ANL/EAD/CP-97318

Update on Cavern Disposal of NORM-Contaminated Oil Field Wastes

John A. Veil
Argonne National Laboratory
Washington, DC

to be presented at:
Ground Water Protection Council 98 Annual Forum
Sacramento, CA
September 19-23, 1998

DISCLAIMER

Update on Cavern Disposal of NORM-Contaminated Oil Field Wastes

John A. Veil
Argonne National Laboratory

Biographical Sketch

John Veil is the manager of the Water Policy Program for Argonne National Laboratory in Washington, D.C. He analyzes a variety of energy industry water and waste issues for the U.S. Department of Energy.

Mr. Veil has a B.A. in Earth and Planetary Science from Johns Hopkins University, and two M.S. degrees - in Zoology and Civil Engineering - from the University of Maryland.

Before joining Argonne, Mr. Veil managed the industrial NPDES, UIC, and oil control programs for the State of Maryland and was on the faculty of the University of Maryland.

Mr. Veil has published many articles and reports and has made numerous presentations on environmental issues. In the past year, he has been an invited keynote speaker at the 4th International Petroleum Environmental Conference and the International Experts Meeting on Environmental Practices in Offshore Oil and Gas Activities and was the technical program chairman for the Minimizing the Environmental Effects of Offshore Drilling conference.

Abstract

Some types of oil and gas production and processing wastes contain naturally occurring radioactive material (NORM). If NORM is present at concentrations above regulatory levels in oil field waste, the waste requires special disposal practices. The existing disposal options for wastes containing NORM are limited and costly. Argonne National Laboratory has previously evaluated the feasibility, legality, risk, and economics of disposing of nonhazardous oil field wastes, other than NORM waste, in salt caverns. Cavern disposal of nonhazardous oil field waste, other than NORM waste, is occurring at four Texas facilities, in several Canadian facilities, and reportedly in Europe. This paper evaluates the legality, technical feasibility, economics, and human health risk of disposing of NORM-contaminated oil field wastes in salt caverns as well. Cavern disposal of NORM waste is technically feasible and poses a very low human health risk. From a legal perspective, a review of federal regulations and regulations from several states indicated that there are no outright prohibitions against NORM disposal in salt caverns or other Class II wells, except for Louisiana, which prohibits disposal of radioactive wastes or other radioactive materials in salt domes. Currently, however, only Texas and New Mexico are working on disposal cavern regulations, and no states have issued permits to allow cavern disposal of NORM waste. On the basis of the costs currently charged for cavern disposal of nonhazardous oil field waste (NOW), NORM waste disposal in caverns is likely to be cost competitive with existing NORM waste disposal methods when regulatory agencies approve the practice.

Introduction

Salt caverns have been used for several decades to store various hydrocarbon products. In the past few years, four facilities in the United States have been permitted to dispose of nonhazardous oil field wastes (NOW) in salt caverns. Several other disposal caverns have been permitted in Canada and in Europe. To date, caverns have not been used to dispose of oil field wastes contaminated with naturally occurring radioactive materials (NORM). Only a few methods have been approved for disposing of NORM wastes and only a handful of commercial disposal facilities are licensed to accept NORM waste. This paper evaluates the legality, technical feasibility, economics, and human health risk of disposing of NORM-contaminated oil field wastes in salt caverns.

In 1995, the U.S. Department of Energy (DOE), Office of Fossil Energy, asked Argonne National Laboratory (Argonne) to conduct a preliminary technical and legal evaluation of disposing of NOW into salt caverns. That study concluded that such disposal is feasible and legal. If caverns are sited and designed well, operated carefully, closed properly, and monitored routinely, they can be a suitable means of disposing of NOW (Veil et al. 1996). Considering these findings and the increased U.S. interest in using salt caverns for NOW disposal, the Office of Fossil Energy asked Argonne to conduct further research on the cost of cavern disposal compared with the cost of more traditional NOW disposal methods and to perform a preliminary identification and investigation of the risks associated with such disposal. The cost study (Veil 1997) found that disposal costs at the four permitted disposal caverns in the United States were comparable to or lower than the costs of other disposal facilities in the same geographic area. The risk study (Tomasko et al. 1997) estimated that both cancer and noncancer human health risks from drinking water contaminated by releases of cavern contents were significantly lower than the accepted risk thresholds.

Since 1992, DOE has funded Argonne to conduct a series of studies evaluating issues related to management and disposal of oil field wastes contaminated with NORM. Included among these studies were radiological dose assessments of several different NORM disposal options (Smith et al. 1996). In 1997, DOE asked Argonne to conduct additional analyses on waste disposal in salt caverns; this time, however, the wastes to be evaluated would be those contaminated by NORM. This paper summarizes Argonne's findings on NORM waste disposal in salt caverns as reported by Veil et al. (1998). Throughout the remainder of this paper, the term "NORM waste" is used to mean "oil field waste contaminated by NORM."

