Mining "Invisible" Gold: Heap Leaching and Nevada's Contribution to Twentieth-Century Gold Mining

By
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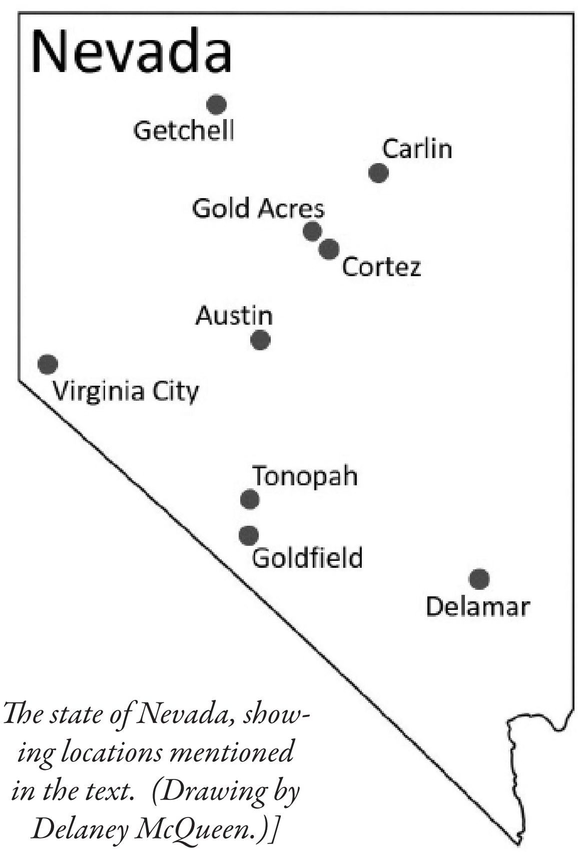
In the late 1960s a small mining district in northern Nevada initiated a new technique to leach low-grade gold ore in open air heaps. Today heap leaching is one of the most universally applied gold-extraction technologies in the world, and is responsible for creating an explosion in precious-metals exploration and for the development of several world-class "Carlin-like" mineral deposits. These include additional finds in Nevada, making the state a preeminent international gold mining area. Heap leaching has now been around for a half century, and this article provides a primer on its development and early physical characteristics.

Beneficiation

Beneficiation, an important mining concept, is the process of upgrading an ore so that it is more economically viable, usually by making the product uncontaminated by other metals or gangue. Through a combination of physical and chemical alteration, mills separate gangue—unwanted, valueless rock—from ore, the mineral being sought. Two common forms of gangue are waste or 'poor' rock, usually dumped right at the mine portal, and tailings, which is the processed waste material discharged from mill buildings onto the landscape.[1]

The grade of an ore body—the percentage, and hence dollar value, of the ore within its larger matrix of unwanted rock—has a tremendous effect on the motivation to mine it. In Nevada's history of mining, this is where a great many would-be miners falter; not so much in the discovery of an ore body, but in failing to understand its extent and what it would take to make the discovery profitable. Time and again, Nevada's mining districts tell stories of an insufficient ore body or an inability to find a way to properly mill the ore.[2]

Successful beneficiation is a balance of technology, chemistry, and economy applied against local geology. Nevada's silver- and, later, gold-milling history is a mixture of technological importation, local invention, innovation, and adaptation. Most of the milling techniques used in Nevada were developed elsewhere in the world, "introduced" to the state, and modified to fit local conditions. Precious-metal milling is a multistep process, which allowed numerous tinkerers to introduce a myriad of different machines or chemicals at various steps in the process—some good and some that were outrightly fraudulent. The successes led to innovations, which, over time, take on wholly new appearances and complexities. Precious-metal heap leaching, developed in the late 1960s, was another giant leap forward in the long history of recovering precious metals, especially gold.



The state of Nevada, showing locations mentioned in the text. (Drawing by Delaney McQueen.)]

Precursors to Heap Leaching

In Nevada, evolving milling technology began with the Washoe process of pan amalgamation developed on Virginia City's Comstock Lode in the early 1860s. The Washoe process evolved directly from the much older, open-air and ground-based patio process that used arrastras. Washoe pans were large iron tubs filled with a slurry of pulverized ore and chemicals such as mercury and then heated with steam. The Washoe pans were a technological advancement but largely relied on the existing, older chemical process. Silver ores in the Reese River Mining District (Austin, Nevada) had a different geochemical composition, and Carl Stetefeldt discovered that they first needed roasting with salt for the Washoe process to be effective. The salt formed silver chlorides that could then be amalgamated. In this case both a new technology, a roaster, and new chemistry were introduced to treat Nevada's ores. These slight but significant additions became known as the Reese River process.[3]

Chloridizing silver ores led to the development of lixiviation, the next advance in milling technology. An Austrian metallurgist, Adolf von Patera, developed lixiviation in 1858. Lixiviation was chemically more complex than earlier milling techniques. It relied on bonding silver with other compounds in an aqueous solution, then separating the soluble and insoluble components. The creation of soluble material required fine crushing, smaller than sand-granule size, and creating slurries. Recovering mineral compounds from an aqueous solution is collectively known as hydrometallurgy.

Early use of lixiviation in the United States met with limited success, its chief fault being the loss of too much silver. In the 1880s American E. H. Russell experimented with the Patera process and developed a better lixiviation, appropriately known as the Russell process. This succeeded in extracting a higher percentage of silver ore, making the technique economically viable. The Russell process still roasted the ore, borrowing the roasting procedure from the Reese River process. Other than additional vats that held ore in different stages of beneficiation, the technological application of the Russell process was not terribly difficult to implement. The Russell process benefited from concurrent advances in crushing technology, namely the replacement of stamps by rolls or ball mills more efficient at pulverizing ore to the fine grain size needed in the process.[4]

In the western U.S. the popularity of lixiviation was relatively short lived, becoming a custom application or subsidiary to other milling processes at a site. Within a few years of lixiviation's arrival in the U.S. came another significant leap forward in precious metal milling: cyanidation. Cyanidation and flotation, the next two milling advancements, would build from both the chemical and the technological advances of lixiviation and eventually pave the way for heap leaching.

