Conference Paper

Disposal of Oil Field Wastes and NORM Wastes into Salt Caverns

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to be presented at the 1999 ASCE Water Resources Planning and Management Conference

June 6 - 9, 1999

Tempe, AZ

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Abstract

Salt caverns can be formed through solution mining in the bedded or domal salt formations that are found in many states. Salt caverns have traditionally been used for hydrocarbon storage, but caverns have also been used to dispose of some types of wastes. This paper provides an overview of several years of research by Argonne National Laboratory on the feasibility and legality of using salt caverns for disposing of nonhazardous oil field wastes (NOW) and naturally occurring radioactive materials (NORM), the risks to human populations from this disposal method, and the cost of cavern disposal. Costs are compared between the four operating U.S. disposal caverns and other commercial disposal options located in the same geographic area as the caverns. Argonne's research indicates that disposal of NOW into salt caverns is feasible and, in most cases, would not be prohibited by state agencies (although those agencies may need to revise their wastes management regulations). A risk analysis of several cavern leakage scenarios suggests that the risk from cavern disposal of NOW and NORM wastes is below accepted safe risk thresholds. Disposal caverns are economically competitive with other disposal options.

Introduction

Each year, the oil and gas exploration and production industry generates large volumes of oily and solid waste that are disposed of by various means, including underground injection (disposal wells, enhanced oil recovery wells, annular injection), on-site burial (pits, landfills), land treatment (land spreading, land farming, road spreading), evaporation, surface discharge, or recycling. In recent years, interest has grown concerning the use of solution-mined salt caverns for disposal of nonhazardous oil field wastes. The U.S. Department of Energy (DOE) has a continuing interest in exploring new and alternative waste disposal methods, especially those that are less costly or risky than existing disposal methods. DOE funded Argonne National Laboratory (Argonne) to conduct four studies that evaluated various aspects of using salt caverns to dispose of nonhazardous oil field wastes (NOW), including those containing naturally occurring radioactive materials (NORM).

The first Argonne study, a feasibility study, evaluated whether any federal or state laws or regulations prohibited or inhibited cavern disposal of NOW (Veil et al. 1996). The feasibility study also reviewed existing uses of caverns, the types of wastes suitable for cavern disposal, cavern design and siting parameters, the actual waste disposal process, and anticipated environmental impacts following cavern closure. The second study, a cost study, compiled a database of available off-site commercial disposal facilities in 31 oil- and gas-producing states (Veil 1997). Costs of cavern disposal were compared with costs of other, more conventional disposal methods. The third study, a risk study, evaluated the human health effects that could result from drinking groundwater exposed to contaminants released from caverns that had been used for disposal of NOW (Tomasko et al. 1997). The risk study calculated cancer and noncancer risks attributable to releases of cavern contents into drinking water supplies. Full copies of the reports referenced above can be downloaded from Argonne's website at www.ead.anl.gov. These three reports represent a comprehensive baseline of information on cavern disposal of oil field wastes. In a fourth DOE-sponsored study, Argonne evaluated the same elements - technical feasibility, legality, costs, and risk - for cavern disposal of NORM wastes (Veil et al. 1998). This paper summarizes the results of the four Argonne studies.

Background on Salt Caverns

Figure 1 (reprinted from Veil et al. 1996) shows the location of the major U.S. subsurface salt deposits. There are two types of subsurface salt deposits in the United States: salt domes and bedded salt. Salt domes are large, generally homogeneous formations of salt that are formed when a column of salt migrates upward from a deep salt bed, passing through the overlying sediments. Salt dome deposits are found in the Gulf Coast region of Texas, Louisiana, Mississippi, and Alabama.

Bedded salt formations occur in layers bounded on the top and bottom by impermeable formations and are interspersed with nonsalt sedimentary materials (anhydrite, shale, and dolomite) having various levels of impermeability. Unlike salt domes, which are large masses of relatively pure sodium chloride, bedded salt deposits are tabular deposits of sodium chloride that can contain significant quantities of impurities. Major bedded salt deposits occur in several parts of the United States.