Background on Salt Caverns

Salt deposits occur in two major forms in the United States: bedded salt and salt domes. Bedded salt formations occur in layers interspersed with such sedimentary materials as anhydrite, shale, dolomite, and other more soluble salts (e.g., potassium chloride). Salt domes are large, nearly homogeneous formations of sodium chloride, although they may contain nonhomogeneous zones. Salt deposits occur in many parts of the United States; however, the occurrence of salt in quantities and locations that would allow for commercial mining is limited. States with major salt deposits are Alabama, Arizona, Colorado, Kansas, Louisiana, Michigan, Mississippi, Montana, New Mexico, New York, North Dakota, Ohio, Oklahoma, Pennsylvania, Texas, and Utah (Veil et al. 1996).

Since the 1940s, the petroleum industry has constructed many salt caverns for storing hydrocarbons. To create salt caverns, water that is not fully salt-saturated is injected into a salt stock, and the resulting brine solution is withdrawn. By controlling the rate of water injection and by injecting through either the tubing or the tubing-casing annulus, the cavern can be shaped to meet the operators' needs.

Initially, the caverns would be filled with brine. NOW or NORM waste would then be introduced as a slurry of waste and a fluid carrier (brine or fresh water). As the slurry is injected, the cavern acts as an oil/water/solids separator. The heavier solids sink to the bottom of the cavern and form a pile. Any free oils and hydrocarbons float to the top of the cavern because they are less dense than water. Clays in the slurry and dissolved chemical constituents from the waste can mix with the brine and form a suspension above a brine/waste interface. Clean brine displaced by the incoming slurry would be removed from the cavern and either sold as a product or disposed of in an injection well.

Once filled with waste, the cavern would be sealed and the borehole plugged with cement. Bridge plugs would be placed in the well bore above and below water-bearing intervals to isolate these intervals permanently. The pressure in sealed caverns increases as a result of salt creep and geothermal heating. These forces can cause internal cavern pressure to build to the point it exceeds the lithostatic pressure of the formation. Potentially, closed caverns can leak or release liquid portions of the cavern contents to the surrounding salt. No disposal caverns have yet been closed, so no actual data are available to characterize post-closure cavern behavior. Veil et al. (1996) and Tomasko et al. (1997) review the recent literature on anticipated post-closure cavern behavior based on modeling and theories.

Background on NORM

Oil and gas production and processing operations sometimes accumulate NORM at elevated concentrations in by-product waste streams. The sources of most of the radioactivity are isotopes of uranium-238 (U-238) and thorium-232 (Th-232) that are naturally present in subsurface formations from which oil and gas are produced. The primary radionuclides of concern in NORM wastes are radium-226 (Ra-226) of the U-238 decay series and radium-228 (Ra-228) of the Th-232 decay series. Other radionuclides of concern include radionuclides that form from the decay of Ra-226 and Ra-228, such as radon-222 (Ra-222).

The production waste streams most likely to be contaminated by elevated radium concentrations include produced water, scale, and sludge (Smith et al. 1996). Spills or intentional releases of these waste streams to the ground can result in NORM-contaminated soils that must also be disposed of. Radium, which is slightly soluble, can be mobilized in the liquid phases of a formation and transported to the surface in the produced water stream. Dissolved radium either remains in solution in the produced water or precipitates out in scales or sludges. Conditions that appear to affect radium solubility and precipitation include water chemistry (primarily salinity), temperature, and pressure.

NORM contamination of scale and sludge can occur when dissolved radium coprecipitates with other alkaline earth elements, such as barium, strontium, or calcium. In the case of scale, the radium coprecipitates, primarily with barium, to form hard, insoluble sulfate deposits. Scale typically forms on the inside of piping, filters, injection wellhead equipment, and other water-handling equipment, but also can form as a coating on produced sand grains. NORM-contaminated sludges can accumulate inside piping, separators, heater/treaters, storage tanks, and any other equipment where produced water is handled. The U.S. Environmental Protection Agency (EPA) estimates that approximately 25,000 tons of NORM-contaminated scale and 225,000 tons of NORM-contaminated sludge are generated annually by the petroleum industry (EPA 1993).