Scottish engineers patented the cyanidation process in England in 1887. It was introduced to the U.S. in the 1890s by way of New Zealand, and by 1896 Nevada had its first two cyanide plants. One plant was erected on the Comstock to process voluminous silver-laden tailings left behind by its earlier Bonanza era, while the other cyanide plant operated in the Delamar District to process raw gold ore.[5] By the early twentieth century the application of cyanidation was a proven success and it contributed directly to Nevada's second mining rush, including that era's hallmark discoveries of Tonopah, Goldfield, and Manhattan, and later places like Rochester and Jarbidge, along with numerous smaller strikes across the state.[6]

Early cyanidation used a basic chemical formula that included sodium cyanide, oxygen, and water to bond gold ore to the cyanide; the gold was then precipitated from the amalgam and collected using zinc shavings.[7] To accomplish this reaction, the ore was crushed very fine, referred to as sand, slime, slurry, or simply "fines." The slurry passed repeatedly through different types of filters and thickeners to concentrate the material.[8] The processing occurred in large steel or wooden vats and several filter machines contained within a large, typically tiered, mill building. Only a small amount of cyanide was needed relative to the ore body, making it cheap to use, and it had a remarkably high recovery rate, in some cases upwards of 90 percent.

Those two factors combined meant cyanide processing could be applied to lower-grade ores. Cyanide leaching is why Nevada saw so many of its shuttered mining camps reopen in the early twentieth century: earlier mills left much ore in their tailings that could be retreated with cyanide, or the mines themselves still contained large bodies of ore previously of too low a grade to mine but now profitable with the new cyanide process. The importance of cyanide leaching to Nevada's mining history cannot be overstated.

Flotation was introduced to Nevada after 1915, having its origins and development in Australia and other parts of the U.S. dating back to the late 1800s.[9] Flotation also relies on ore being in an aqueous solution, but with reagents including oil and frothers. Giant tanks acting as frothing machines inject air and oil into the solution, bonding with the ore particles and floating them to the surface where they are skimmed off (decanted) as concentrate.[10] Whereas cyanide works particularly well with gold and silver ores, flotation's advantage is in its applicability to a wider range of metals or to complex ore bodies where there is a desire to recover more than one metal.[11] Nevada's geology of mixed-metal deposits was amenable to flotation. In the 1920s and 1930s mines in many Nevada mining districts erected or modified mills to use flotation. Like cyanidation, flotation allowed for the profitable mining of lower-grade ores and encouraged exploration into new areas.

The concept of leaching has been around for a long time: The Romans collected leached copper from their mines in Rio Tinto, Spain, and Agricola applied a crude form of leaching to piled copper ores in Europe in the 1500s.[12] In the 1920s some copper mines in the U.S. were using outdoor leach facilities as part of their recovery process, including in Nevada. In the early twentieth century, with cyanide and flotation mills successfully recovering gold and silver across the U.S., and open-air copper leaching also proving its worth, it is easy to envision a mining engineer pondering the feasibility of combining these processes into an outdoor leaching facility to extract a precious metal like gold.[13] However, precious-metal heap leaching was still several decades away and it required the alignment of technology and economy to get off the ground.

Mid-century Mining

Precious-metals mining in Nevada encountered setbacks as the early decades of the twentieth century progressed. As mentioned, the turn of the century was a boon for Nevada's gold and silver camps, both newly discovered deposits and old districts receiving a second life. Copper mining also boomed, thanks both to the national growth in consumption of electricity and to increased prices resulting from global interruptions associated with the Great War. However, the double whammy of the cessation of hostilities in 1918 and the Great Depression in 1929 sank Nevada's mineral industry. It also did not help that the existing gold and silver districts were getting depleted and new discoveries were rare.[14]

The stock market crash of 1929 created a run on the dollar, at a time on the gold standard when people could trade paper currency for gold coin. To counteract a fear that the government would run out of gold, Congress passed the Gold Reserve Act in 1934. The act had several repercussions for Nevada mining. First, the U.S. Treasury became the sole repository of all gold in the U.S.: any gold mined was sold directly to the Treasury at its fixed rate. Second, the act raised the price of gold from $20.67 to $35 per ounce, a 60 percent price increase.

The increase to thirty-five dollars was a huge motivator to Nevada residents, many of whom were out of work. Throngs of unemployed men, and quite a few women, went into Nevada's old mining camps to snipe on old claims and placer deposits.[15] Larger mining companies were also able to maintain some level of production, and with the new potential for higher profits a few companies even invested in larger or more up-to-date mills. For a state with few other commodities, the federal government's gold action provided a modicum of relief and hope to many of Nevada's rural communities. However, gold production was still significantly curtailed compared to earlier eras.

Like the rest of the country, the U.S.'s involvement in World War II finally brought Nevada out of the Depression. Before the U.S. even entered the war Nevada saw significant increases in demand for its non-precious metals, including copper, mercury, tungsten, and manganese.[16] Gold production also increased, but gold quickly found itself in a precarious situation. Unlike base metals that were clearly being converted into ships, planes, and armaments, gold mining was viewed as something of a luxury.

In 1942 the War Production Board—which, in coordination with the military, determined how the U.S. economy operated on a war footing—determined that gold mines were in direct competition with and draining resources from other industries producing war-critical materials. In October 1942, Federal Order L-208 gave the nation's gold mines sixty days to shut down.

Gold-mine operators howled at the order. Besides obvious monetary losses, they argued that gold miners would not or could not easily transfer to other mines like copper, and if they did it might be difficult to get them back. Idle mine machinery would likely get carted off or scrapped, and shafts and pits would flood. A flooded mine would be useless to an owner and usually impossible to reopen without incurring tremendous expense. Additionally, owners argued that gold would be needed to finance the war and its aftermath. Many of their concerns proved true and after the war many of the nation's shuttered gold mines never reopened.[17]

The Gold Reserve Act, World War II, and Order L-208 together had a peculiar, lingering effect on domestic gold production. After the war, gold mining in the U.S. became, as a writer to the *Engineering and Mining Journal* stated, "pathetic."[18] From World War II until 1970 gold production in Nevada languished. Rather, following the war, Nevada continued its prominence in base-metal mining, especially copper, but also tungsten, iron ore, and zinc, the latter being somewhat ironic as mills used zinc in the recovery of gold. These minerals succeeded in part because of favorable prices, increased scale of operations (including open-pit mining and the introduction of significantly larger excavation and haulage equipment), and Cold War government encouragement to mine those minerals through the federal Defense Minerals Exploration Administration (DMEA).[19]

Gold mining suffered because of high labor costs, its slow conversion to open-pit mining, and because of the U.S. Treasury's continued control of the gold market and its unchanged rate of only thirty-five dollars per ounce. While the cost of producing gold rose from the 1940s through the 1960s, the price the mines received was stagnant. Under those conditions only high-grade gold deposits or large-scale operations were profitable. In 1967 the U.S. Bureau of Mines (USBM) estimated that, at thirty-five dollars an ounce, only 2 percent of the nation's gold reserves could be profitably mined.[20]

Gold exploration continued in this era, however, and gold's low market price encouraged finding ways to lower production costs. Technological advances in core drilling allowed for larger exploration programs, and open-pit mining, bulldozers, loaders, and larger haul trucks all increased mining's economy of scale. North-central Nevada's Gold Acres Mine and Getchell Mine were two places that took early advantage of these practices.