Salt caverns are created by injecting fresh water into a salt formation and withdrawing the resulting brine solution. Much of the world's salt and brine supply comes from such solution-mined caverns. Figures 2 and 3 (reprinted from Veil et al. 1996) show the idealized construction for caverns in domal salt and bedded salt, respectively.

The most common use for salt caverns is to store hydrocarbons such as propane, butane, ethane, ethylene, fuel oil, gasoline, natural gas, and crude oil (Querio 1980). In 1975, the U.S. Congress created the Strategic Petroleum Reserve (SPR) program to provide the country with sufficient petroleum reserves to reduce any impacts that might be caused by future interruptions in the oil supply. The SPR consists of 62 leached caverns in domal salt with a total capacity of 680 million bbl. DOE has prepared a plan for, but is not currently pursuing, the development of an additional 250 million bbl of storage capacity. Highly compressed air has also been stored in some caverns where it can later be withdrawn to generate electricity.

The petroleum industry has constructed many salt caverns to store hydrocarbons. To provide guidance for designing and operating hydrocarbon storage salt caverns, several organizations have developed standards documents (Canadian Standards Association 1993; American Petroleum Institute 1994; Interstate Oil and Gas Compact Commission 1995). Details on the design, location, and construction of salt caverns are provided in those reports.

Another use for salt caverns is to dispose of various wastes. In the United States and other countries, only a limited number of salt caverns have been issued permits for waste disposal. The Railroad Commission of Texas (TRC) has issued permits for disposal of NOW to six caverns, four of which are currently operating as disposal caverns. At least four caverns in Canada have been permitted for disposal of NOW. Veil et al. (1996) describe other types of cavern disposal activities in the United Kingdom, Germany, the Netherlands, and Mexico. As of January 1999, the author is not aware of caverns in any country that have been approved for disposal of NORM wastes.

Regulatory Considerations

On July 6, 1988, the U.S. Environmental Protection Agency (EPA) published a list of those oil field wastes that were exempt from regulation as hazardous wastes under Subtitle C of the Resource Conservation and Recovery Act (RCRA) (53 FR 25477). On March 22, 1993, EPA issued clarification of the 1988 determination, adding many other wastes that were uniquely associated with oil and gas exploration and production operations to the list of wastes exempt from RCRA Subtitle C requirements (58 FR 15284).

EPA's Underground Injection Control (UIC) regulations define Class II injection wells as wells that inject fluids that are brought to the surface in connection with natural gas storage operations or conventional oil or natural gas production. Most, but not all, of the wastes exempted by the 1988 RCRA regulatory determination would meet the UIC program's criterion to be "in connection with" oil and gas production. Some wastes (e.g., hydrocarbon-contaminated soil) would not meet the UIC criterion, but EPA's guidance on the subject allows states to have the discretion to determine whether such wastes may be injected into Class II wells.

At the state level, only the TRC has formally authorized disposal of NOW into salt caverns. The TRC has issued permits for six facilities, but only four of these are active. In April 1996, the TRC released draft proposed amendments to TRC Rule 9, the regulation that governs injection into a formation not productive of oil, gas, or geothermal resources. As of January 1999, the TRC had not finalized those regulations. Ten other states were contacted about their interest in disposing of NOW in salt caverns. Although several states were interested, none had cavern disposal programs or had authorized any cavern disposal activities. Oil and gas agencies in Mississippi, New Mexico, and Louisiana have investigated the idea of developing cavern disposal programs but have not completed such programs yet. A review of regulations and telephone interviews with state and EPA officials identified no apparent regulatory barriers to the use of salt caverns for disposal of NOW at either the federal level or in the 11 states contacted for this analysis.

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. NORM regulatory programs in Louisiana, Mississippi, New Mexico, Oklahoma, and Texas address 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 regulations and regulations from the five states listed above 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.

Types of Wastes to Be Accepted

The types of oil field waste proposed for disposal in salt caverns are those that are most troublesome to dispose of through regular Class II injection wells because they contain high levels of solids. Wastes containing water that is not fully saturated with salt may increase the size of caverns, because the unsaturated water will leach salt from the cavern walls. The presence of fresh water in wastes should not preclude their disposal in salt caverns, but the operator must account for the increased volume of the cavern and what effect it will have on such cavern siting parameters as distance to adjacent caverns and roof span or thickness. The solids-containing NOW most likely to be disposed of in salt caverns include used drilling fluids, drill cuttings, completion and stimulation waste, produced sand, tank bottoms, and crude-oil- or salt-contaminated soil. NORM wastes are also suitable for cavern disposal.