Regulatory Considerations

Currently, no federal regulations specifically address handling and disposal of NORM wastes. In the absence of federal regulations, individual states have taken responsibility for developing their own regulatory programs. These programs have been evolving rapidly over the last few years. The existing state regulatory programs establish requirements for (1) NORM exemption standards or action levels; (2) licensing of parties possessing, handling, or disposing of NORM waste; (3) the release of NORM-contaminated equipment and land; (4) worker protection; and (5) NORM waste disposal. Veil et al. (1998) evaluate the potential for salt cavern disposal of NORM waste in five states that have existing or proposed NORM disposal regulations and that have expressed serious interest in disposal of NOW in salt caverns: Louisiana, Mississippi, New Mexico, Oklahoma, and Texas. Each of these state programs addresses the disposal of NORM waste into Class II injection wells, either directly or indirectly. The regulation of underground injection of NORM waste is relevant to the potential disposal of NORM waste in salt caverns, because disposal into salt caverns is considered by most states to equate to underground injection into Class II wells.

A review of federal Underground Injection Control (UIC) regulations and NORM and UIC regulations from the five states that have expressed some interest in cavern disposal indicated that there are no outright barriers or prohibitions against NORM disposal in salt caverns, except for Louisiana, which prohibits disposal of radioactive wastes or other radioactive materials in salt domes. Presently, however, only Texas and New Mexico are working on disposal cavern regulations, and no states have issued permits to allow cavern disposal of NORM waste. State regulatory agencies may need to revise their NORM waste management or UIC regulations to accommodate cavern disposal. These agencies may need time to further investigate the concept of NOW disposal in caverns before they are willing to develop regulations and issue permits authorizing NORM waste disposal in caverns.

Existing NORM Waste Disposal Practices and Their Costs

The largest volume oil and gas waste stream that contains NORM is produced water. Except at offshore platforms, which discharge produced water to the ocean, nearly all produced water is injected into the subsurface through injection wells. At this time, the radium content of produced water going to injection wells is not regulated. Consequently, radium that stays in solution in the produced water stream does not present a significant waste management problem from a regulatory perspective and is not considered further in this paper.

Some operators dispose of NORM wastes at their own sites, although most use off-site commercial disposal facilities. Pipes and casing with NORM contamination may be recycled as scrap steel if NORM levels are below the action level. In the past, NORM was commercially managed by surface treatment through which NORM was blended with nonradioactive materials to reduce the NORM activity below action levels and then spread on the land. Today, the primary method used for disposal of NORM wastes is underground injection. Smaller quantities of NORM waste are disposed of at licensed radioactive waste landfills, encapsulated in the casing of a well being abandoned, or managed on lease sites through land spreading.

It is difficult to quantify the total cost for disposing of NORM waste. The cost components that must be considered, in addition to the actual disposal cost, include analytical costs, transportation costs, container decontamination costs, and possibly permitting costs. One other cost component that cannot readily be quantified, but that is important nonetheless, is the potential for long-term liability if the disposal site eventually causes environmental contamination and is subject to a Superfund cleanup.

Only four off-site commercial NORM disposal companies have been identified in the United States; two of these inject the NORM waste underground and the other two bury NORM waste in landfills. Identification of disposal companies by name in this paper does not constitute an endorsement of those companies or provide any indication of their performance capabilities. The companies are included solely to provide an indication of the types of commercial disposal options available to operators in the early 1998 time frame.

Underground Injection - Two of the four U.S. off-site commercial NORM disposal companies utilize underground injection. Both facilities crush, mill, and slurry the incoming NORM waste before injecting it. Newpark Environmental Services, Inc., operates a NORM disposal facility near Winnie in eastern Texas that receives the majority of all NORM wastes disposed of commercially in the United States. Newpark charges \$150/bbl for disposal of NORM wastes through injection. This cost includes inspection and verification of contents as well as the necessary analytical costs. The cost of decontamination is \$25 for a drum and \$150 for a bulk container (Sammons 1998). Transportation costs are not included in these figures.

In July 1997, Lotus, LLC opened a NORM waste disposal facility in western Texas near Andrews. Lotus charges \$132 per 55-gal drum and \$100/bbl for disposal by injection. Gamma spectroscopy analysis costs an additional \$100 per sample. Transportation cost is not included but is estimated to be about \$3 per loaded mile for a full 72-bbl roll-off box (Kelly 1998).

BPF, Inc., is developing a system that dissolves the radioactive component of NORM into an aqueous solution that can then be disposed of through underground injection. The residual solids no longer contain radioactivity above levels of regulatory concern and can be disposed of as NOW (Capone et al. 1997). As of early 1998, the BPF process is at the pilot-scale stage of development. BPF estimates that costs of the full-scale system, when commercially available, will be approximately \$140/bbl ± 20%. These costs would include an initial survey, obtaining the necessary permits, labor, off-site disposal costs for the resulting NOW solids, chemicals, and a final survey. The cost of an injection well is not included if the operator does not already have a functioning injection well (Bush 1998).