Gold Acres was one of the first open-pit gold mines in the country, converting from an underground operation in the late 1940s.[21] In the 1930s and 1940s Gold Acres was intriguing geologists and confounded the mine's operators, as their assaying samples continually found microscopic, "invisible" gold in the supposed waste and overburden. The gold was diffuse but consistently present. Miners were finding similar "invisible" deposits fifty miles to the northeast and were only partially successful in recovering the gold.[22]

By the 1960s the increased scale of Nevada's gold mining, and the large capital investment necessary to pull it off, placed an urgency on finding a way to profitably recover ever-lower grades of ore like the Gold Acres deposits. From the 1930s, government mining men like USBM engineer William Vanderburg and United States Geological Survey (USGS) geologist Ralph Roberts, were working in Nevada and reporting on these disseminated gold deposits. Vanderburg, for example, noticed that the deposits were found in geologic formations that would have been overlooked by earlier prospectors. Importantly, the deposits were found in several Nevada locations, and Roberts observed some patterning to their occurrence.[23]

In 1960 Roberts published a paper on this patterning. The following year two exploration geologists working for Newmont Corporation, John Livermore and Alan Coope, heard Roberts speak on his discovery and put his observations to practice north of Carlin, Nevada. They discovered a massive but highly diffuse goldfield that soon became known as the "Carlin Trend," and in 1964 Newmont started mining what would soon become the largest gold-mining complex in North America. The associated milling entailed large, outdoor cyanide leach vats and used activated carbon to recover the gold.[24]

Gold Heap Leaching Begins

While the federal DMEA was of little help to gold miners, another division of the Department of the Interior, the Bureau of Mines, was a different story. Founded in 1910, the USBM actively collaborated with the mining industry to improve all aspects of mining, from exploration to extraction and processing, and mine safety. The agency worked closely with the U.S. Geological Survey, often sharing employees, and was a prolific publisher of its research.

In the 1960s the USBM was working on two parallel projects aimed at improving the recovery of lower-grade gold deposits. One trajectory was on the use of activated carbon as a cheaper alternative to the still-popular zinc dust recovery method, the latter commonly referred to as Merrill-Crowe.[25] Another was on improved leaching, either in vats or in outdoor piles, called heaps.

The breakthrough came in 1969, when George Potter, Bureau of Mines metallurgist in the Salt Lake City office, published a report describing the bureau's success in recovering low-grade gold ore from "stripping waste" via percolation cyanide leaching.[26] The leach tests occurred in a laboratory setting and included traditional vats and very small, open-air heaps, with leaching runs set at time intervals ranging from forty-eight to one thousand hours. A sodium cyanide and lime solution was applied to the test samples, and the gold-laden runoff, called a pregnant solution, was passed through activated carbon to recover the gold. Lime was included in the mix to help maintain the heap's pH at around 10 which reduces cyanide decomposition.

The strip waste samples averaged 0.03 gold ounces per ton prior to leaching, a very low grade by the standards of the time. In comparison, in 1969 Newmont's Carlin Mine was averaging 0.32 ounces of gold per ton. The heap tests recovered 67 to 95 percent of the gold. In addition to separating the gold, the recovery process was devised to save most of the cyanide, activated carbon, and water for reuse, significantly reducing costs. As Potter explained, the results offer a "simple and low-cost" recovery of low-grade gold deposits, and can be applied without the construction of a large cyanide mill.

The Bureau of Mines obtained the low-grade strip waste samples from a "Nevada producing mine," the Cortez Mine located seven miles from Gold Acres.[27] The Cortez Mining District is one of Nevada's oldest mining locations. Silver was discovered there in 1863, and in 1927 Cortez was the state's largest silver producer. The last mills in the district shuttered in the 1930s and the silver mining essentially stopped. Based on the gold anomalies at nearby Gold Acres, after World War II the U.S. Geological Survey started examining Cortez's geology and found similar disseminated gold deposits. The gold at Cortez was found in a completely different geologic location from the historic silver mines, and as Vanderburg observed in other mining camps, for nearly ninety years miners had overlooked the ore body.[28]

In the 1960s American Exploration and Mining Company (AMEX) was also exploring Cortez's potential for gold and, with the help of the Geological Survey's data, identified a large, high-grade but diffuse gold deposit. Based on its exploration program and the Geological Survey's geochemical tests, in 1964 AMEX formed the Cortez Joint Venture with three other companies, and in 1968 began open-pit gold mining.[29] The operation's counter-current decantation cyanide mill, completed in 1969, was built by the same firm that had constructed Newmont's Carlin Mill just five years earlier. The Cortez Mine was expected to have a life of six years.[30] Cortez instantly became the third largest gold mine in the country, principally because there were few active gold mines at the time.[31]

The Cortez Mine donating some of its stripping waste to the Bureau of Mines for leach tests is fitting. Throughout its history the district experimented with each of the milling technologies explained above, and here it was, three decades later, doing it again.[32] Cortez Joint Venture's managers knew that if they could start recovering the low-grade gold in their mine they could extend the mine's life. The Cortez company also discovered

The first commercial gold recovery heap-leach pad, front left, at Cortez, c. 1971. Note the pregnant pond and recovery building in front, and equipment constructing an adjacent heap at center right. The mill and shops for the open pit operation are at upper right. (Photo by Don Duncan courtesy of Lynn Duncan.)

a large, untapped disseminated gold deposit at nearby Gold Acres that contained high- and low-grade ores. The Gold Acres deposit could also extend mine life, *if* there was a way to profitably recover the lower-grade ores.[33]

In 1968 the Cortez company worked with the Bureau of Mines to construct a larger pilot heap-leach pad at the mine itself, which better simulated a real-world application. The experiment involved five hundred tons of run-of-mine (non-crushed) ore placed on a gently sloped, impervious pad. Over 60 percent of the gold was successfully recovered and Cortez immediately constructed two additional test pads to refine the experiment. The results were so good that the mine immediately designed a full-scale leach pad. In 1971 Nevada's Cortez Mine started the world's first commercial-scale, gold recovery heap-leach pad.[34]