Cavern Disposal Operations

In cavern disposal operation, caverns initially are filled with clean brine. Wastes are introduced as a slurry of waste and a carrier fluid (brine or fresh water). A carrier fluid that is not fully saturated with salt will eventually leach salt from the cavern walls or roof. Expansion of cavern diameter is generally not a problem as long as the anticipated degree of expansion is accounted for in the cavern design, and the actual degree of expansion is monitored throughout the waste emplacement cycle. To avoid excessive leaching of the cavern roof, operators may intentionally introduce a hydrocarbon pad that, by virtue of its lower density, will float to the top of the cavern and keep the unsaturated carrier fluid from coming in contact with the cavern roof.

As the waste slurry is injected, the cavern acts as an oil/water/solids separator. The heavier solids fall to the bottom of the cavern, forming a pile. Any free oils or hydrocarbons that are associated with the waste float to the top of the cavern. Clean brine displaced by the incoming slurry is removed from the cavern and either sold as a product or disposed of in an injection well. When the cavern is filled, the operator removes the hydrocarbon pad and plugs the cavern.

Post-closure Impacts

There is no actual field experience on the long-term impacts from disposing of NOW or NORM waste in salt caverns. The literature contains theoretical studies that estimate what might happen after such a cavern is closed. Researchers agree that pressures will build in a closed cavern because of salt creep and geothermal heating, but the actual fate of the caverns and their contents is still hypothetical. In perhaps the only actual careful investigation of the behavior of a sealed cavern, Staudtmeister and Rokahr (1994) report that a test cavern held under pressure for more than two years lost brine gradually to the salt in the roof of a cavern. Slow leakage into the low-permeability salt prevented the internal cavern pressure from exceeding lithostatic pressure and experiencing rapid or large-volume leaking.

Argonne National Laboratory has joined with Sandia National Laboratories, the University of Texas-Bureau of Economic Geology, and the Solution Mining Research Institute to form a salt cavern research partnership. The partners are coordinating their research efforts to answer key questions concerning salt caverns. One of the most important issues being studied by the partnership is a better understanding of post-closure processes and impacts. However, as discussed in a later section of this paper, Argonne's calculations indicate that even if all caverns leak their contents into the surrounding formations, the human health risk from leaking caverns that have previously been filled with NOW or NORM wastes is extremely low.

Technical Feasibility of Cavern Disposal

NOW is currently being disposed of without difficulties in four U.S. salt caverns and in several Canadian caverns. NORM waste is physically and chemically similar to NOW. Its primary difference from NOW is the presence of radionuclides in NORM waste. 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. There is no technical reason why disposal caverns could not equally well accept NORM waste.

Disposal Costs

Table 1 (based on Veil 1997) summarizes disposal costs for commercial companies that accept NOW. Disposal facilities use any of three cost rates — dollars per barrel ($/bbl), dollars per cubic yard, and dollars per ton. Table 1 shows a composite of the reported rates for 85 disposal facilities. Overall the costs range from $0 to $57/bbl, $4.20 to $50/cubic yard, and $12 to $150/ton.

The disposal options in Table 1 can be compared on a dollars-per-barrel cost basis. Land spreading operations have a significant share of the commercial disposal market, with costs ranging from $5.50 to $57/bbl. Landfills and pits represent another important disposal option, with costs ranging from $0.50 to $36/bbl. Only one landfill/pit facility charged less than $2.25/bbl. Two facilities evaporate the liquid fraction of the waste and send the solids to a landfill. They charge $2.50 to $2.75/bbl. Several facilities treat the wastes before reusing or disposing of them. These facilities charge from $0 to $12/bbl, although only one facility charges less than $3/bbl. Several facilities incinerate wastes, with costs ranging from $10.50 to $38/bbl. Finally, the four cavern disposal facilities charge from $1.95-$6/bbl.

