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WASTE DISPOSAL
A NATIONAL PROBLEM

Industry and municipalities face no greater modern problem than that of waste disposal. Industrial growth and the spread of housing have far outrun the traditional methods of handling liquid and solid wastes. Disposal of liquid waste that is low in solids is a monumental problem for many industrial plants, especially chemical and steel plants, and there is no truly satisfactory answer at the present time.

The volumes of this waste are enormous, ranging from 60,000 gallons per day for a small chemical or food plant to 60,000,000 gallons per day for a steel mill. Many methods are used, such as allowing liquid waste to trickle into a handy swamp; putting it into a holding pond and hoping seepage or evaporation will take care of it; dumping it into an already polluted stream or -- as in the case of the Great Lakes and the Chesapeake Bay -- using large volumes of water as a diluent. These methods are in disfavor under the 1965 Federal Water Pollution Control Law.

The nation's military establishment too has had to furrow its brow over the problem. The experience of the Army's Rocky Mountain Arsenal near Denver, Colorado, illustrates the difficulties inherent in liquid waste disposal. The Arsenal has tried ~~almost every~~ several known waste disposal systems without success, wrestling with associated problems ranging from crop damage to earthquakes.

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The Army learned that the general rules for solving the problem of waste disposal are relatively simple but the exact solution is extremely complicated and expensive. The general rules are: Reduce all uses of water to the lowest practical limit and get the greatest use and re-use from this water; segregate water uses, especially those that cannot be easily treated or disposed of, and keep the volume of contaminated or polluted water to the lowest possible volume; and find the cheapest and safest method of contaminated waste disposal. Present disposal methods are:

Evaporation by open flame or submerged flame.

Precipitation of contaminants by settling or filtration.

Multiple-effect evaporation by the incineration of the remaining solids.

Injection into a well after cleaning up the solids.

Neutralization of acids.

Cooling towers for evaporation in dry climates.

Sealed evaporation ponds, or lakes.

Dilution with a large volume of water after adequate treatment.

Toxicity Problem

The Rocky Mountain Arsenal problem of disposal of liquid wastes is particularly acute because the materials manufactured there are chemicals and insecticides that are toxic to animals, plants and man.

The Arsenal was built in 1941 on a plot of 20,000 acres of dry land fifteen miles from downtown Denver. Since that time a condition developed that is typical of many industrial problems. As the plant grew the volume of waste became larger and more toxic, people moved in to be close to their work, and the simple means of waste disposal that once appeared to be a sure-fire method were no longer adequate or acceptable.

In the early 1940's the Arsenal site was located at a satisfactory distance from the city of Denver. Fumes and other by-products of a chemical manufacturing plant did not affect the city. The site was considered suitably isolated for Rocky Mountain Arsenal's facilities. Since that time, however, population growth and municipal expansion have seen Aurora, Derby, Commerce City and Denver itself extend to the very borders of the Arsenal.

Waste disposal was considered carefully in planning for the Arsenal's original manufacturing operations. The design and construction of the Arsenal were handled by some of the country's leading architects and engineers; one of the largest chemical manufacturing companies provided consultants. To design the waste disposal system itself, a group of prominent engineers from industry, a Denver area geologist and members of the Army Corps of Engineers combined their professional talents.

A lake which has subsequently been removed—Lake A—was designed to serve as the industrial waste disposal facility at the Arsenal (See Fig. 1). Waste material coming from the Arsenal was passed through six settling basins before being dumped into Lake A. The material flowing into the lake was kept highly alkaline. According to the best advice, this created a reaction with soils in this area that would normally form a non-leaking bottom for any pond or lake.

From 1945 to 1950 several industrial concerns leased facilities at the Arsenal and used the Arsenal waste disposal facilities without adverse effect.

1951 - 1954: Expanded Use of Lakes

This waste disposal system was used throughout World War II and until 1954 with no indication that it was not a satisfactory method. In 1951, at the outbreak of the Korean War, the Army decided to ~~manufacture~~ increase ~~a classified chemical agent~~ its manufacturing activities at Rocky Mountain Arsenal. The impact of the new agent plant on the disposal facilities was closely studied as it added considerably to the input of waste into Lake A. The new plant began operating in 1953, and within a year it became evident that additional disposal lakes would be needed for evaporation of the waste material.

