mines, but for medium to large mines the closing price time delay was longer for U+V mines. This suggests that the co-production of vanadium stabilized mine operations for medium and large mines, even in the declining price environment prior to 1974, which supports our hypothesis.

Impacts of larger mines

Small mines were more negatively impacted by larger sized mines than were medium sized ones. This conclusion is based on the higher values of the Impact of Larger Mines coefficient for smaller mines than medium sized mines (Table 3a). In addition to competition from larger mines, exhaustion of mineable resources by smaller mines, which was not included in the model, may have affected the responsiveness of smaller mines to price.

Scarcity and Market Flooding

The U market and industry has been historically plagued by large fluctuations in price and demand. From its early discovery through the development of nuclear power, factors such as the identification of new resources, dumping of reserves, stockpiling, and fear of scarcity have affected the industry. For example, the Westinghouse Electric Company offered a guaranteed U_2O_8 price of \$6/lb. for its customers who purchased their pressurized light water reactors in the early 1970s (Roskill, 1991). However, many companies were developing small modular reactors that increased demand for U, and the prices began to rise in the mid-1970s and peaked at over \$40/lb. in 1978 (Roskill, 1991). Unable to buy U from existing producers or identify new resources, Westinghouse confirmed it could not meet its obligation to provide U at \$6/lb. to its customers, and the market was again plagued by both real and imagined scarcity. After 1978, the supply of U outpaced its demand for nuclear power (Roskill, 1991), which constrained the market and caused spot prices to decline by more than a quarter between 1978 and 1980 and by nearly a third a year later.

Non-modeled factors influencing future mining operations

The results of this study reveal previously unquantified relationships between mining and external drivers and serves to illuminate the economic and policy considerations affecting possible renewed uranium mining in the region. It is also important to recognize that factors such as permitting and environmental regulations, tribal issues and public acceptance, and access to U mills which received little concern in the past will likely affect decisions regarding future U production.

During the historic U boom years in New Mexico, very few state and federal regulations existed which governed the environmental impacts of mining operations and waste disposal. Lack of environmental protection early on led the DOE to comment that "State and Federal controls [were] non-existent or totally inadequate," (written commun. with DOE, documented in SJBRUS, 1980). Subsequent legislation has addressed many of these shortcomings. Although passed towards the end of U production in NM, four federal laws address uranium mining and milling activities: Uranium Mill Tailings and Radiation Control Act (UMTRCA, 1978), Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA, 1980,1986), US Forest Service Mining Regulations and Minerals Management (1974), and BLM Mineral Land Management (1981) (Dixon, 2015). In addition, the state of New Mexico has passed important laws to address the safety of mine workers, air and water quality, and waste disposal (Dixon, 2015).

While the environmental impacts of U mining and milling operations were not often a factor historically, human impacts were even less of a consideration. In particular, the effect of these operations on Native American tribes, who own land and comprise a significant proportion of the population in the region, is an important consideration should operations resume in the future. Legacy impacts of radiation exposure to mine workers, environmental impacts of abandoned mines, and accidents like the Church Rock mill tailings pond failure (the largest radioactive spill in U.S. history) have disproportionately affected tribes in the region.

The number of U mills likely had an impact on mine operations. Between 1948 and 1982 eight mills operated in New Mexico (McLemore, 1983) whereas currently there is only one operating U mill in the U.S., the White Mesa mill in Utah (US EIA, 2016). Location of nearby mills would affect transportation costs and the marketability of U ores, an especially important fact for small U mines.

Conclusions

The objective of this study was to use systems dynamics modeling to quantify how historic uranium operations in New Mexico during 1948–1985 may have been influenced by economic and government policy factors. The number of mines operating in New Mexico during the uranium boom from 1948 to 1985 were grouped by size and classified as either U-only or U+V producing mines. To assess the impact of government policy on mining operations, four time periods were delineated that related to specific enactments of uranium-related federal legislation and policies.

We used the model to test three hypotheses: 1) subsidies from the U.S. government both promoted and sustained smaller mines prior to 1964, 2) smaller mines responded more quickly to changes in price than do large mines, 3) mines that produced both uranium and vanadium were more stable than mines that produced uranium only because of diversified production and the relatively stable historic price of vanadium.

Declining opening-related price coefficients with time is consistent with government subsidies encouraging mines of all sizes. Although closing-related price coefficients decline over time as well, their values exceed those of opening-related price coefficients after 1964 indicating that closing rather than opening had greater sensitivity to price changes following the lapse in government subsidies. Examination of historical data indicates that no small mines and only a few medium-sized mines opened after the elimination of these subsidies. Therefore, government subsidies and/or higher U prices in 1948–1963 vs. 1963–1974 may have helped promote these mine sizes prior to 1964. Economies of scale and lower milling costs for larger mines may also have contributed to the closing of all small and medium sized mines by 1974. Furthermore, the lapse of government subsidies, which were designed to encourage the development of the U industry, were likely an important factor in the relatively low amount of openings and total mines in operation during 1974–1985. This is particularly significant given that real prices were relatively high during most of this time period.

Our modeling generally supports our second and third hypotheses. Small mines opened and closed rapidly (≤1 year). Medium and large sized mines took 0.65–1.2 years to open and 2–5 years to close throughout the 37-year period model, with closing time delays of both medium and large mines being less after 1964 than prior to 1964 (Table 3a). The economic advantage of producing both vanadium and uranium was evident in longer closing times for medium and large mines, but small-medium U+V mines were more sensitive to changes in U price.

Economics, policy, and the regulatory frameworks governing the uranium industry have changed markedly since the U boom of the 1950s and 1960s, which encouraged mines of all sizes to produce U. Public perception, including awareness of legacy impacts of past mining activities and the risk of potential negative impacts on the environment and human health now plays a role in current and future U development decisions. Renewed mining activities will require consideration of all of these factors and will likely result in extensive planning, lengthy permitting times, and investment in public outreach efforts. In addition to planning and regulatory costs, future mines must have approved plans for mine closing and post-operative remediation, as well financial guarantees for the protection of cultural sites, the environment, and human health which will likely increase the unit cost of production as compared to historic costs. As a result, the high ratio of large vs. mid- to small-size mines, which began ca. 1960 is likely to persist into the future should activities resume. Consideration of these factors as well as their potential for change will undoubtedly play a role in future development decisions.

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