At least two companies, Apollo Services and National Injection Services, provide on-site NOW and NORM disposal at an operator's facility. Wastes are ground up, slurried, and injected into the operator's own injection well. The process of injecting ground and slurried NORM waste could potentially plug the receiving formation. Operators should consider the potential cost of an injection well workover when estimating total disposal costs for these companies. As of early 1998, Apollo was primarily disposing of NORM at offshore platforms. Apollo estimates that NORM waste disposal costs range from \$100/bbl to \$300/bbl, depending on the volume of NORM to be disposed of (Reddoch 1998). National Injection Services disposes of NOW and NORM through on-site injection. National's cost ranges from \$15/bbl to \$150/bbl, depending on the nature of the materials to be disposed of (Page and Guidry 1998).

Burial in Landfills - US Ecology operates a low-level radioactive waste disposal landfill in Washington State that receives various types of radioactive waste, including NORM waste. Because the facility primarily receives radioactive wastes other than oil field wastes, the requirements are more stringent and costs are higher than those for an oil field NORM facility. Base disposal costs range from \$500 to \$550 per 55-gal drum or from \$66.67 to \$73.33 per cubic foot, depending on the volume. The State of Washington does not recognize the RCRA exemption from hazardous waste status for exploration and production wastes. Therefore, each waste stream must be analyzed for hazardous waste characteristics and radionuclides. Transportation cost is not included but is estimated to be about \$2.10 per mile. All waste generators shipping waste to US Ecology must obtain a site use permit from the Washington Department of Ecology. Obtaining the site use permit will add to the total cost. All shipments are subject to a minimum disposal charge of \$2,500 (White 1998).

Envirocare of Utah, Inc., operates a landfill for mixed wastes and low-specific activity radioactive wastes that has, on occasion, accepted NORM waste for disposal. Envirocare declined to provide a standard price for disposal but indicated that it set prices on a case-by-case basis. According to the company contact, Envirocare is competitive when bidding on large disposal jobs but is not competitive on small jobs because its overhead costs, set for all low-level radioactive waste disposal activities, are quite high and are constant regardless of the job size. For large jobs, the overhead is spread over many drums of waste and is, therefore, low on a \$/drum basis (Rafati 1998).

Encapsulation - Under the encapsulation disposal option, an operator encapsulates NORM waste either inside a section of pipe that is then sealed on both ends and lowered into a wellbore or directly in the wellbore. A plug is placed on top of the waste-containing zone. Scaife et al. (1994) report on two encapsulation projects conducted in the offshore Gulf of Mexico. In the first project, NORM waste was placed into eight joints of casing as the pipe was being lowered into the hole. In the second project, 31 drums of NORM waste were placed into 21 joints of casing onshore and sealed on both ends. The sealed joints were transported offshore and lowered into the well bore. In both projects, cement plugs were placed on top of the waste-containing joints. Encapsulation works well for NORM waste disposal, but each well can handle only a relatively small volume of waste. Because of this restriction, the process is not widely used. No cost information was available for encapsulation.

Land Spreading - The principle behind land spreading is to mix NORM wastes having an activity concentration higher than the action level with clean soil so that the resulting blend has an activity concentration lower than the action level. Sanifill/Campbell Wells operated a commercial land spreading site until recently, when it no longer was economical to operate. Some producers utilize land spreading on their lease sites to blend patches of high-activity NORM soils with other low-activity NORM soils. However, the present use of land spreading for disposal of NORM waste is limited. No cost information was available for this process.

Technical Feasibility of NORM Waste Disposal in Salt Caverns

NORM waste is physically and chemically similar to NOW; the primary difference is the presence of radionuclides in NORM. The presence of radionuclides may require additional safety precautions when handling the NORM waste, but the actual disposal process would be no different from that for NOW. NOW is currently being disposed of in four U.S. salt caverns and in several Canadian caverns without technical difficulties. There is no technical reason why these caverns or other future disposal caverns could not accept NORM waste equally well.

