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# Dose Assessment for Management Alternatives for NORM-Contaminated Equipment within the Petroleum Industry*

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# DOSE ASSESSMENT FOR MANAGEMENT ALTERNATIVES FOR NORM-CONTAMINATED EQUIPMENT WITHIN THE PETROLEUM INDUSTRY

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## INTRODUCTION

The contamination of drilling and production equipment by naturally occurring radioactive material (NORM) is a growing concern for the petroleum industry and regulators. Large volumes of NORM-contaminated scrap metal are generated by the industry each year. The contamination generally occurs as surface contamination on the interior of water-handling equipment. The source of this contamination is accumulation of by-product wastes, in the form of scale and sludge contaminated with NORM that are generated by extraction processes. The primary radionuclides of concern in petroleum industry NORM-wastes are radium-226 (Ra-226), and radium-228 (Ra-228). These isotopes are members of the uranium-238 and thorium-232 decay series, respectively. The uranium and thorium isotopes, which are naturally present in the subsurface formations from which hydrocarbons are extracted, are largely immobile and remain in the subsurface. The more soluble radium can become mobilized in the formation water and be transported to the surface in the produced water waste stream. The radium either remains in solution or precipitates in scale or sludge deposits, depending on water salinity and on temperature and pressure phase changes. NORM-containing scale consists of radium that has coprecipitated with barium, calcium, or strontium sulfates, and sludge typically consists of radium-containing silicates and carbonates.

Currently, no federal regulations apply to management of NORM-contaminated scrap metal. However, some individual states have promulgated their own regulations for management of NORM. As a result, the petroleum industry has begun to research methods for managing and disposing of NORM-contaminated wastes that are protective of human health and the environment. The current management alternatives for contaminated scrap metal include (1) decontamination and reuse of equipment, (2) disposal at a licensed facility, (3) encapsulation inside an abandoned well (applicable for small equipment only), and (4) sale of scrap metal overseas. Another option that is also being considered is smelting of scrap metal for reuse.

This assessment is limited to the evaluation of potential radiological doses from management options that specifically involve recycle and reuse of contaminated metal. Doses from disposal of contaminated equipment are not addressed. Radiological doses were estimated for workers and the general public for equipment decontamination and smelting. Results of this assessment can be used to examine policy issues concerning the regulation and management of NORM-contaminated wastes generated by the petroleum industry.

## SOURCE TERM CHARACTERIZATION

Adequate characterization of the source term concentration presents a major limitation in terms of estimating potential health effects. Most data describing source term concentrations have been collected at the state and company levels and have not been aggregated to provide a comprehensive data set. The only national-level survey conducted to date, sponsored by the American Petroleum Institute (API), measured external gamma exposures from contaminated equipment.[1] The data from that survey cannot be used to derive statistically representative source term concentrations because (1) the survey did not provide adequate coverage of some geographical areas, (2) the survey was limited to those companies that responded, (3) statistically designed sampling schemes were not used, and (4) the survey is considered to be biased toward high concentrations because measurements were collected only from equipment expected (from previous survey results) to be contaminated with NORM. In addition, the conversion from external gamma readings to radium concentration is heavily dependent on several highly variable factors (e.g., equipment geometry, shielding factors, internal distribution of radium).

The source term concentrations used in this assessment were based on the scale and sludge composite concentrations used in a risk assessment conducted by the U.S. Environmental Protection Agency (EPA) and the state of Louisiana.[2] In that study, median, 75th-percentile, and maximum concentrations in scale and sludge were derived from more than 3,000 external gamma measurements collected as part of the API survey. The median and 75th-percentile concentrations calculated for the Louisiana data, provided in Table 1, were used for this assessment because they represent the most complete set of data available. Although definitive data describing the concentration ratio of Ra-226 to Ra-228 are not available, a ratio of 3:1 was assumed. To be conservative, secular equilibrium was assumed for the radium decay progeny. These assumptions are consistent with previous studies.[2,3]

## EQUIPMENT DECONTAMINATION

Cleaning facilities have been established to remove NORM-contaminated scale and sludge from equipment that has been taken out of service. The types of equipment that can be cleaned for reuse in the industry include piping and storage vessels. Estimated doses from equipment decontamination were assessed for four individuals: a pipe cleaner, a vessel cleaner, a storage yard worker, and a resident living adjacent to a storage yard. The purpose of this assessment was to evaluate reasonable, maximum, annual doses to (1) workers cleaning contaminated equipment at a licensed facility, operating in compliance with the Louisiana NORM regulations,[4] and (2) to an adjacent resident. Worker doses at unregulated facilities are also discussed. Median and 75th-percentile concentrations of total radium from Table 1 were used to place boundaries on the uncertainty associated with the source term concentration to the extent possible, given the available data.