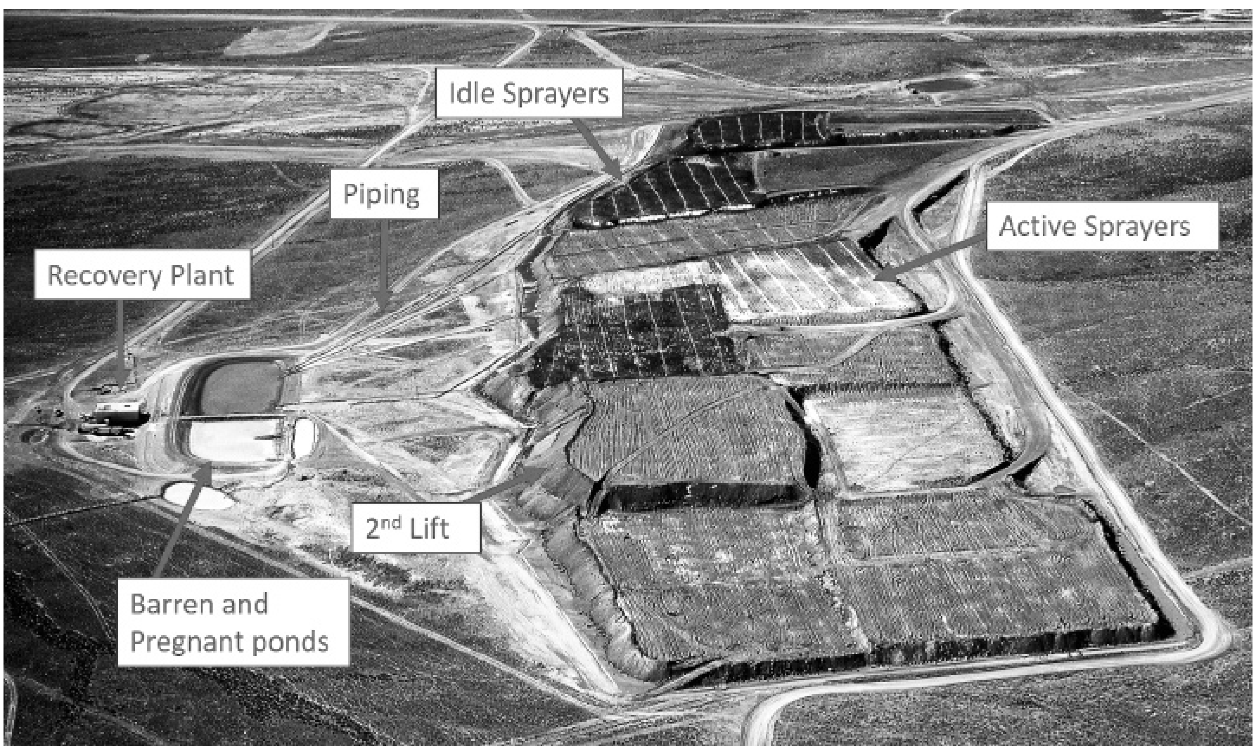
Newmont paid close attention to Cortez's heap experiments, and Cortez's mine manager, Don Duncan, noted that many people came to the mine to tour the new heap-leach facility. Concomitant with the heap leach, Duncan also noted the importance of the activated carbon, specifically the development of the carbon-in-column recovery process.[35] Newmont constructed its first heap-leach pad within one year of Cortez doing so, and other mines were taking a serious look into its efficacy. Heap leaching's proponents lauded several key aspects about the new recovery technique, foremost being several avenues of cost efficiency: low capital investment, low labor needs, use of existing equipment and mills, use of run-of-mine ore which eliminated costly crushing, low chemical consumption, and ease of operation.[36]

The introduction of gold heap leaching came at a fortuitous moment in history. The same year that Cortez built its commercial heap leach pad, President Richard Nixon announced that the U.S. dollar would no longer be tied to the nation's gold reserves. Taking U.S. currency off the gold standard meant gold producers could finally sell on an open market. Within one year gold had doubled in price, within two years it hit one hundred dollars an ounce and continued to rise.[37]

As could be expected, a 400 percent increase in the price of gold had an immediate and robust effect on Nevada mining. Exploration companies spread out across Nevada seeking the "Carlin-like" invisible gold deposits. Heap leaching successfully pushed gold's cutoff grade—the lowest grade that an ore can be mined profitably—lower than at any point in history. Nearly all new gold mining projects factored heap leaching into their mine plans. By the mid-1970s Newmont's leach pads were recovering gold as low as 0.02, Cortez's at 0.04, and Gold Acres' at 0.05 ounces per ton, all at recovery rates above 75 percent and some nearing 90 percent, proving the potential for profits.[38]

Pit mining ceased at Cortez in 1973 and at Gold Acres in 1976, but their associated leach pads continued to produce gold into 1978. In the end only two men, one full- and one part-time, were needed to monitor the leach pads. In less than a decade the Cortez and Gold Acres mines leached a combined 5 million tons of ore—material that prior to heap leaching would have gone to the waste dumps.[39]

Cortez was not idle for long, however; in 1980 new gold deposits were located on the other side of the mountain, and a simple haul road could be used to move this new ore deposit to the existing mill and leach pads.[40] This gave Cortez another five years of mine life, enough time to find even more gold reserves in the same area. Fifty years



Gold Acres heap-leach pads nearing the end of their life cycle, c. 1973. All of the basic components of a heap-leach pad are on display. The heaps in the foreground are exhausted. (Photo by Don Duncan courtesy of Lynn Duncan.)

