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Analysis of the Application of Decontamination Technologies to Radioactive Metal Waste Minimization Using Expert Systems

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1. INTRODUCTION

Radioactive waste resulting from power generation, defense, research, and industrial activities requires disposal which comes increasingly at a significant cost. Most of this waste can be divided into three categories: high-level waste (HLW), transuranic (TRU) waste, and low-level waste (LLW). HLW is generated by the reprocessing of spent reactor fuel and irradiated targets. TRU waste refers to waste materials containing greater than 100 nCi/g of elements with atomic numbers greater than 92 and half-lives greater than 20 years. This waste is the result of reprocessing plutonium-bearing fuel and fabricating nuclear weapons. LLW, defined as a radioactive waste not classified as HLW, TRU waste, spent nuclear fuel, or by-product material specified as uranium or thorium tailings and waste, makes up the greatest portion of radioactive waste. Approximately 85 percent of the volume of all categories of radioactive waste generated in the U.S. is LLW (Oak Ridge National Laboratory, 1991; Office of Technology Assessment, 1989). Of this LLW, a significant amount is metal waste that is potentially recoverable. Reuse or recycle of this metal could reduce the amount of radioactive waste sent to disposal sites. By minimizing the quantity of radioactive waste being sent for burial, radioactive waste disposal costs and risks to public and environmental health could be reduced and the lives of existing and future waste disposal sites could be extended.

The major objective of waste minimization is to reduce the amount of waste, the hazard of the waste, or the difficulty of managing the waste. For hazardous waste in the United States, waste minimization is a policy specifically mandated by Congress in the 1984 Hazardous and Solid Waste Amendments to the Resource Conservation and Recovery Act (RCRA). This policy, together with other RCRA provision, has resulted in unprecedented cost increases in the management of hazardous wastes and has heightened general interest in waste minimization.

Although waste minimization is not required for radioactive waste by the Nuclear Regulatory Commission (NRC), waste minimization techniques, which eliminate waste from being generated, and treatment techniques, which reduce the volume of wastes once they are generated, are encouraged. The driving force behind the volume reduction of LLW, the largest volume of radioactive waste in all categories, has been the Low-Level Radioactive Waste Policy Act (LLRWPA) of 1980 and its Amendments (LLRWPAA) in 1985. The 250 percent increase in LLW disposal costs over the last decade, due to costs associated with new disposal regulations and disposal surcharges established in the LLRWPAA, prompted the reduction, by 55 percent, of commercial LLW shipped for disposal between 1980 and 1988 (Office of Technology Assessment, 1989).

The cost-effectiveness of recycling scrap metal will depend on the demand for scrap, price for scrap, decontamination costs, and waste disposal costs. If costs for LLW disposal continue to rise as they have over the last 20 years, it will be increasingly economical to decontaminate, for reuse or recycle, metal components generated from both the operations and the decommissioning of nuclear facilities.

To recover radioactive metal waste, effective decontamination methods must be employed. There are currently a number of such technologies both in use and under development. These technologies offer potential recovery of metal waste depending upon various contamination and substrate characteristics of the waste. These variables affect the applicability of a decontamination technology to a waste, its technical feasibility, cost, and effectiveness.

The complex problem of bringing together knowledge of decontamination technologies with regulations and cost information to determine appropriate and effective management strategies for a given metal waste lends itself to the use of expert systems. Through the application of expert systems techniques, a comparison can be made between several decontamination technologies along with simply disposing of the waste, given the regulations for unrestricted release of decontaminated materials and for re-classification of the waste.

The structure of expert systems makes it an effective means of analyzing radioactive metal waste management strategies. An expert system consists of a knowledge base containing information about a specific problem, an inference mechanism that performs reasoning by referring to a set of rules for using the knowledge to resolve a given situation, and a user interface that accesses the information in order to produce solutions. The system can offer intelligent advice and justify its line of reasoning in a manner directly understandable to the system user.

Figure 1.1 illustrates the developed knowledge base which contains decontamination technology technical information, waste management regulations, and cost analysis data. The reasoning mechanism furnished by the expert system shell, a development tool, manipulates the knowledge base to provide the user, according to the metal waste characteristics entered, with recommendations for management of the identified waste.