These data show that disposal caverns can be cost-competitive with other NOW disposal methods. In the oil fields of western Texas and eastern New Mexico, numerous commercial disposal facilities are competing. Three of the four operating disposal caverns are located in this area. They have rates that are comparable to or less costly than facilities using other disposal methods.

Current NORM waste disposal costs range from $15/bbl to $420/bbl, as shown in Table 2 (based on Veil et al. 1998). The costs presented in this study reflect the information provided by disposal companies to the authors in early 1998 and may not reflect actual total disposal costs. It is also difficult to compare cost figures from one disposal company with those of another company because the companies do not always include the same types of services in their quoted prices.

Operators of the four permitted disposal caverns in Texas were contacted to see if they had made any 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. 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 made even preliminary cost estimates, one 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 allowed NORM disposal in caverns, competition would drive the price lower (Moore 1998). NOW disposal caverns have proven cost-competitive with other NOW disposal facilities in the same geographic area. 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.

Human Health Risks from Disposal Caverns

Caverns are located deep below the earth's surface. The process of filling caverns with waste is performed at low pressure and should not cause cavern failure. Following cavern plugging and closure, internal cavern pressure could increase from salt creep and geothermal heating to a point at which leaks or releases might occur. Tomasko et al. (1997) identified several scenarios under which a disposal cavern could leak or fail. These include:

- Cavern intrusion, in which a new well is inadvertently drilled into the cavern;
- Failure of the cavern seal at the wellbore plug or casing seat;
- Loss horizontally through cracks in the salt or in anhydrite layers; and
- Collapse of the cavern roof.

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 365 meters laterally from the cavern at either the depth of the cavern [365 meters] or a shallow depth [18 meters]), various physical, chemical, biological, and radiological processes occur that reduce the concentration of the contaminants. Fate and transport modeling was used to estimate the contaminant concentrations at the receptor point (exposure point concentrations).

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 to 0.1, and averaged worst-case estimates ranged from 0.04 to 0.29. To provide an even more conservative estimate, we used the true worst-case condition — the 100% Probability of Release case — under which all caverns release fluids during the 1,000-year period of concern.

Table 3 (based on Veil et al. 1998) shows the calculated human health cancer and non-cancer risks for cavern disposal of NOW and NORM wastes. On the basis of assumptions that were developed for a generic cavern and generic NOW and NORM wastes, the estimated worst-case human health risks from NOW (which are exactly the same as the risks attributed to the chemical constituents of NORM waste) are very low. The excess cancer risks fall between 1×10^{-8} and 2×10^{-17}, and the hazard quotients (referring to noncancer health effects) for NOW fall between 6×10^{-5} and 1×10^{-7}. Even under the extremely conservative 100% Probability of Release case, the highest risk from the NOW (same as the chemical constituents of NORM waste) is 2×10^{-7}. Normally, risk managers consider risks of less than 1×10^{-6} and hazard quotients of less than 1.0 to be acceptable.

The excess cancer risks estimated for the radiological contaminants are orders of magnitude lower. Even for the 100% Probability of Release Case, risks are estimated at 1×10^{-13} to 3×10^{-22} and, consequently, are dwarfed by the risks from the chemical contaminants. No noncancer health risks were estimated for radionuclides.

Conclusions

Argonne National Laboratory has extensively studied the practice of disposing of nonhazardous oil field wastes in salt caverns. The following conclusions result from our investigations:

- Cavern disposal of NOW is clearly feasible, as several U.S. and Canadian companies are already using the practice. Cavern disposal of NORM waste should follow the same technical approach and, therefore, should also be feasible. Cavern disposal can be a valuable disposal option where salt formations are of sufficient size and quality to support caverns safely.
- There are no apparent regulatory barriers that would keep states from establishing cavern disposal programs, with the exception of a Louisiana law that prohibits disposal of radioactive wastes or other radioactive materials in salt domes. Disposal of NOW is not prohibited in Louisiana. Several states are considering authorizing cavern disposal, which would most likely require changes to existing state waste management regulations.
- NOW disposal caverns are cost-competitive with other, more conventional disposal methods in the same geographical area. Disposal of NORM waste in caverns, when authorized, is also expected to be cost-competitive.
- Post-closure behavior of caverns is not well-understood. Salt creep and geothermal heating will cause internal cavern pressure to increase and potentially lead to cavern leaks, although many experts believe that the rate of pressure increase will be sufficiently slow that leakage will not occur.
- Even if caverns do leak, the risks to human health through drinking water contamination appear to be very low.