External doses for workers were calculated with the Microshield Version 4 computer code.[5] The inhalation and ingestion pathways were modeled with the RESRAD-BUILD computer code only for workers who use dry pipe cleaning methods.[6] All other workers at an equipment-cleaning facility were assumed to be protected from inhalation and ingestion exposures because (1) wet pipe cleaning processes typically are conducted inside a closed system, (2) vessel cleaners are required to wear respirators with supplied air to protect themselves from hazards associated with hydrocarbons, and (3) storage yard workers have minimal contact with dry, respirable, NORM-contaminated particulates. In addition, workers at licensed facilities who handle NORM-contaminated wastes directly are required to wear respirators and protective clothing.

On the basis of median source term concentrations, the total estimated dose for workers at equipment cleaning facilities ranges from 4 to 50 mrem/yr (Table 2). These estimated doses are considered to be very conservative because of the nature of the input parameters and the assumption that workers would be exposed only to equipment contaminated at median or higher source term concentrations. For the pipe cleaner, external doses are estimated at 4 mrem/yr. Pipe cleaners who use dry processes without respirators have the highest estimated total dose of 50 mrem/yr from all pathways (i.e., inhalation, ingestion, and external irradiation). This estimate is based on a conservative dust loading factor and secular equilibrium. For the vessel cleaner, who cleans contaminated sludge from a large, enclosed vessel, the dose from external irradiation is estimated at 5 mrem/yr. For the storage yard worker, who spends the most time around the contaminated equipment, the external dose is estimated at 40 mrem/yr. The resident living adjacent to a storage yard is estimated to receive an annual dose of approximately 0.2 mrem.

## EQUIPMENT SMELTING

Recycle of NORM-contaminated scrap metal by smelting is currently being considered as a potentially viable management option for the petroleum industry. The industry is estimated to generate about 170,000 tons of NORM-contaminated scrap each year.[7] Given the magnitude of waste generated, recycle and reuse of the steel may represent an attractive alternative to conventional landfill in terms of cost and resource use. A major obstacle in implementing this alternative is that no guidelines are in place for recycle of radioactive contaminated metal. The petroleum industry does not have a centralized facility for scrap metal processing or storage. In addition, the steel industry operates independently from the petroleum industry and is very reluctant to accept any radioactive material, regardless of the source.

One of the key issues in determining the feasibility of smelting as a management option for the petroleum industry is evaluation of potential health impacts. This study evaluates the potential doses to workers and the general public from the smelting process and several end-point uses of both the recycled metal and slag. Several scenarios were modeled to estimate potential radiological doses to commercial metal workers, the general public, and petroleum industry workers related to the smelting of NORM-contaminated equipment. These scenarios were modeled by adapting a methodology used by Argonne National Laboratory to assess the radiological impacts to workers and the general public from the recycling of radioactive scrap metal generated by the U.S. Department of Energy.[8] Consistent with this methodology, potential doses were evaluated for representative steps of the recycling process, including the transportation of contaminated scrap metal, smelting, manufacture of industrial products, fabrication, and distribution and use of products made from the recycled steel and slag. The radiological impacts of recycling contaminated metal were evaluated on the basis of maximum individual dose equivalents. Radiological doses were analyzed with the RESRAD-BUILD computer code.[6] The pathways evaluated included external irradiation, inhalation of contaminated particulates, and incidental ingestion. Potential doses to the public from emissions released during the smelting process were analyzed with the CAP88-PC computer code.[9]

The nature and magnitude of radiological impacts from recycling depend upon many factors, including the annual throughput, radionuclide source concentrations, dilution factor, radionuclide partition factors, and distribution of contaminated scrap in the steel industry. Detailed information concerning many of these factors is not currently available (e.g., adequate characterization of the source term, geographic distribution of NORM-contaminated equipment). In light of these limitations, baseline calculations were estimated for a unit concentration of NORM radionuclides of interest. These estimates can be used to scale annual doses associated with recycle of NORM-contaminated equipment, using site-specific information about throughput, radionuclide source term concentration, and dilution with uncontaminated metal.