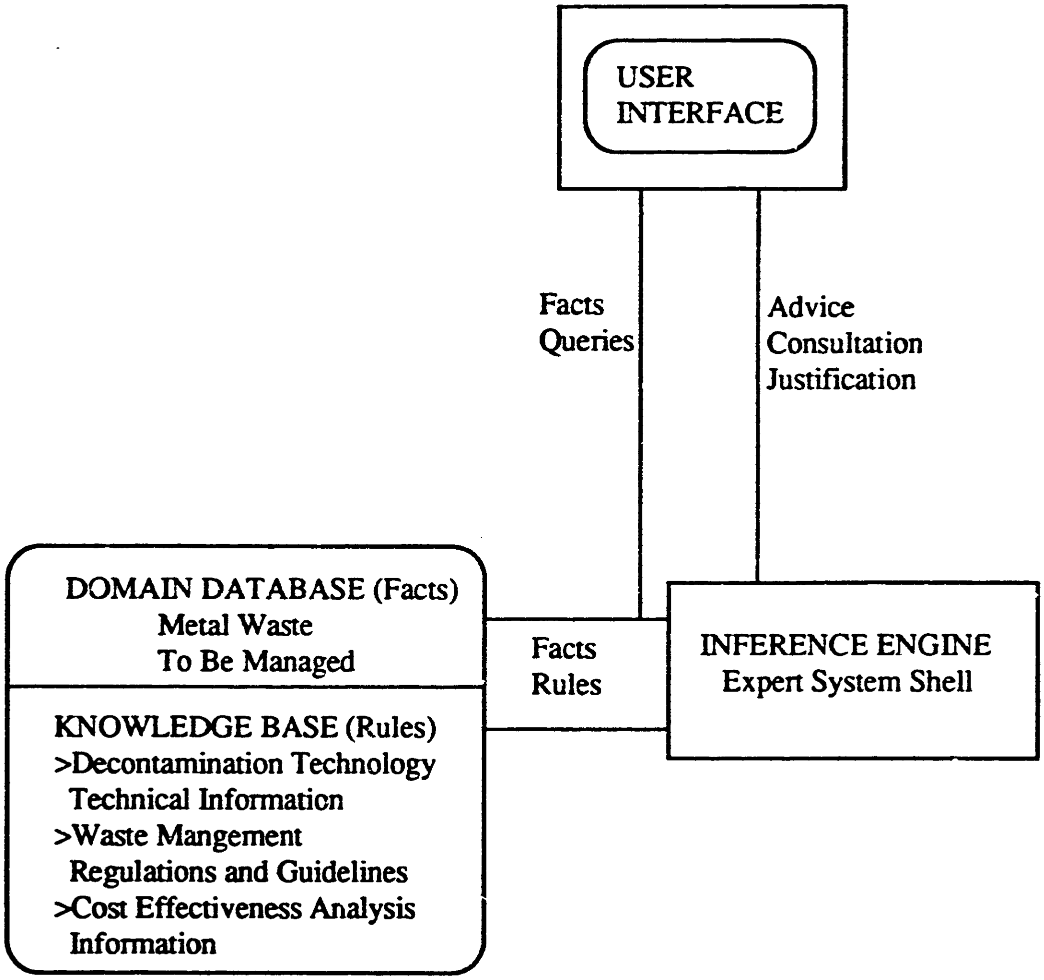

Figure 1.1 Expert system structure

2. OBJECTIVE

A laser technology to decontaminate radioactive metal waste for recycle is under development at Ames Laboratory. It is in the interests of this project to determine the utility and applicability of such a technology to minimizing radioactive waste volumes sent for disposal. Through the development and use of expert systems a comparison of this technology can be made with currently available decontamination technologies for applicability to the types of metal waste being generated and the effectiveness of these versus simply disposing of the waste. Attempts were made to take an inventory of metal waste data from both government and commercial sectors in the U.S. but it was discovered that only very recently was the DOE, on a nationwide scale, beginning to compile this type of data in any sort of detail. Commercial waste generators have also failed to record, in detail, much characterization of the wastes resulting from their activities.