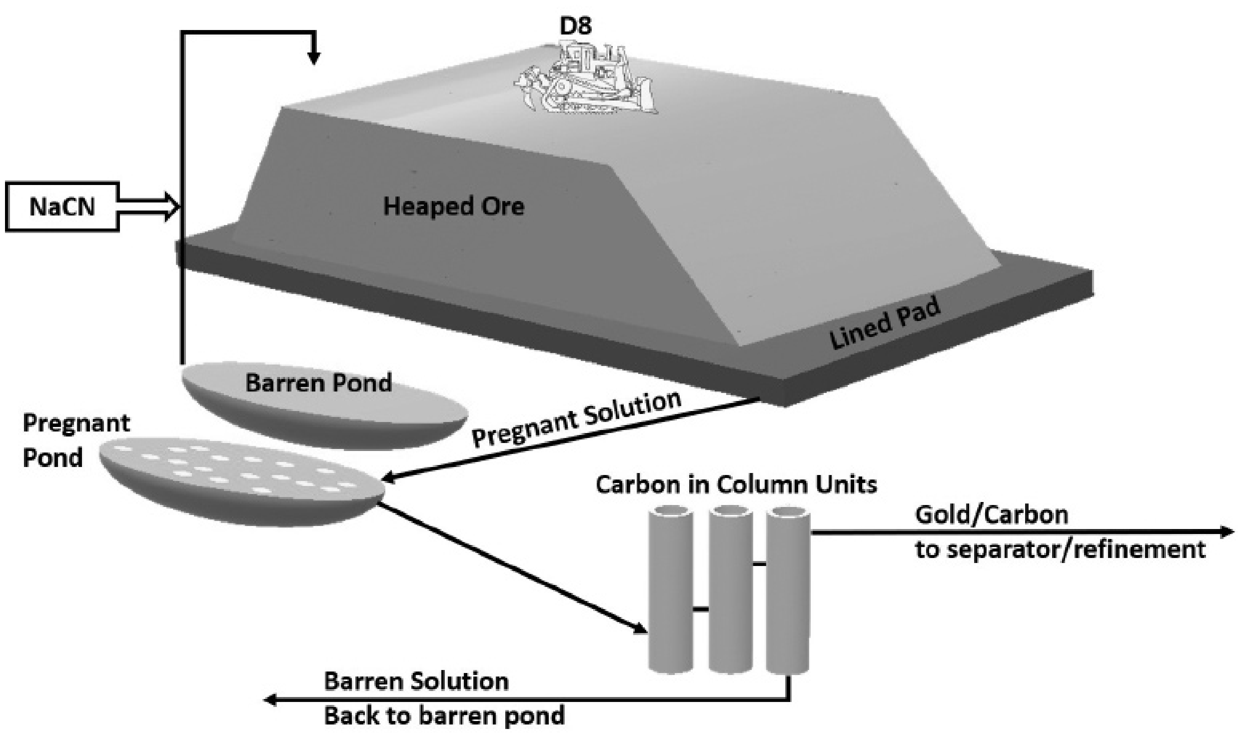
later, Cortez remains one of the most active gold mining locations in Nevada. Newmont's mines on the Carlin Trend have also remained highly productive and profitable.[41]

Early Heap Leach Design

Throughout the 1970s heap leaching expanded to several goldfields and underwent recurrent experiments, lessons from failures, and refinements on a range of variables, leading to ever larger and more efficient heap leach practices. Some of the issues addressed in early heap leach use include: compaction of the heap which hinders percolation; pad construction and materials; saturation, evaporation, and general application of the reagent cyanide solution; lixiviant strengths; leach times; heap particle size and uniformity, which affects permeability of the solution through the heap; and gangue, including unwanted minerals that rob the solution of its cyanide by bonding to the cyanide, preventing the gold from doing so. High clay content was particularly troublesome.[42] As a result of these refinements, today's heap leach pads are over three times as large as early pads, have more complex construction, and are better designed to prevent short- or long- term environmental damage.

In basic terms, heap leaching is a hydrometallurgical process that percolates a solution of cyanide, water, and other reagents, such as lime, specific to the needs of the ore body being mined, onto a pile of ore that has been loaded onto an impervious surface. The cyanide solution works its way through the heap, bonding with microscopic gold particles.

The now gold-laden solution, called a pregnant solution, reaches the impervious base and is channeled to a collection pond. The pregnant solution is piped to a recovery unit where the gold is separated from the cyanide. The recovery unit might be the same mill that is processing higher-



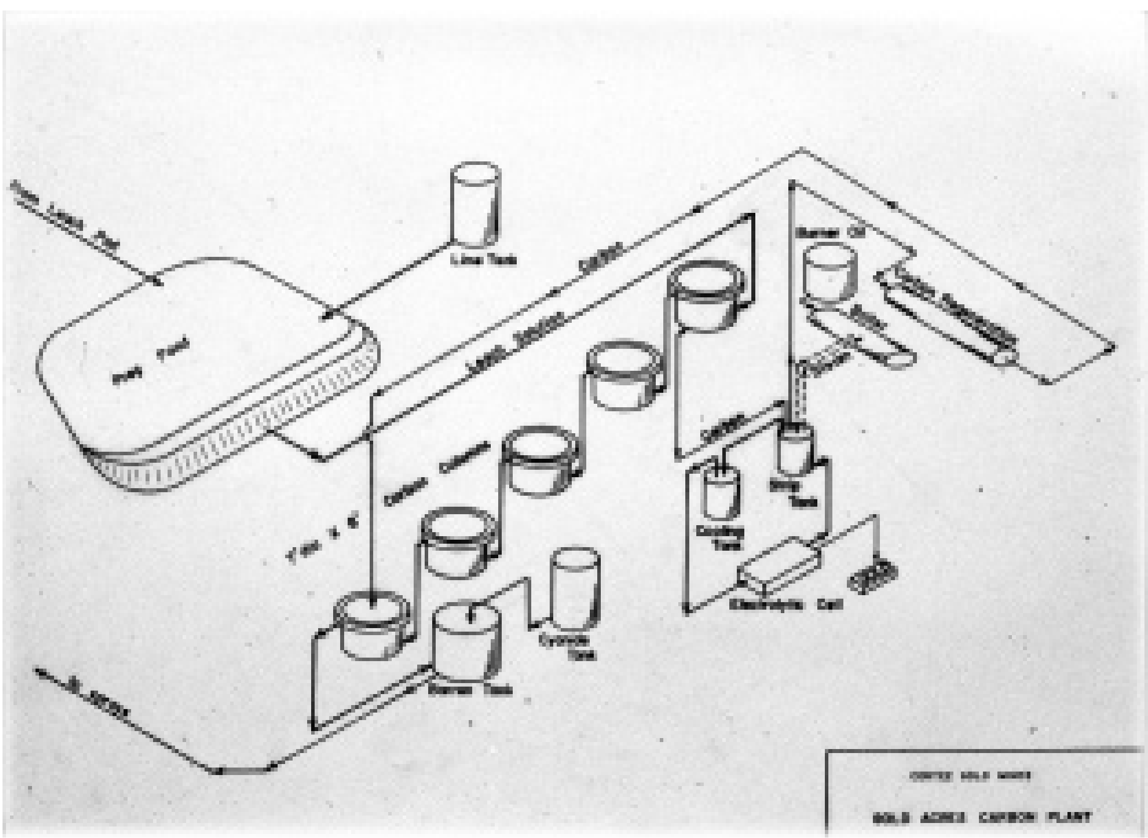
Conceptual drawing of a heap leach operation. (Drawing by the author and Delaney McQueen.)

grade ores from the same pit, or it might be a stand-alone processing plant. The Merrill-Crowe process of zinc precipitation was commonly used to recover lower-grade ores in the 1950s and 1960s, but after 1970 carbon adsorption became more popular with heap leaching. After the gold is removed, the now-barren solution is returned to the heap cycle.