Economics of NORM Waste Disposal in Salt Caverns

Operators of the four permitted disposal caverns in Texas were contacted to see if they had made any cost estimates of what they might charge customers if they were authorized to accept NORM wastes. They currently charge from $1.95/bbl to $6/bbl to dispose of NOW wastes (Veil 1997). To be authorized to dispose of NORM wastes, cavern operators would need to upgrade their aboveground waste-handling facilities and analytical capabilities, among other things. Although none of the cavern operators had even preliminary cost estimates, one cavern operator believed that he could realistically operate at costs below $150/bbl, the cost charged by the company receiving the majority of NORM waste in this country. He also noted that if regulatory agencies allow NORM disposal in caverns, competition will drive the price lower (Moore 1998). NOW disposal caverns have shown that they are cost competitive with other NOW disposal facilities in the same geographic area (Veil 1997). This study does not constitute a formal market analysis, and the costs to upgrade a cavern disposal operation for NOW to one that disposes of NORM waste have not been quantified. Nevertheless, there is a reasonable chance that NORM waste disposal caverns would be able to compete economically with existing off-site commercial NORM disposal facilities once regulatory agencies allow the practice to occur.

Risks from Disposal of NORM Waste in Salt Caverns

Argonne has previously analyzed the potential radiological doses associated with several disposal methods, including underground injection into Class II disposal wells (Smith et al. 1996). Last year, Argonne completed an analysis of the potential human health risks resulting from exposure to contaminants released from the caverns in domal salt formations used for NOW disposal (Tomasko et al. 1997). The evaluation assumed normal operations but considered the possibility of leaks in cavern seals and cavern walls during the post-closure phase of operation. Veil et al. (1998) builds on these previous Argonne studies to estimate the human health risks from disposing of NORM waste in salt caverns. The approach and findings from Veil et al. (1998) are summarized below.

NORM waste contains the same chemical contaminants as NOW (those considered by Tomasko et al. [1997] include arsenic, benzene, cadmium, and chromium) but also contains radionuclides. The risk from the chemical contaminants in NORM remains the same as was estimated for NOW (Tomasko et al. 1997). Veil et al. (1998) performed a separate radiological risk analysis. Initially, several radionuclides were considered as potential contaminants of concern for the assessment. All but two of these were subsequently dropped from further consideration because of low predicted activities produced by a combination of their high retardation coefficients and short half-lives at a time of 1,000 years in the future, the time frame selected for the risk analyses. The remaining contaminants were Ra-226 and Rn-222.

The release scenarios considered (Tomasko et al. 1997) included inadvertent intrusion by unintentionally drilling a well into a closed cavern; failure of the cavern seal due to increased pressure from salt creep and geothermal heating; release of contaminated fluid through cracks, leaky interbeds, or nonhomogeneous zones composed of higher permeability material; and partial cavern roof fall. Most releases would be to deep aquifers at or near the top of the cavern, although under two scenarios, released contaminants can move upward through the well casing and leak out into shallow aquifers.

No disposal caverns have ever been closed, so no cavern failure data are available. The probability of cavern failure was based on "best-estimate" and "worst-case" estimates provided by a panel of experts. Averaged best-estimates of probability for the different scenarios ranged from 0.006 for partial roof fall plus cavern seal failure and fluid release at shallow depth, to 0.1 for partial roof fall plus fluid release at depth. Averaged worst-case estimates ranged from 0.04 for seal failure with fluid release at shallow depth, to 0.29 for partial roof fall plus fluid release at depth (Tomasko et al. 1997). To provide an even more conservative estimate, Veil et al. (1998) additionally calculated the true worst-case condition by assuming that all caverns would have releases during the 1,000-year period of concern (i.e., probability = 100%).

Once contaminated fluids leave the cavern, they are expected to migrate laterally through different formations and aquifers. During the time the fluids travel from the point of release to the receptor site (assumed to be 1,000 ft laterally from the cavern at either the depth of the cavern or a shallow depth), various physical, chemical, biological, and radiological processes occur that reduce the concentration of the contaminants. Fate and transport modeling were used to estimate the exposure point concentrations, (i.e., the contaminant concentrations at the receptor point) (Tomasko et al. 1997; Veil et al. 1998).

Risk calculations were then conducted on the basis of the exposure point concentrations and standard assumptions regarding drinking water intake rates, exposure time, duration, and frequency. The primary exposure pathway considered in the analysis is ingestion of groundwater, hence exposures are limited to only internal exposures. Exposure to internally deposited radioactive contaminants is expressed in terms of the 50-year committed effective dose equivalent (CEDE). This concept, developed by the International Commission on Radiological Protection (ICRP 1977), represents the weighted sum of the dose equivalent in various organs. CEDEs were converted to carcinogenic risks by using risk factors identified in Publication 60 of the ICRP (1991). The risk caused by inhalation of radon that volatilizes during showering was also investigated but was found to be orders of magnitude lower than the internal exposure risk. The results are shown in Table 1 (from Veil et al. 1998).