In place of a detailed examination of these wastes, a general inventory of the radioactive metal wastes generated was taken to determine the impact metal decontamination may have on the overall radioactive waste management problem. A subset of the U.S. DOE metal wastes was also analyzed as a case study by the expert system. Personnel from Westinghouse Idaho Nuclear Company (WINCO) at the DOE's Idaho National Engineering Laboratory (INEL) interested in laser decontamination for some of their decommissioning projects provided metal waste characteristic data on these projects for the case study.

The main objectives of the research are itemized as follows:

1. To determine the applicability of laser decontamination and other decontamination technologies to the types of radioactive metal waste being generated and to evaluate laser decontamination against alternative decontamination technologies

2. To develop a tool that, for an identified metal waste; i) provides a comparison of decontamination technologies' technical capabilities, ii) carries out a cost analysis of possible waste management strategies, and iii) makes cost-based waste management recommendations as well as presenting information on qualitative aspects of decontamination technologies (i.e. worker safety) to allow the user to make waste management decisions based on their own criteria. This would be a tool that could be used, in combination with other tools, by a waste manager, to assist in decision-making for the identification of waste management strategies and applicable technologies.

3. To consider the social and economic issues associated with different waste management strategies that cannot be easily quantified to be included in the analysis carried out by the expert system.

4. To determine the impact of metal waste decontamination on radioactive waste minimization.

The broad objective of this research is to determine the applicability of laser and other metal decontamination technologies to minimizing the radioactive metal waste that is being generated by DOE and commercial sectors given the technical, social, regulatory, and economic issues associated with the management of this waste. Given that decontamination technologies are mechanisms for recovery of a valuable resource, an expert system permits an objective evaluation of the potential of these to carry out this task.

3. LITERATURE REVIEW

3.1 Introduction

The knowledge carried by a human being is encoded somewhere in the neural system, the exact location being unknown. Studies have shown that over the last thirty thousand years there has been little change in the memory and mental processing power of individual humans, yet during this time there has been a notable increase in humankind's ability to store and process information (Frost, 1986). Improvements in techniques for the communication of knowledge coupled with the development of methods for the mechanistic processing of knowledge have made these gains possible.

One of these methods, represented by the field of artificial intelligence (AI), involves some exploration into the nature of human intelligence or cognition but more often is an examination of how computers can be used to solve specific problems. Barr and Feigenbaum (1981) indicate that "AI is the part of computer science concerned with intelligent computer systems, that is, systems that exhibit the characteristics we associate with intelligence in human behavior." Rauch-Hindin (1988) gives another definition of AI, stating that "data are represented symbolically. Reason with data symbolically, and, by so doing, solve symbolic, rather than numeric problems."

AI has progressed in a relatively short period of time from an academic discipline to a commercially viable technology, especially in the area of expert systems, also known as knowledge-based systems. Expert systems offers the opportunity to organize human expertise and experience into a form that can be manipulated by a computer. They use the knowledge, facts, and reasoning techniques in a specific subject domain to solve problems that normally require the abilities of human experts. These problem solving systems were initially called "expert systems" to suggest that they functioned as effectively as human experts at their highly specialized tasks.

An expert system program implements a combination of concepts, procedures, and techniques derived from AI research. These techniques allow people to design and develop computer systems that use knowledge and inference techniques to analyze and solve problems. According to Harmon, Maus, and Morrissey (1988) the key ideas from AI being applied in expert systems are: 1) new ways to represent knowledge, 2) heuristic search (rules of thumb), which allows problem solving to take place even with only incomplete information, and 3) the separation of knowledge from inference and control.

An expert system simulates reasoning by applying specific knowledge and inferences. According to Rolston (1988) an ideal expert system can be characterized by the following:

1. extensive specific knowledge from the domain of interest
2. application of search techniques
3. support for heuristic analysis
4. capacity to infer new knowledge from existing knowledge
5. symbolic processing
6. an ability to explain its own reasoning.

Where conventional computer programs tend to carry out calculations (numeric processing), expert systems are more applicable to problems that require a series of judgements (symbolic processing). Given that most of the world's knowledge is non-numeric, expert systems presents itself as an effective means of manipulating this information knowledge for human use.