The physical footprint of a heap facility includes: the heap pad; separate reservoirs for barren and pregnant solutions; a recovery plant; ditches and pipelines connecting to the heap, reservoirs, and recovery plant; roads or conveyors that deliver heap material to the pad; and a piping and pumping system to deliver and disperse the barren cyanide solution on the top of the heap.

Early heap-leach pads were large square or rectangular pads up to 450 feet long, built on open, flat terrain with a grade of 1 to 6 percent that directed pregnant solution into a ditch that ran to the collection pond. Any higher gradient risked collapse of the heap. Some early heap-leach pads removed the leached material after every run, replacing it with fresh ore. These single-run pads were usually smaller, with a preferred base layer of supposedly impervious asphalt. Alternatively, new ore was stacked on top of exhausted ore, called lifts. Adding new lifts benefitted by giving the lower lifts one more run through solution, potentially collecting even more gold. Cyclic pads were usually much larger than single-run pads.

Mines experimented with different impervious base layers, including compacted clay, mill tailings, concrete, or different kinds of thick plastic sheeting.[43] Gravels or sand were put on the base layer to help protect it from large and sharp rocks



Expanded flow diagram of the carbon-in-column recovery plant at Gold Acres. Actual plants could be quite compact. (Image courtesy Lynn Duncan.)

that comprise the heaped ore. Because of environmental laws in the U.S., modern heap-leach pads are exclusively lined with high-density plastic.

The heap pad is surrounded by one or more ditches and berms that help contain and divert runoff. The ditches had to account for collecting the percolated, pregnant solution as well as any potential runoff resulting from heavy snow or rainstorms. The ditches were also usually lined to prevent seepage of pregnant solution into the ground, resulting in lower gold recovery.

Storage ponds could be one large depression separated by a berm, or two distinct reservoirs. In either case they were typically of uniform size. Some early storage ponds were lined with impervious clay or compacted tailings, and the pregnant pond sometimes with plastic to retain the gold solution, but again environmental laws resulted in today's ponds all having plastic liners. The ponds had to be large enough to hold all solutions used in the leaching process, as well as potentially heavy snow or rainfall. In some locations, even in arid Nevada, nature's annual spring runoff was a concern.

Early heap-leach pads used run-of-mine ore. As a result the heaped material ranged wildly in size, from small gravels to boulders several feet in diameter. In one respect this size discrepancy was good: the heap pad had to be porous throughout to allow oxygen, a needed chemical in the cyanide reaction, into the system.

However, the uneven particle sizes also created problems. Large boulders had less surface area and contact with the cyanide solution and would not release all their gold, and the uneven porousness made it difficult to control percolation rates,

Aerial view showing the top of the heap-leach pad at Gold Acres, circa 1971, with its completed and very skillfully ripped surface, and sprayer lines in place. (Photo by Don Duncan courtesy of Lynn Duncan.)

sometimes resulting in solution ponding within the heap, which could lead to a breech or collapse. Although eliminating crushing was presented as one of heap leaching's cost-saving measures, mines learned early that a more uniform ore eliminated several problems and increased gold recovery. Although in later years most heaped material was crushed down to a size of just a few inches diameter, the ore was still larger than the fines required in a mill-tank system.

Heaps could be built in one of two ways: by haul truck or by conveyor. Haul trucks were the more common method, as the equipment and personnel were already available at the mine site, and with run-of-mine ore a haul driver went from the pit directly to the heap without any additional processing steps.[44]

Haulage entailed the trucks driving onto the top of the heap to prescribed locations and dumping their loads, which a bulldozer or loader then pushed and flattened. Loaded haul trucks, however, compacted the heap with their weight, resulting in a need to rip the top of the heap. Most bulldozers assigned to heap construction, such as the wildly popular Caterpillar D8, had rippers installed on their back ends to tear up the heap's surface.[45] Ripping was the last step before laying out the percolation system.

One part of the heap process that received much attention was the physical application of the cyanide solution to the heap. The very earliest heaps raided the local farmers' supply store for irrigation equipment of pipes and applicators. The first heap-leach pad at Cortez used six-inch pipe to deliver solution to the top of the pad, with the surface gridded with three-inch diameter PVC pipes spaced fifty feet apart. Plastic sprinklers with a fifty-foot spray radius applied the solution.[46] Other mines reported using oscillating sprinklers, sprayers, "wigglers," or "wobblers" to distribute the solution onto the heap. Wigglers are pieces of surgical tubing that flail large droplets, and wobblers spray a finer mist than sprinklers.[47]

In the early years, solution application on heaps suffered several problems. Because heaps are outdoors they are subject to the whims of nature, including seasonality. Freezing created problems for the pipes and companies faced with this circumstance idled their heaps during the winter. Heavy rains could dilute the solution and alter its chemical balance and pH, or force the solution to run off of the heap instead of through it. With sprinklers, high winds would disperse the cyanide across the landform instead of onto the heap. This last issue was not only a cost concern but it raised serious questions about potential adverse effects to the surrounding environment. Another issue was scaling, the buildup of trace minerals or compounds in the barren solution, which could clog the applicators.

With time, most of these issues have been resolved or knowledge now exists about how to remedy them when they occur. Most modern heaps use a dripline irrigation system very similar to what people install in their flowerbeds. Driplines have several benefits over earlier applicators: driplines are made of highly flexible tubing and are easy to move as the heap expands, a drip-type application eliminates wind dispersal, and it is easier to monitor and control the application rate across the surface of the pad.[48]

Early heap lifts were 20 to 30 feet in height each, tapered slightly for stability, and generally topped off at no more than three lifts; anything taller risked failure, reduced gold recovery, or both. Today's heap leach pads have several lifts and can be over 150 feet high. When early heaps reached their maximum height, and if space was available, the mine just extended the heap outward onto the landform, growing ever longer and creating an artificial, butte-looking hill.