The baseline calculations are based on a unit concentration of 1 pCi/g, full-time exposure (i.e., 2,000 hours per year), and no dilution. The partition factors, which describe the fraction of the original radionuclide concentration that ends up in each by-product of smelting, were derived from available literature and bench-scale testing.[10,11] For the steel ingots, off-gas, and slag, the partition factors were conservatively assumed to be 0.1, 0.0005, and 1, respectively. Because the majority of radioactivity partitions with the slag,[10] the estimated doses are the highest for the worker who handles the slag product. Baseline dose estimates for the constraining worker scenario (i.e., slag worker) and end-use products made of recycled metal and slag are presented in Table 3. Doses to the general public from reuse of the recycled steel and slag by-product were estimated with the assumption that the steel was recycled into an automobile and the slag was recycled in construction of a parking lot.

As a preliminary estimate of health impacts from recycle of NORM-contaminated equipment, radiological doses were estimated on the basis of the median and 75th-percentile source term concentrations for scale (Table 1). The amount of scale was estimated to be 5% of the total mass of contaminated equipment, assuming no initial decontamination of the equipment other than removal of sludge from vessels. A dilution factor of 1:10 was assumed. Table 4 summarizes the estimated doses for recycle of NORM-contaminated equipment for the constraining worker and end-use scenarios. On the basis of these conservative assumptions, the estimated annual dose to the slag worker is approximately 14 mrem, of which more than 95% is attributable to the external irradiation pathway. Increasing the radionuclide concentrations from the median to 75th-percentile values increased the dose to approximately 80 mrem/yr. Doses to the general public associated with reuse of the recycled steel and slag for the median source term concentrations were estimated at about 0.02 mrem/yr. Dose to a petroleum industry worker, assuming that the metal was recycled into piping, was estimated at about 0.03 mrem/yr.

Doses related to smelter emissions were estimated at $4 \times 10^{-4}$ mrem/yr for the maximally exposed individual who lived 500 m from the stack. This estimate was based on an annual throughput of 50,000 tons, which conservatively represents throughput at a regional level. The efficiency of the baghouse filtration system was assumed to be 99.95% for particulate emissions. Radon emissions were based on 100% partition through the stack with no filtration. The dose associated with the

75th-percentile source term concentrations was estimated to be about 2 x $10^{-3}$ mrem/yr.

Given the large degree of uncertainty related to the radionuclide source term concentrations, annual throughput, and amount of scale contamination contained in the initial throughput, these preliminary estimates should be interpreted in a relative manner only. Overall, this assessment indicates that doses to the general public from smelter emissions or from reuse of recycled steel and slag by-products are negligible. The limiting health impact from recycle of NORM-contaminated equipment is to the worker who handles the slag by-product. If smelting were to be implemented by the industry, doses could be controlled by limiting the contamination level in the initial throughput, thereby limiting resultant concentrations in the slag by-product. Limiting of radioactivity concentrations in the slag could also provide greater flexibility in disposing of the slag and potentially relieve the industry of having to dispose of that material at a regulated disposal facility. This approach for controlling smelting of contaminated equipment has been proposed by two states. The NORM regulatory programs for the states of Louisiana[4] and Texas[12] both specify an allowable total radium concentration of 5 pCi/g in the melt by-product, with authorization by specific license to smelt contaminated equipment. While limiting the resultant concentration of the melt by-product may be effective in controlling potential doses to workers, it may not be practical if large volumes of contaminated equipment containing significantly elevated contaminant concentrations require recycling.

Potential doses from exposure to the slag by-product could also be controlled by remote handling. Because more than 95% of the total dose is from external irradiation, remote handling would be very effective in controlling doses to the slag worker. Remote handling might be a viable option if the petroleum industry were to consolidate recycling of equipment at a central facility. A central facility could be an alternative for the industry given the large volumes of NORM-contaminated wastes that are generated. Smelting of contaminated equipment would effectively concentrate the radioactivity into the slag by-product, which would ultimately reduce the volume of waste requiring disposal.