Expert systems can be developed using AI languages or software development tools. In recent years, as more practical AI tools have become commercially available, their use has increased (Rivera and Ferrada, 1990). Expert system software was developed during the early 1970s and was initially confined to well-defined problem areas. Gradually this software has become more robust and has evolved into domain-independent software that can facilitate the construction of applications. These expert system software development tools are referred to as "shells". Expert systems are currently being used in a wide variety of functional categories including diagnosis and repair, planning, forecasting, design, interpretation, monitoring and control, and instruction.

3.2 Overview of Environmental Expert Systems

Waterman (1986) recently assembled a list of 181 expert system applications, none of which fell into the environmental expert systems category. Reasons for this omission include the fact that environmental expert systems generally require expertise in a number of areas and the rules of thumb for environmental decision-making are not codified. Hushon (1987) describes 21 expert systems for environmental problems listed in Table 3.1. Most of these fall into the interpretation category and none are used for monitoring, instruction, or design. Tasks carried out by these expert systems include:

1. waste site characterization (RPI site assessment system)
2. remediation technology selection (GEOTOX)
3. evaluation of the potential to contaminate groundwater (Toxic waste advisor, DEMOTOX, AQUISYS)
4. environmental permit preparation/generation (Permit Writer's Assistant, RCRA Permit Generator, SEPIC)
5. recommendation of response strategies for environmental emergencies (FRES, CORKES)
6. cleanup cost and scheduling (Work Assignment/Work Plan Generator, SCEES)
7. analytical lab services selection (LABSYS)
8. technology performance prediction (FLEX)
9. operations control (MUMS)
10. river water quality simulation (QUAL2E)
11. runoff and flood model selection (Flood Advisor, EXSRM)
12. recommendations to reduce health and environmental risks at hazardous waste sites (HAWAMAX)
13. hazardous waste incinerator monitoring
14. activated sludge diagnosis in wastewater treatment

Eleven of the 21 systems described by Hushon were either still under development or had yet to be validated by comparison of the system's results with those of human experts.

3.3 Review of Waste Management Expert Systems

Other environmental expert systems, more specifically tied to the area of waste management, have also been developed. For hazardous and low-level radioactive wastes,

Table 3.1 Environmental expert systems (Hushon, 1987)

Category	System	Developer
Interpretation	RPI site assessment system	RPI
	GEOTOX	Lehigh
	Toxic waste advisor	Penn/WESTON
	DEMOTOX	Utah State
	Permit Writer's Assistant	Software A&E
	RCRA Permit Generator	CDM
	SEPIC	Intelligent Advisors, Inc.
	AQUISYS	WESTON
	FRES	WESTON
	CORKES	WESTON
Planning	Work Assignment/Work Plan	CDM
	SCEES	CDM
	LABSYS	WESTON
Prediction	FLEX	EPA, Cincinatti
	MUMS	WESTON
	QUAL2E Advisor	EPA, Athens
	Flood Advisor	-------
	EXSPM	DOA/ARSHL
	HAWAMAX	University of Texas
Diagnosis & Repair	Waste Incineration	Kansas State
	Activated Sludge Diagnosis	University of Washington

there is a need to retrieve and make effective use of waste information deposited in databases, text files, graphics files, and other types of computer programs (Ferrada et. al, 1988). Expert systems can help integrate such diverse data with waste management technology expertise to facilitate effective management of these wastes.

3.3.1 Waste processing technology selection

At the Chemical Technology Division of Oak Ridge National Laboratory (ORNL) limited prototype expert system design efforts have been conducted to develop a tool for waste processing technology selection, an important problem in waste management (Rivera and Ferrada, 1990; Ferrada and Osborne-Lee, 1988). The domain of this expert system encompasses treatment processes for low level radioactive waste.

For the waste stream, relevant physical, chemical, and possibly radiological characteristics must be considered, as well as the potential environmental effects. Cost and performance must also be weighed for the treatment processes themselves. In selecting the best among alternative technologies, the expert system considers the user's priorities (e.g. cost vs. efficiency) as well as the guiding advice of the expert. To establish the relative importance of criteria used to make decisions different from the defaults proposed by experts, the user is queried and these entries are compared against criteria weighted by the experts.

The knowledge base prototype was developed using information obtained from several reports on low-level radioactive waste management. It is intended that the final knowledge base will include information derived from several experts in the field.