Again the Corps of Engineers was called on to study the matter. After consultations with a New York industrial firm, the Army Engineers decided that Rocky Mountain Arsenal's disposal system was adequate for the additional chemical ~~agent~~ plant and that it would have no adverse effect on the surrounding countryside. The only change recommended was an increase in the capacity of Lake A. Accordingly, the dike impounding water in Lake A was raised about five feet.

There were several favorable aspects about the Arsenal waste disposal system: almost three miles separated Lake A from Arsenal boundaries; the area was characterized by low precipitation and high evaporation; and there was a successful history of similar systems used by other manufacturers throughout the country.

EA The [agent] plant constructed in 1953 discharged large quantities of water into Lake A — as much as 800 gallons per minute — along with a considerable amount of salt which was a by-product of the manufacturing process. JA

Time soon proved that Lake A — even with its increased capacity — could not handle the added volume, and so Lakes C, D, and E were designed and established (See Fig. 1). These expanded facilities were installed [without civilian consultation,] based on experience with Lake A and ten years background with this kind of waste disposal at the Arsenal. (The surface area of the lakes is considerable. This assumes extreme importance in view of the fact that the evaporation rate in the Denver area is between one and two gallons per acre per minute.)

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1954: First Complaints of Pollution

In June 1954 Rocky Mountain Arsenal received a complaint from a local farmer that his crops had been damaged by water taken from one of his irrigation wells. In response, the following organizations were asked to meet in October 1954 to discuss the matter: U.S. Army Chemical Corps; U.S. Army Corps of Engineers; Soil Conservation Service, U. S. Department of Agriculture; U.S. Bureau of Reclamation; U.S. Geological Survey; Colorado State Water Conservation Board; Colorado State Department of Health; and the West Adams Soil Conservation District of Colorado.

A committee representing these groups launched an investigation into the reported crop damage to learn if it was the result of Arsenal operations. Representatives of the Great Western Sugar Co., Colorado A & M College, and the U. S. Department of Agriculture were contacted and Army specialists in plant pathology at Fort Detrick, Md., sought to determine the nature of the materials in the irrigation water that the farmer felt was damaging the plant growth.

More experts were summoned. The Corps of Engineers recommended that a study of Arsenal operations be made by an engineering consulting firm and a contract was awarded in May 1955 to identify the waste materials and recommend what the Arsenal could do to retain the waste matter.

During the same period the Army's Omaha District Engineer and the U. S. Geological Survey made studies of the flow of water through Arsenal property, particularly from the lakes. These studies pointed out certain facts:

1. Circumstantial evidence indicated that Rocky Mountain Arsenal was responsible for ground water pollution resulting from waste disposal procedures at the Arsenal.

2. The principal pollutant was sodium chloride along with a number of unidentified materials in smaller concentrations. One of these was later found to be sodium chlorate.

3. The actual cause of the crop damage remained unknown and could not be explained solely on the basis of the high salt content of the irrigation water.

<u>1955: Installation of Sealed Lake</u>

These studies and resulting recommendations led to a re-evaluation of Rocky Mountain Arsenal's waste disposal procedures.

A cooling tower installed at the new chemical manufacturing plant reduced the waste water by about 90%. A new waste disposal lake — Lake F — was installed and was constructed with an impermeable asphalt membrane designed to prevent seepage into the ground. Its cost was $700,000 and it is the largest sealed lake of its kind in the world. Upon completion in 1955, it was used to receive all the water previously stored in Lake A.

1956-1957: Sampling Wells Installed; New Complaints

In order to determine the movement of the underground water, 51 sampling wells were installed by the Army's Omaha District Engineer throughout the Arsenal during 1956 and 1957. Many older wells, either on the Arsenal or nearby, were sampled for salinity and contamination. However, this sampling procedure, along with water analysis, failed to reveal the cause of the toxic effects on plant life.

In May 1956 a contract was awarded to the University of Colorado to identify phytotoxic compounds causing the crop damage and to develop a method for neutralizing their effects. Meanwhile, work continued at Fort Detrick to determine what these materials were and how to analyze them.

During this period the Omaha District Engineer submitted to the Chemical Corps a detailed study of methods for removing contaminated underground water. The study was never implemented, but the Army maintained a continuing interest in the matter.

It became obvious by 1957 that the sealed lake was not going to be able to handle the waste material generated on the Arsenal by both the Government and tenant operations.