As a comparison, when completed in 1977, the first commercial heap pad at Cortez measured about half a mile long by two-tenths of a mile wide, covering about 60 acres. A heap pad constructed at Cortez in 2009 measures half a mile long on each side, is three times taller than the 1970s heap, and covers about 150 acres, or nearly a quarter section of land. The footprint of the 1880s townsite of Cortez, its cemetery, the Tenabo Mill, and the old silver tailings flow would only cover half of the modern leach pad's surface. Modern heap-leach pads at other mines in Nevada are even larger. The scale and sophistication of heap leaching has developed considerably in the last fifty years, concurrent with the massive scaling up of modern open-pit gold mining.

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Notes:

1. In open pit mines the initial waste material is called overburden or stripping waste. As the pit progresses it generates different grades of ore, and anything below cutoff grade is simply discarded, though usually still segregated in case changes in economy or technology create a desire to mill it.
2. Historic texts refer to the inability to "properly" mill their ore, although more specifically they mean being unable to *profitably* mill it. The usual issue was too much loss in the tailings, which was the result of using the wrong milling or chemistry process. For example, early in Nevada's mining history the Washoe Process was exported to several new discoveries in the state. Results were generally poor, as the new ore deposits were geologically different from those of the Comstock, and it took time to realize the distinctions.
3. Donald Hardesty, *Mining Archaeology and the American West: A View from the Silver State* (Reno: University of Nevada Press, 2010), Ch. 2.
4. Manuel Eissler, *The Metallurgy of Silver* (1891; reprint: Boston: Adamant Media, 2006), 213-7 and Ch. 13.
5. Hardesty, *Mining Archaeology*, 83-7; Joseph Tingley, Robert Horton, and Francis Lincoln, "Outline of Nevada Mining History," *Nevada Bureau of Mines and Geology Special Publication 15* (Reno: Mackay School of Mines, University of Nevada, Reno, 1993), 21.
6. Russell Elliot, *Nevada's Twentieth-Century Mining Boom: Tonopah, Goldfield, Ely* (Reno: University of Nevada Press, 1966), 153-8; Joseph Tingley, T. Lugaski, and A. McLane, "Discovery of Mining Camps in South-Central Nevada," *Mining History Journal* 8 (2001): 18-29.
7. Cyanidation was also being applied to silver ores but the emphasis of this article is on the ramifications the process had for gold mining. In the U.S., and Nevada especially, heap leaching for silver is not nearly as common as for gold.
8. Hardesty, *Mining Archaeology*, 83-7.
9. Dawn Bunyak, *Frothers, Bubbles and Flotation: A Survey of Flotation Milling in the Twentieth-Century Metals Industry* (Denver: U.S. National Park Service, 1998), Ch. 3.
10. T. A. Rickard (comp. and ed.), *The Flotation Process* (San Francisco: Mining and Scientific Press, 1916), 9-52.
11. Bunyak, *Survey of Flotation Milling*, xi.
12. Lorna Anguilano, "Roman Lead Silver Smelting at Rio Tinto: The Case Study of Corta Lago" (Ph.D. diss., University College London, 2012), Ch. 4; Lee W. John, "The Art of Heap Leaching" (Johannesburg: Southern African Institute of Mining and Metallurgy, 2011), 17-9; Thomas Seal, "Introduction, History and Theory of Heap Leach Technology for Precious and Base Metals," Short course, American Exploration and Mining Association Annual Meeting, 2 Dec. 2019, Reno, NV.
13. Uranium leaching started in the early 1960s, and, like copper leaching, it provided insights toward successful gold leaching. Russell R. Elliot, "History of Nevada Mines Division, Kennecott Copper Corporation" (unpublished study, Nevada Historical Society, Reno, 1956). https://utahrails.net/pdf/Elliott_KCC-Nevada-History.pdf
14. Tingley, et al., "Nevada Mining History," 23-7.
15. Benjamin Barna, "The Rabbit Hole Snipers: Mining, Making Do, and the Great Depression in Northern Nevada," *Nevada Historical Society Quarterly* no. 54 (2011): 75-100; Dean Heitt, *Before the Gold: Early Mining History of the Carlin Trend, 1874-1961* (Las Vegas: Southern Nevada Conservancy, 2019), 130-41.
16. Collectively, non-precious minerals are known as base metals.
17. Gage McKinney, "Order L-208: The Closing of America's Gold Mines During World War II," *Mining History Journal* 25 (2018): 56-74.
18. "Cortez Gold Mine Helps Boost U.S. Output," *Engineering and Mining Journal* (hereafter *EMJ*) 170, no. 5 (May 1969): 105-7.
19. Dana Bennett, "Nevada Mining Innovates and Endures," *Elko [NV] Daily Free Press,* 1 June 2015; "Defense

Minerals Exploration Administration (DMEA)," United States Geological Survey (USGS), accessed 12 Feb. 2021: https://pubs.usgs.gov/ds/1004/ds1004_dmea.htm