Estimated lifetime risks due to NORM and NOW releases from salt caverns are presented in Table 2 (from Veil et al. 1998). The estimated worst-case cancer risks from the chemical contaminants of NORM waste are very low (1×10^{-8} to 2×10^{-17}), and even under the extremely conservative 100% Probability of Release case, the highest chemical contaminant risk is 2×10^{-7}. The excess cancer risks estimated for the radiological contaminants are orders of magnitude lower; even for the100% Probability of Release case, risks are 1×10^{-13} to 3×10^{-22}, and, consequently, are dwarfed by the risks from the chemical contaminants. In all cases, the estimated human health risks due to ingesting groundwater contaminated with releases from NOW or NORM disposed of in salt caverns are significantly below the target risk range (10^{-4} to 10^{-6}) that the EPA established for remedial actions at National Priority List sites (40 CFR 300.430(e)(2)(i)(A)(2)).

The major radiological health concern from exposure to NORM is induction of cancer. The EPA classifies all radionuclides as Group A (known) carcinogens. Radionuclides are also mutagenic, teratogenic, and highly toxic. However, because the cumulative risk of cancer is many times greater than the risk of genetic or teratogenic effects (EPA 1989), and because there are so few data quantifying the relationships between dose and effect for noncancer effects of low doses of Ra-226, only cancer risks are estimated for the radiological constituents of NORM in Veil et al. (1998) and this paper. The chemical constituents of NORM pose a noncancer as well as a cancer risk. On the other hand, the radiological constituents of NORM are considered to pose only a cancer risk. Therefore, the noncancer risk of NORM waste is the same as the noncancer risk attributed to NOW. Tomasko et al. (1997) estimated risks for the 100% Probability of Release case (expressed as hazard quotients) for NOW ranging from 1×10^{-3} to 6×10^{-7}. The accepted risk threshold for noncancer risks is a hazard quotient less than 1.0.

The risk calculations are intended to estimate the risk over the 1,000 years following cavern sealing. It is unlikely that an abandoned cavern would begin leaking immediately. Leakage, if it occurred, would most likely begin many years after the cavern was sealed. The fate and transport models, however, estimate the concentration of contaminants at a time 1,000 years after the release of contaminants, not after cavern sealing. Therefore, the risk estimates are effectively measuring the risk over a period of time longer than 1,000 years. This procedure provides an additional measure of conservatism to the risk estimates.

This paper is subject to several caveats. First, the assessment does not address risks to workers at the cavern disposal site. Smith et al. (1996) estimate radiation doses to workers involved in cleaning pipes, cleaning vessels, and working in storage yards where NORM-contaminated equipment is cleaned prior to NORM waste disposal. The risk to workers is likely to be the same regardless of the ultimate disposal method used. Second, the assessment does not determine whether any health effects will occur in the future; it only estimates cancer risk and potential for noncancer effects. Third, risks have been estimated only for contaminants for which toxicity values were available; just because no toxicity value is available does not necessarily mean there is no risk.

Conclusions

This paper provides evidence that cavern disposal of NORM waste is technically feasible and poses a very low human health risk. From a legal perspective, a review of federal regulations and regulations from several states indicated that there are no outright prohibitions against NORM disposal in salt caverns or other Class II wells, except in Louisiana, which prohibits disposal of radioactive wastes or other radioactive materials in salt domes. Presently, however, only Texas and New Mexico are working on disposal cavern regulations, and no states have issued permits to allow cavern disposal of NORM waste.

Cavern operators would probably charge more for NORM waste disposal than the $1.95/bbl to $6/bbl that they currently charge for NOW disposal (Veil 1997). Given that the companies handling most of the NORM waste are currently charging $100/bbl or more for NORM waste disposal, there is probably plenty of leeway to make facility upgrades and still produce a profit. The ability for a NORM waste disposal cavern to be cost competitive looks promising, assuming regulatory agencies approve the practice.

Acknowledgments

The work described in this paper was sponsored by the U.S. Department of Energy, National Petroleum Technology Office (NPTO), under Contract W-31-109-ENG-38. The author acknowledges John Ford of the NPTO for supporting and encouraging the work. The author of this paper is the program manager for Argonne's salt cavern work, but the study on which this paper is based was co-authored by Karen P. Smith, David Tomasko, Deborah Elcock, Deborah L. Blunt, and Gustavious P. Williams.

References

Bush, T.O., 1998, fax from Bush, BPF, Inc., Duncanville, TX, to K. Smith, Argonne National Laboratory, Denver, CO, January 15.

Capone, D.W., S. Chatterjee, T. Cleland, D. Fortunato, G. Roehrig, H.B. Walker, and T.O. Bush, 1997, "Results of Bench Scale Testing of a Mobile On-Site NORM Treatment System in Texas and New Mexico," in proceedings of U.S. Department of Energy's Natural Gas Conference, Houston, TX, March 24–27.