Decision for a Deep Well

With the results of all the investigations in hand, representatives of the Chemical Corps met in New York City with four experienced consultants to reach the best solution to the continuing problem and to recommend a course of action to the Army's Chief Chemical Officer. The consultants were John Grebe, Dow Chemical Company; General Clifford L. Sayre, Food Machinery Corporation; Dr. Ralph L. Evans, Evans Research and Development Corporation; and Dr. George P. Vincent, Olin Mathieson Chemical Corporation.

It was their recommendation that a deep well be drilled at Rocky Mountain Arsenal similar to deep wells used successfully for waste disposal by Dow Chemical Company at Midland, Michigan, and E.I. duPont de Nemours and Company at Orange, Texas. Dow Chemical Company had operated its wells since 1931 and duPont had been using its wells for more than ten years. Both companies reported good results but emphasized the need to remove all solid materials from the water prior to its injection into the well.

Theory of Deep Well Waste Disposal

Deep well waste disposal is a widely misunderstood method. Among the most common misconceptions are that waste flows into a rock strata that includes caves or large fissures; that the waste flows into a dry, loose sand and fills up the spaces between particles; and that when the hole is drilled deep enough there is dry rock that absorbs the water or waste.

Nothing is farther from the truth. The facts are that -- except shale -- almost all underground formations carry water and are saturated and under pressure.

Once the formations are sealed and below fresh water, the water content of all normal strata is salt. (The water below the 6,500 feet of shale in the mile-high Denver area has the same composition as sea water.)

All rock -- igneous, metamorphic, and sedimentary -- under the proper circumstances has sufficient porosity and permeability to act as reservoirs for injected fluids. However, sedimentary rock is the most likely to have the desirable characteristics of high porosity, area, and permeability as a waste storage reservoir. Most sedimentary rock with these characteristics was deposited in a marine environment and below the present level of fresh water circulation; therefore it contains salt water in the rock pores. with the waste displacing the salt water.

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Finding the correct strata for a waste disposal well is almost as difficult as finding oil. Much geological data in the area must be examined and expert knowledge and interpolation are required. (Figures 4, 5, 6 and 7)

A conforming strata that is impermeable must overlie and underlie the injection reservoir to prevent the vertical escape of the injected waste. Unfractured shale, clay, salt, anhydrite, gypsum, marl and bentonite have been found to make a good seal against upward flow.

After deciding that there is a suitable geological formation, the next question is: will it hold sufficient waste water to make it economically feasible? A way to determine this is to core the well while it is being drilled and test the cores for permeability (See well log, figure 9). With knowledge of the thickness of the strata and permeability of the rock, the capacity of the reservoir can be calculated.

Each cubic foot of rock with a porosity of 20 percent can contain about 1-1/2 gallons of waste. The storage volume available to a well in an underground reservoir can be computed to be (by ignoring the effect of the well bore):

$$V \doteq 7.481\pi\, r^2 h \phi = 23.505\ r^2 h \phi \text{ gal}$$

where: r = radius of available storage area, ft
h = thickness of reservoir stratum, ft
ϕ = porosity

A reservoir 50 feet thick with a porosity of 0.20 could contain about 2.1 billion gallons of waste per square mile -- or 590,000 gallons within 50 feet of the well and 410 million gallons within a quarter of a mile.

In most cases the ultimate storage capacity of an injection well is probably controlled by the rate at which injection pressure increases at the desired injection rate. Injection pressure is a limiting factor because excessive pressures cause hydraulic fracturing and consequent possible damage to confining strata; the pressure capacity of injection well pumps, tubing and casing is limited; and in some states maximum injection pressures are specified by regulatory agencies.

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With the type and location of rock determined and the possible capacity of the reservoir calculated, the next concern is cleaning up the liquid waste so solids and bacteria will not clog the pores in the rock and so the material in the liquid will not react with the salts in the rock. Under normal conditions it is better if the liquid is on the acid side -- pH 6+ or below -- rather than on the basic side; this serves to increase the porosity of the rock. If the liquid is to be injected into limestone strata, the lower the pH the better.

Normally the waste is treated to precipitate the solids and these are settled, final-polished with a filter, and then accumulated in a surge tank.

1961: The "Go Ahead" at Rocky Mountain Arsenal

The realities of a deep well disposal system for Rocky Mountain Arsenal were impressive. Original estimates placed the cost at $660,000 for a complete well and water treatment facilities.

Again, the Chemical Corps sought expert opinion and experience, consulting the Colorado Department of Natural Resources, Colorado Department of Health, Colorado Water Commission, the University of Colorado, the U.S. Geological Survey, and a number of oil companies with experience in drilling deep wells. Also queried were the Army's Missouri River Division and Omaha District Corps of Engineers.