## CONCLUSIONS

Although based on preliminary and incomplete data, this study provides valuable insight into the relative significance of the radiological health impacts associated with alternatives for recycle and reuse of NORM-contaminated equipment. In general, the results indicate that doses to workers at an equipment decontamination facility could be significant if the workers were continually exposed to contaminated equipment over a long period. Additional information about the dry pipe cleaning processes (e.g., dust loading factors, worker practices) and the source terms are needed to fully quantify the doses related to the inhalation and ingestion pathways. Estimated doses from equipment smelting are the highest for the worker who handles the slag product, but could be kept to acceptable levels by controlling the amount of radioactivity in the initial charge or by modifying worker practices (e.g., by using remote handling). Doses to the general public from reuse of the recycled metal or slag by-product are estimated as negligible. From a health risk perspective, recycle of contaminated equipment may be a viable alternative to disposal or long-term storage.

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**TABLE 1 Source Term Concentrations for Scale and Sludge**

| Radionuclide | Concentration (pCi/g) Median Scale | 75th-Percentile Scale | Median Sludge |
|---|---|---|---|
| Radium-226 | 360 | 2,025 | 56 |
| Lead-210 | 360 | 2,025 | 56 |
| Radium-228 | 120 | 675 | 19 |
| Thorium-228 | 120 | 675 | 19 |
| Total-radium | 480 | 2,700 | 75 |

**TABLE 2 Summary of Doses Associated with Equipment-Cleaning Facilities**

| | | Annual Dose (mrem)[a] | |
|---|---|---|---|
| Scenario | Pathway | Median | 75th-Percentile |
| Pipe cleaner (wet processes) | External gamma | 4 | 25 |
| Pipe cleaner (dry processes) | External gamma | 4 | 25 |
| | Ingestion | 35[b] | –[c] |
| | Inhalation | 11[b] | –[c] |
| | Total | 50 | |
| Vessel cleaner | External gamma | 5[d] | –[c] |
| Storage yard worker | External gamma | 40 | 220 |
| Adjacent resident | External gamma | 0.2 | 1 |

[a] All doses, except those calculated for the vessel cleaner, are based on a 2,000-hour exposure time.

[b] Dose calculations include ingrowth and decay over a 1-year period.

[c] Doses were not calculated for the 75th-percentile concentration.

[d] Doses based on a 100-hour exposure time, assuming 10 vessels were cleaned in a year.

**TABLE 3 Baseline Annual Doses for the Constraining Scenarios[a]**

| | Annual Dose (mrem/yr) | | | |
|---|---|---|---|---|
| Scenario/Receptor | Ra-226 | Ra-228 | Th-228 | Pb-210 |
| Smelter worker/slag worker[b] | 5.4 | 2.3 | 4.1 | $8.1 \times 10^{-3}$ |
| Product end-use/Automobile | $8.2 \times 10^{-3}$ | $3.6 \times 10^{-3}$ | $5.8 \times 10^{-3}$ | $1.2 \times 10^{-4}$ |
| Product end-use/parking lot | $6.5 \times 10^{-3}$ | $2.8 \times 10^{-3}$ | $4.7 \times 10^{-3}$ | $4.1 \times 10^{-6}$ |

[a] Based on a unit concentration of 1 pCi/g. Ingrowth and decay are accounted for over a 1-year period.

[b] Based on full-time exposure (i.e., 2,000 hours per year).

**TABLE 4 Summary of Doses Associated with Smelting NORM-Contaminated Equipment**

| | Annual Dose (mrem) | |
|---|---|---|
| Scenario/Receptor | Median | 75th-Percentile |
| Smelter worker/slag worker[a] | 14 | 80 |
| Product end-use/general public[b] | 0.02 | 0.1 |
| Product end-use/industry worker[c] | 0.03 | 0.2 |
| Smelter emissions/general public | $4 \times 10^{-4}$ | $2 \times 10^{-3}$ |

[a] Doses are presented for the constraining worker scenario (i.e., slag worker) for a 2,000-hour exposure time.

[b] Doses are presented for reuse of the recycled steel into an automobile or reuse of slag into construction of a parking lot.

c Doses are presented for a petroleum-industry worker installing piping made out of recycled steel.