3.3.2 Waste Minimization Expert System (WMES)

A Waste Minimization Expert System (WMES) prototype has been developed to assist in organizing and coordinating waste minimization programs, carrying out a characterization of all wastes and suggesting a waste minimization plan (Ferrada and Rodgers, 1992). This system is applicable to low-level radioactive liquid waste and hazardous waste and focuses on reducing the generation of waste at the source and treatment of wastes.

The two main areas of waste minimization addressed by the expert system include information and implementation. The information section provides the regulations and scheduling required to minimize waste while the implementation phase characterizes the waste streams and conducts research, development, and process analysis of prioritized streams. WMES has been designed as a waste minimization methodology applicable to waste on any site, but oriented to DOE operations.

3.3.3 Radioactive liquid waste management

Another expert system prototype has been developed at ORNL to support system analysis activities in the area of liquid waste management (Ferrada, 1992). Radioactive liquid waste streams will be prioritized by the expert system by considering the severity and treatability of the problem waste. Waste management strategies include treatment and disposal. Objectives of the system include 1. collecting information on process treatment technologies for liquid low-level waste that can be incorporated in the knowledge base of the expert system and 2. producing a prototype that suggests processes and disposal technologies for the ORNL liquid low-level waste system. The expert system involves three general procedures: waste identification, a matching procedure to determine, according to waste acceptance criteria, the fate of the identified waste (either the Process Waste Treatment Plant (PWTP) or the Liquid Low-Level Waste System (LLLW)), and a technical evaluation that provides information about waste production and the characteristics and acceptance criteria for the final waste form.

3.3.4 Decontamination and decommissioning expert systems

BALADIN is an expert system used in the analysis, management, and modeling of all the steps of the dismantling of a nuclear facility which includes the decontamination and management of both radioactive and non-radioactive wastes (Lorin, 1992). This system specifies, from its knowledge bases (cutting up, decontamination, and waste management), the techniques to be used, operations and scheduling, the scenario best suited for the intended facility, and the planning and cost of the work. User input must include a characterization (geometric and radioactive) of part or all of a nuclear facility intended for decommissioning and a listing of available resources (i.e. cutting equipment, decontamination techniques and equipment, and waste management and measurement apparatus) or those which can be added for use in the dismantling project operations. Given the user entries, the expert system generates a list of one or more applicable dismantling scenarios for the dismantling project, a sequence of operations, operations planning, cost of operations to be carried out, and the total dismantling cost. Each scenario is analyzed by the system to generate a recommendation of the one that results in minimum worker exposure, minimum cost, and can be carried out in an acceptable amount of time.

3.4 Conclusion

Although this review covered twenty-five expert systems employed in the environmental field, few of them are applied to waste management problems and fewer still deal with radioactive waste. The WMES, although concerned with waste minimization, focused on hazardous and low-level liquid radioactive waste. Of the four waste management expert systems surveyed, only the waste processing technology selection system and BALADIN could be considered applicable to radioactive metal waste. However, the domain of the technology selection system spans only LLW. Technologies and regulations governing the recovery or re-classification of TRU metal waste to LLW are not considered. Also, there is no analysis carried out by the system that determines the cost-effectiveness of different waste management strategies.

BALADIN encompasses a broad range of tasks associated with decontamination and decommissioning of nuclear facilities. This is the most comprehensive of the radioactive waste management expert systems in that all phases of decommissioning, from dismantling to decontamination to waste management, are analyzed. All waste types generated from decommissioning are handled by the system and a cost analysis of the entire process is performed. Although this system could be used to handle all classes of radioactive waste, the main purpose of it is to recommend, plan, and schedule a decommissioning strategy for a given facility.

From review of the literature, it is clear that a gap exists in the development of expert systems that could be filled by the proposed study. Determination of the applicability of decontamination technologies to radioactive metal waste and the impact these technologies could have on the overall radioactive waste management problem have not been taken up by previous expert systems research.