Certain requirements had to be met. For example, the State of Colorado wanted assurance that Rocky Mountain Arsenal would drill and dispose of the waste in a strata deep enough to avoid adverse effects on the state's potable water supplies. Several corporations with oil and gas interests in the state requested that the waste be disposed of in a strata deeper than 8,900 feet to protect possible oil and gas strata from the chemicals. It was agreed to drill to granite, or bottom, and then review the various injection areas above this strata.

With this information and the necessary funds, the Omaha District, Corps of Engineers, assumed the project, retaining E.A. Polumbus, Jr., and Associates, Denver petroleum geologists and engineers, to design the disposal well and to supervise its drilling and development. A.J. Ryan and Associates of Denver were retained to design the waste treatment and pumping plant.

Work on the well began March 10, 1961, and was completed and tested ready for fluid injection by September 20, 1961. It was drilled to granite, providing a bottom beyond which waste will not flow due to impermeability and higher pressures (figure 8). As a seal against upward flow there is approximately 6,500 feet of good shale, starting at 1,500 feet and extending to 8,000 feet.

Figure 2 is an illustration of the well with its casings, showing how these casings are sealed with cement to protect both the water and oil strata.

Since 1931 industry has placed twenty similar disposal wells into operation throughout the United States and a wide variety of wastes is being successfully injected into various rock formations at different depths. These DA operations are listed in figure 3.

The waste treatment plant installed was a system designed for the Rocky Mountain Arsenal well on the basis of experimental work done by Dow Chemical Company and A.J. Ryan and Associates. Its function was to precipitate the solids, which are then settled, final-polished with a filter and accumulated in a surge tank.

The total cost of the well, with all equipment, was $1.4 million.

After the Arsenal well was drilled and cased, and all treating equipment was installed, the well was ready for injection. To minimize the possibility of interaction of the waste with the salt water in the rock pores, an extra precaution was taken. About 400,000 gallons of fresh water was pumped into the well to push the salt water before it and prevent the waste from coming into contact with the salt water in the form of an ever-growing liquid diaphragm.

1962: Deep Well in Operation

The first full month of operation was March 1962.

The maximum pumping rate was 9,345,000 gallons per day. Positive pressure pumps capable of pumping 2,000 pounds per square inch are installed. However, the pressure at the well head has never exceeded 1,050 pounds per square inch since in fact very little pressure is required for injection. Most of the head is dissipated in the 12,000-foot, 5-inch pipe and the 2.5-inch packer at the 9,000-foot depth.

When the treatment plant was put into operation, adequate settling could not be obtained economically. The filters were then used to carry the whole load, using filter aid. The cost of treatment went to about $2.00/1000 gallons to remove solids.

At this time it was discovered that the lake carried a high bacteria count -- one aerobic bacteria which concentrated on the surface and an anerobic type in the deep areas of the sealed lake. This discovery was the key to the settling problem. The bacteria, using the ingredients in the waste -- sulfur, phosphorus, chlorine and nitrogen products -- made food for one another and prospered, building up a sludge that would not settle and was difficult to filter because of its slime characteristics. The solution turned out to be that the water in the sealed lake should be evaporated, using a spray system. The well took the water directly from the plants after the inlet end of the sealed lake was dammed to hold about 1,000,000 gallons, providing a surge pond for the well. Because of rapid changes in pH and flow, the bacteria never got started in this portion of the lake and after 12 hours settling in the surge pond the waste could be filtered at a cost of about fifteen cents per thousand gallons.

Injection was a simple matter of solving maintenance problems on the 93-gallons-per-minute reciprocating piston pumps. Four pumps were installed but operations never required more than three. Therefore, one served as an installed spare. (See chart of pumping from March 1962 to 1965 -- Figure 10.) Over the period of pumping, one, two, or three pumps were used on a one-, two-, or three-shift basis on a seven-day or five-day basis, depending on the required rate of waste disposal and rate of evaporation from the lake. The natural evaporation rate was 1-2 gallons per minute per acre of lake surface, with 86.5 acres of surface when full. Spray raft evaporation could double natural lake surface evaporation.

Nature interfered with natural and spray evaporation. During the four winter months of December, January, February and March the lake surface is frozen, the sprays cannot be used because of freezing, and ice builds up on the spray raft. During high winds -- which are frequent in the area -- the sprays must be turned off at 20 miles per hour so salt and insecticide residues from the lake will not be blown over the Arsenal land areas.