EPA, 1989, "Risk Assessment Guidance for Superfund, Volume I, Human Health Evaluation Manual (Part A)," EPA/540/1-89/002, U.S. Environmental Protection Agency, Office of Emergency and Remedial Response, December.

EPA, 1993, "Draft Diffuse NORM-Waste Characterization and Preliminary Risk Assessment," U.S. Environmental Protection Agency, Office of Radiation and Indoor Air, Washington, DC.

ICRP, 1977, "Recommendations of the Commission on Radiological Protection," ICRP Publication 26, Annals of the ICRP 1(3), Commission on Radiological Protection, Pergamon Press, New York, adopted January 17.

ICRP, 1991, "1990 Recommendations of the International Commission on Radiological Protection," ICRP Publication 60, Pergamon Press, Oxford, United Kingdom.

Kelly, J., 1998, letter from Kelly, Lotus LLC, Andrews, TX, to J. Veil, Argonne National Laboratory, Washington, DC, January 9.

Moore, G., 1998, personal communication between Moore, Taylor Invesco LLC, Carthage, TX, and J. Veil, Argonne National Laboratory, Washington, DC, January 28.

Page, W., and N. Guidry, 1998, personal communication between Page and Guidry, National Injection Services, Inc., Lafayette, LA, and J. Veil, Argonne National Laboratory, Washington, DC, February 11.

Rafati, A., 1998, personal communication between Rafati, Envirocare of Utah, Inc., Salt Lake City, UT, and J. Veil, Argonne National Laboratory, Washington, DC, February 11.

Reddoch, J., 1998, personal communication between Reddoch, Apollo Services, Lafayette, LA, and J. Veil, Argonne National Laboratory, Washington, DC, January 21.

Sammons, J., 1998, personal communication between Sammons, Newpark Environmental Services, Houston, TX, and J. Veil, Argonne National Laboratory, Washington, DC, January 23.

Scaife, W.W., S.G. Mueller, and D.R. Young, 1994, "Downhole Disposal of NORM Wastes in an Offshore Setting: Lessons Learned," in Proceedings of the International Petroleum Environmental Conference, Houston, TX, March 2–4.

Smith, K.P., D.L. Blunt, G.P. Williams, and C.L. Tebes, 1996, "Radiological Dose Assessment Related to Management of Naturally Occurring Radioactive Materials Generated by the Petroleum Industry," ANL/EAD-2, Argonne National Laboratory, Argonne, IL, September.

Tomasko, D., D. Elcock, J. Veil, and D. Caudle, 1997, "Risk Analyses for Disposing Nonhazardous Oil Field Wastes in Salt Caverns," prepared for U.S. Department of Energy, Office of Fossil Energy, Argonne National Laboratory, Argonne, IL, December.

Veil, J.A., 1997, "Costs for Off-Site Disposal of Nonhazardous Oil Field Wastes: Salt Caverns versus Other Disposal Methods," DOE/BC/W-31-109-Eng-38-2, prepared for U.S. Department of Energy, National Petroleum Technology Office, Argonne National Laboratory, Washington, DC, September.

Veil, J., D. Elcock, M. Raivel, D. Caudle, R.C. Ayers, Jr., and B. Grunewald, 1996, "Preliminary Technical and Legal Evaluation of Disposing of Nonhazardous Oil Field Waste into Salt Caverns," prepared for the U.S. Department of Energy, Office of Fossil Energy, Argonne National Laboratory, Washington, DC, June.

Veil, J., K. Smith, D. Tomasko, D. Elcock, D. Blunt, and G. Williams, 1998, "Disposal of NORM-Contaminated Oil Field Wastes in Salt Caverns," prepared for the U.S. Department of Energy, National Petroleum Technology Office, Argonne National Laboratory, Argonne, IL, August.

White, C., 1998, letter from White, US Ecology, Richland, WA, to J. Veil, Argonne National Laboratory, Washington, DC, letter undated but received in January.

Table 1- Exposure Point Concentrations, Committed Effective Dose Equivalents, and Carcinogenic Risks Estimated for Ingestion of Ra-226 in Groundwater[a] (reprinted from Veil et al. 1998)