Acknowledgments

The author wishes to acknowledge the efforts and contributions of the other Argonne salt cavern team members on some or all of the Argonne studies: David Tomasko, Deborah Elcock, Karen Smith, Deborah Blunt, Mary Raivel, Dan Caudle, Robert C. Ayers, Jr., Gustavious Williams, and Ben Grunewald. This work was sponsored by the U.S. Department of Energy, Office of Fossil Energy, National Petroleum Technology Office, under Contract W-31-109-ENG-38. The author extends his appreciation to DOE's Nancy Johnson and John Ford for their support on the salt cavern projects.

References

American Petroleum Institute, 1994, *Design of Solution-Mined Underground Storage Practices*, Recommended Practice 1114, American Petroleum Institute, Washington, DC, June.

Canadian Standards Association, 1993, *Storage of Hydrocarbons in Underground Formations - Oil and Gas Industry Systems and Materials*, Standard Z341-93, Canadian Standards Association, Rexdale, Ontario, Canada, July.

Interstate Oil and Gas Compact Commission, 1995, *Natural Gas Storage in Salt Caverns: A Guide for State Regulators*, Interstate Oil and Gas Compact Commission, Oklahoma City, OK, October.

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

Querio, C.W., 1980, *Design and Construction of Solution-Mined Caverns for LPG Storage*, presented at Solution Mining Research Institute's fall meeting, Minneapolis, MN, October 12-15.

Staudtmeister, K., and R.B. Rokahr, 1994, *Pressure Build-Up Test in the Etzel K 102 Cavern,* prepared for the German cavern consortium Konsortium Druckaufbautest, (English translation available from Solution Mining Research Institute, Encinitas, CA.)

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

Veil, J.A., 1997, *Costs for Off-Site Disposal of Nonhazardous Oil Field Wastes: Salt Caverns versus Other Disposal Methods*, prepared by Argonne National Laboratory, Washington, D.C., for the U.S. Department of Energy, April.

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 by Argonne National Laboratory, for U.S. Department of Energy, June.

Veil, J.A., K.P. Smith, D. Tomasko, D. Elcock, D.L.Blunt, and G.P. Williams, 1998, *Disposal of NORM-Contaminated Oil Field Wastes in Salt Caverns*, prepared by Argonne

National Laboratory, for U.S. Department of Energy, August.

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Table 1 - Disposal Costs for Oily and Solid NOW

Method	$/bbl	$/cubic yard	$/ton
land spread	5.50 - 57	14 - 40	20 - 95
landfill/pit	0.50 - 36	6.50 - 37.50	17 - 150
evaporation	2.50 - 2.75	4.20 - 18.90	
treatment then	0 - 12	12.50 - 28.50	12 - 45
incineration	10.50 - 38		20 - 100
salt cavern	1.95 - 6	50	

Note: Costs were provided by disposal companies from June 1996 to March 1997 and may not reflect current costs. Costs do not include transportation expenses.

Source: Veil (1997)

Table 2 - 1998 Commercial Disposal Costs for NORM

Disposal Company	Disposal Method	On-site/Off-site	Costs ($/bbl)
Newpark Environmental Services, Inc.	Injection	Off-site	$150
Lotus LLC	Injection	Off-site	$100
US Ecology	Landfill	Off-site	$380 - $420
Envirocare of Utah, Inc.	Landfill	Off-site	Variable - no costs provided
Apollo Services	Injection	On-site	$100 - $300
National Injection Services	Injection	On-site	$15 - $150

Source: Veil et al. (1998)

Table 3 - Estimated Cancer Risks and Hazard Quotients from NORM and NOW

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.
Source: Veil et al. (1998)