The Denver Earthquakes

As time went on after March 1961 and the process of waste disposal became more routine, Mr. Charles Bushey of Rocky Mountain Arsenal observed whenever the well operated there seemed to be more earthquakes reported in the Denver area; when the well was inoperative there were fewer tremors than when it was operating. Mr. Bushey's observation was discussed with [illegible] authorities, studies were made of the geology and the reported depths of the tremors (figure 11), and no correlation could be seen between the well operation and the earthquakes.

By 1965 plans were being made to dry up the sealed lake and generally clean up the waste disposal problems. Apparently all problems had been solved, including the pump maintenance and waste treatment for elimination of solids by filtration.

However, as quite common in dealing with waste disposal -- and as it happened so often in the past at Rocky Mountain Arsenal -- this was just a lull before another onslaught of problems and additional costs.

The first indication of new trouble was a radio announcement, followed by numerous newspaper stories. On November 24, 1965, Denver geologist David M. Evans dropped the bomb: "Arsenal Waste Disposal Well Linked to Denver and Derby Earthquakes" (see announcement, figure 12). [Evans' action came without any discussion with Rocky Mountain Arsenal even though much of the data for his study had been furnished by the Arsenal.] DA

The situation immediately took on a political coloration as Colorado Congressman Roy H. McVicker held a press conference with Government and Denver officials present. Mr. McVicker called for immediate action and telephones were busy for a week between Denver, Washington, Edgewood Arsenal (Maryland), the Munitions Command headquarters in [Picatinny Arsenal] (New Jersey), and the Corps of Engineers local office at Omaha, Nebraska. DA

The Corps of Engineers were given the responsibility for a solution to the earthquake problem. A committee of renowned geologists was appointed to study the matter.

All pumping of waste into the well was suspended as of January 20, 1966. Waste was diverted to the Arsenal's sealed lake and evaporation once more became the method of waste disposal. Rocky Mountain Arsenal was back at the point where it had been in January 1962 before it had a modern method of disposal. How long before the lake filled up was a matter for serious thought. What new method should be tried now that the 1.6 million dollar experiment of deep well disposal had been completed?

A distinguished panel of consultants was selected to tackle the new problems: Dr. W. W. Rubey, geologist, geophysicist and professor emeritus of the University of California at Los Angeles; Dr. Dean S. Carder, seismologist, Environmental Science Service Administration, Earthquake Mechanism Laboratory, U. S. Department of Commerce; Dr. L. Don Leet, seismologist, Harvard Seismograph Station, Harvard University; Dr. H.K. Van Poollen, reservoir engineer, Marathon Oil Company, Littleton, Colorado; and Dr. J.H. Healy, geophysicist and seismologist, U.S. Geological Survey, Denver.

They submitted their report in October 1966 and the following conclusions were drawn by the Army Corps of Engineers:

1/ "1. Although the investigations which have been made have revealed some very suggestive correlative statistics, no scientific proof of a relationship between the operation of the Deep Waste Disposal Well at the Rocky Mountain Arsenal and the Derby earthquakes has been established.

1/ Report of Investigations, Injection Well - Earthquake Relationship, Rocky Mountain Arsenal, Prepared by Omaha District, Corps of Engineers, 1 October 1966.

1/ "2. None of the earthquakes recorded during the period of injection operations have been of a magnitude that would have prompted more than passing note had they occurred in an area of previously recognized seismicity.

"3. Use of the well could continue without fear of initiating an earthquake of higher magnitude than already experienced. The injection of fluid may minimize earthquake potential, but is unlikely to accentuate it.

"4. The deep well offers great research potential for the advancement of the knowledge of seismology and for possible use as an instrument in the study of earthquake mechanisms. The risk involved in continued operation of the well as a test facility in the national interest is considered desirable.

"5. The possibility exists that future testing might demonstrate that injection in the pre-Cambrian or the higher Fountain or Lyon formations could be accomplished without risk.

"6. Based on initial evaluation of reservoir properties and study of performance of the well, it appeared that the reservoir was normal and would predictably react to fluid injection as a reservoir consisting of fractured rock.

"7. The possibility of pollution of fresh water aquifers through injection operations, past or future, may be safely disregarded."

1/Report of Investigations, Injection Well - Earthquake Relationship, Rocky Mountain Arsenal, Prepared by Omaha District, Corps of Engineers, 1 October 1966.