	Best-Case Probability Estimates			Worst-Case Probability Estimates			100% Probability of Release Case		
Release Scenario	Exposure-point Concentration (pCi/L)	Committed Effective Dose Equivalent	Estimated Cancer Risk	Exposure-point Concentration (pCi/L)	Committed Effective Dose Equivalent	Estimated Cancer Risk	Exposure-point Concentration (pCi/L)	Committed Effective Dose Equivalent	Estimated Cancer Risk
Cavern seal fails, releases fluid at depth	3×10^{-19}	2×10^{-17}	1×10^{-23}	1×10^{-18}	6×10^{-17}	4×10^{-23}	8×10^{-18}	5×10^{-16}	3×10^{-22}
Cavern seal fails, releases fluid to shallow aquifer	5×10^{-11}	3×10^{-9}	2×10^{-15}	2×10^{-10}	1×10^{-8}	6×10^{-15}	4×10^{-9}	2×10^{-7}	1×10^{-13}
Release from crack	2×10^{-19}	1×10^{-17}	7×10^{-24}	1×10^{-18}	6×10^{-17}	4×10^{-23}	8×10^{-18}	5×10^{-16}	3×10^{-22}
Release from leaky interbed	3×10^{-15}	2×10^{-13}	1×10^{-19}	2×10^{-14}	1×10^{-12}	7×10^{-19}	2×10^{-13}	1×10^{-11}	5×10^{-18}
Roof fall + release at depth through crack	8×10^{-19}	5×10^{-17}	3×10^{-23}	2×10^{-18}	1×10^{-16}	9×10^{-23}	8×10^{-18}	5×10^{-16}	3×10^{-22}
Roof fall + release at depth through leaky interbed	9×10^{-15}	6×10^{-13}	4×10^{-19}	2×10^{-14}	2×10^{-12}	9×10^{-19}	2×10^{-13}	1×10^{-11}	5×10^{-18}
Roof fall + cavern seal failure + release at depth	5×10^{-19}	3×10^{-17}	2×10^{-23}	1×10^{-18}	8×10^{-17}	5×10^{-23}	8×10^{-18}	5×10^{-16}	3×10^{-22}
Roof fall + cavern seal failure + release at shallow depth	2×10^{-11}	2×10^{-9}	9×10^{-16}	2×10^{-10}	1×10^{-8}	8×10^{-15}	4×10^{-9}	2×10^{-7}	1×10^{-13}

[a] Risks presented in this table are solely from the radiological constituents of NORM and do not include any risks from the chemical constituents.

Table 2 - Estimated Cancer Risks and Hazard Quotients from NORM and NOW (reprinted from Veil et al. 1998)

Release Scenario	Best-Case Estimate			Worst-Case Estimate			100% Probability of Release Case		
	Cancer Risk		Hazard Quotient	Cancer Risk		Hazard Quotient	Cancer Risk		Hazard Quotient
	NOW[a]	NORM[b]		NOW[a]	NORM[b]		NOW[a]	NORM[b]	
Cavern seal fails, releases fluid at depth	5×10^{-18}	1×10^{-23}	7×10^{-8}	2×10^{-17}	4×10^{-23}	3×10^{-7}	2×10^{-16}	3×10^{-22}	2×10^{-6}
Cavern seal fails, releases fluid to shallow aquifer	3×10^{-9}	2×10^{-15}	1×10^{-5}	9×10^{-9}	6×10^{-15}	5×10^{-5}	2×10^{-7}	1×10^{-13}	1×10^{-3}
Release from crack	4×10^{-18}	7×10^{-24}	5×10^{-8}	2×10^{-17}	4×10^{-23}	3×10^{-7}	2×10^{-16}	3×10^{-22}	2×10^{-6}
Release from leaky interbed	3×10^{-16}	1×10^{-19}	2×10^{-8}	1×10^{-15}	7×10^{-19}	1×10^{-7}	1×10^{-14}	5×10^{-18}	6×10^{-7}
Roof fall + release at depth through crack	2×10^{-17}	3×10^{-23}	2×10^{-7}	5×10^{-17}	9×10^{-23}	6×10^{-7}	2×10^{-16}	3×10^{-22}	2×10^{-6}
Roof fall + release at depth through leaky interbed	7×10^{-16}	4×10^{-19}	5×10^{-8}	2×10^{-15}	9×10^{-19}	1×10^{-7}	1×10^{-14}	5×10^{-18}	6×10^{-7}
Roof fall + cavern seal failure + release at depth	1×10^{-17}	2×10^{-23}	1×10^{-7}	3×10^{-17}	5×10^{-23}	4×10^{-7}	2×10^{-16}	3×10^{-22}	2×10^{-6}
Roof fall + cavern seal failure + release at shallow depth	1×10^{-9}	9×10^{-16}	7×10^{-6}	1×10^{-8}	8×10^{-15}	6×10^{-5}	2×10^{-7}	1×10^{-13}	1×10^{-3}

[a] This is the risk from the chemical constituents of NORM waste. It is exactly the same as the risk from NOW as reported in Tomasko et al. (1997).
[b] This is the risk from the radiological constituents of NORM waste.