20. Harold J. Heinen, D. G. Peterson, and R. E. Lindstrom, "Processing Gold Ores Using Heap Leach-Carbon Adsorption Methods," *Information Circular 8770*, U.S. Bureau of Mines (1978), 1.
21. Edna Patterson, "Thar's Gold in Them Hills, Parts One and Two," *Northeastern Nevada Historical Society Quarterly* 3, no. 2 (1972): 2-11.
22. Heitt, *Before the Gold*, "Bootstrap District."
23. William O. Vanderburg, "A Reconnaissance of Mining Districts in Lander County," *Information Circular 7043*, U.S. Bureau of Mines (1939), 42; Ralph Roberts, *A Passion for Gold* (Reno: University of Nevada Press, 2000). Roberts' autobiography provides good historical context on his research across Nevada that led to his famous paper on disseminated gold occurrences.
24. Jack H. Morris, *Going for Gold: The History of Newmont Mining Corporation* (Tuscaloosa: University of Alabama Press, 2010), Ch. 1.
25. Surprisingly to this author, the activated carbon came from coconut shell, which has an incredible porosity. Carbon adsorption as a recovery method dates to the 1950s; carbon-in-column recovery developed at about the same time as heap leaching. The Merrill-Crowe zinc process dates to the beginning of the twentieth century. See: Omar A. Muhtadi, "Metal Extraction (Recovery Systems)," (1982), accessed 17 Mar. 2021: https://www.911metallurgist.com/blog/wp-content/uploads/2016/03/Merrill-Crowe-process.pdf
26. George M. Potter, "Recovering Gold from Stripping Waste and Ore by Percolation Cyanide Leaching," U.S. Bureau of Mines, *Technical Progress Report 20* (U.S. Dept. of the Interior, Dec. 1969).
27. Mr. Donald Duncan managed the Cortez Mine at the time of the heap leach experiments, and his oral history conducted after his retirement provides a wealth of information on the subject. Donald Duncan, Interview by Victoria Ford, 3 Aug. 1999, *Nevada Mining Oral History Project* (Reno: University of Nevada Oral History Program, 2008), Ch. 5.
28. R. L. Erickson, G. H. Van Sickle, H. M. Nakagawa, J. H. McCarthy, Jr., and K. W. Leong, "Gold Geochemical Anomaly in the Cortez District, Nevada," *Geological Survey Circular 534* (Washington, D.C.: USGS, 1966); John D. Wells, Lee R. Stoiser, and James E. Elliott, "Geology and Geochemistry of the Cortez Gold Deposit, Nevada," *Economic Geology* 64 (1969): 526-37.
29. The Cortez Joint Venture (CJV) was formed by AMEX, a wholly-owned subsidiary of Placer Development, Ltd. (later Placer Dome); the Bunker Hill Company of Kellogg, Idaho; Vernon Taylor, Jr., of Denver, Colorado; and Webb Resources, also of Denver. After forming the CJV the Cortez district, mine, and company became intertwined and known simply as "Cortez". In 2006 Barrick acquired Placer Dome and 100 percent controlling interest in Cortez, and remains active there today.
30. *EMJ*, "Cortez Gold Mine Helps Boost," 105-7; "Gold Mine Construction to Begin," [Reno] *Nevada State Journal*, 10 Mar. 1968, 11.
31. "Cortez Mine Increases World's Supply of Gold," *Reno Gazette-Journal*, 25 Jan. 1969, 31.
32. Erich Obermayr and Robert McQueen, *Historical Archaeology in the Cortez Mining District: Under the Nevada Giant* (Reno: University of Nevada Press, 2016), Ch. 4.
33. Donald Duncan and T. J. Smolik, "How Cortez Gold Mines Heap-Leached Low Grade Gold Ores at Two Nevada Properties," *EMJ* 178, no. 7 (July 1977): 65-9; Steve Fiscor, "The 1970s: The Great Mining Buildout," *EMJ* 217, no. 10 (Oct. 2016); "Gold Price Ups Mine Earnings," *Nevada State Journal*, 17 May 1973, 18.
34. Duncan, "Interview"; Duncan and Smolik, "How Cortez Gold Mines Heap-Leached," 65; Potter, "Percolation Cyanide Leaching," 5.
35. Duncan, "Interview"; Morris, *History of Newmont*, 112.
36. Duncan and Smolik, "How Cortez Gold Mines Heap-Leached," 66-9. Harold J. Heinen and Bernard Porter, "Experimental Leaching of Gold from Mine Waste," U.S. Bureau of Mines, *Report of Investigations 7250* (U.S. Dept. of the Interior, Apr. 1969); Daniel W. Kappes, "Leaching of Small Gold and Silver Deposits" (paper presented at the Small Scale Mining of the World Conference, Jurica, Querétaro, Mexico, Nov. 1978): https://www.kcareno.com/professional-papers; George Potter, "Design Factors for Heap Leach Operations," *Mining Engineering* 33, no. 3 (1981): 277-81.
37. Macrotrends, LLC, "Gold Prices—100 Year Historical Chart," accessed 12 Mar. 2021: https://www.macrotrends.net/1333/historical-gold-prices-100-year-chart
38. Current cutoff grades are as low as 0.015 ounces per ton. Duncan and Smolik, "How Cortez Gold Mines Heap-Leached," 66; Morris, *History of Newmont*, xi; Richard Reid, "History of the Modern Gold Rush in Nevada," virtual lecture presented to the Geological Society of Nevada, 25 Mar. 2021; "Gold Mine Interest Up in Nevada," *Reno Gazette-Journal*, 29 Nov. 1974, 17; Tingley et al., "Nevada Mining History," 41.
39. Peter G. Chamberlain and Michael G. Pojar, "Gold and Silver Leaching Practices in the United States," U.S. Bureau of Mines, *Information Circular 8969* (U.S. Dept. of the Interior, 1984), 26-8; Duncan and Smolik, "How Cortez Gold Mines Heap-Leached," 69.
40. "BLM [U.S. Bureau of Land Management] Claims Suc-

cess at Cortez Gold Mine," *Elko Daily Free Press*, 20 June 1981; D. Snyder, "Supply of Gold is Exhausted, Cortez Mine is Almost Shut Down," *Nevada State Journal*, 7 Nov. 1976, 37.

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44. Duncan and Smolik, "How Cortez Gold Mines Heap-Leached," 66.
45. Francesca R. Ammon, *Bulldozer* (New Haven, CT: Yale University Press, 2016); Paul D. Chamberlin, "Heap Leaching and Pilot Testing of Gold and Silver Ores," *Report 36* (Reno: Nevada Bureau of Mines and Geology, 1983), 77-83; Jeff Dean, "Iron Profile: The Caterpillar D8 through History," posted 4 Oct. 2013, accessed 15 Mar. 2021: https://ccmodels.com/iron-profile-caterpillar-d8-throug/; I. S. Parrish, G. Austin, and D. W. Kappes, "Sterling Mine Joint Venture: Anatomy of a Small Underground Mine and Heap Leach" (Feb. 1982), 4: https://www.kcareno.com/professional-papers
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47. Duncan, "Interview;" Heinen, et al., "Processing Gold Ores," 7-9; Potter, "Design Factors," 3-4.
48. Duncan, "Interview;" Daniel W. Kappes, "Precious Metal Heap Leach Design and Practice," in: Andrew L. Mular, Doug N. Halbe, and Derek J. Barratt (eds.), *Mineral Processing Plant Design, Practice, and Control Proceedings* (Littleton, CO: Society for Mining, Metallurgy, and Exploration, 2002), v. 2, sec. 12, ch. 86, 13-15; C. Arthur Lefler, "Leaching Practices at Smoky Valley Mine," *Report 36* (Reno: Nevada Bureau of Mines and Geology, 1983), 84-6.