4. EXPERT SYSTEM

4.1 Introduction

The goal of the expert system is to evaluate the waste management possibilities, including decontamination and disposal, for radioactive metal waste generated by government and commercial activities. Development of this expert system involved bringing knowledge together from diverse subject domains. Characteristics and quantities of radioactive metal wastes that are being generated and stored, decontamination technology technical information, regulations for the management of waste materials, and costing of decontamination and disposal are all required for the system to generate useful radioactive metal waste management recommendations. The system also required software on which to develop the knowledge base and on which to compile and store data generated and manipulated by the program.

The expert system was created using, VP-Expert, a commercial expert system development tool, and dBASE III+, database software which interacts with VP-Expert. The only two options for such database software were dBASE and VP-Info, VP-Expert's own database software. dBASE was chosen over the alternative due to its more widespread use.

4.2 Selection Procedure For the Expert Systems Software

Final selection of the platform for the expert system involved two tiers of decision-making. First, the use of an AI programming language was considered against the employment of a development tool such as an expert system shell and, second, the selection of a commercial shell was carried out, given that this tool was chosen over the use of a programming language.

4.2.1 Shells versus AI programming languages

The two most common methods of expert system include: 1) programming languages and 2) expert system shells. Each approach was assessed for its potential effectiveness in supporting development of an expert system application for the evaluation of radioactive metallic waste management options. Of the programming languages, OPS5 was considered, first, due to its availability on VAX at Iowa State University (ISU) and, second, due to the writer's familiarity with it. OPS5 is also the language of preference in the expert systems course offered in the computer science department at ISU and access was therefore available to some technical support on campus. OPS5 allows the programmer more control over the structure and execution of the software than shells without requiring the time-consuming programming and testing efforts involved in developing applications in lower level languages such as LISP or PROLOG (Raz, 1988).

Although a programming language such as OPS5 provides greater control and flexibility of the expert system in addressing specific aspects of a problem, the time required to master the power, control, and added features of such a language was found to be excessive in relation to the scope of the project.

A significant advantage expert system shells have over traditional programming languages is that there are major portions of the code that do not require development. The shell provides a substantial amount of AI programming code including the user interface, the control strategy, and an inference engine for reasoning that has been tested, debugged, and maintained. Shells also provide several features including editors, utilities for allowing users to ask "how" or "why", and various other natural language components difficult to develop from scratch that prove valuable during the early stages of prototyping. A shell is able to load and consult different knowledge bases and apply the same rules of inference to solve a variety of problems. Most importantly, a shell allows the developer to focus on the capture of the knowledge of the application.

For the intended purpose, use of a shell resulted in a shorter development time without a loss of features. The advantages of using an expert system shell appeared to outweigh any benefits of expert system development through the use of a programming language. An expert system shell was, therefore, the chosen platform for system development.

4.2.2 Selection of an expert system shell

Having selected the shell format over the OPS5 programming language, a general review of commercially available shells was conducted. Inductive, rule-based, and hybrid tools are the three main types of shell currently available. Inductive tools were derived from experiments conducted in machine learning. These tools generate rules from examples and are useful for simple tasks but cannot be used to develop complex knowledge representations. Rule-based tools are of two types: simple and structured. Simple rule-based tools use if-then rules to represent knowledge and are effective for systems containing fewer than 500 rules. Structured rule-based tools use if-then rules arranged into sets and are most useful for a large number of rules that can be subdivided into sets. An example of a typical if-then rule is as follows: IF Felix is a cat and all cats have fur THEN Felix has fur. Hybrid tools are the most complex expert system development environment. These tools make use of object-oriented programming to represent elements of each problem as objects. An object, in turn, can contain facts, if-then rules, or pointers to other objects.

Expert system shells in the rule-based category were selected for further examination. The proposed system design was expected to be easily adapted to the shell's rule-based representation of knowledge. Compared with other representation approaches, a rule-based (if-then structure) approach generally allows a clearer understanding of the knowledge base.

Information was collected and various features of the shells were compared (including cost). Personnel at Ames Laboratory, experienced in developing expert system through the use of shells, were consulted for further recommendations (Imani, 1992; Helland, 1992). A suggested approach involved the creation of a prototype program on one of the expert system shells available at Ames Laboratory (VP-Expert or CLIPS). Through development of a prototype program, the features relevant to this particular expert systems application might be more readily determined. Upon establishing the necessary features, an appropriate final shell could then be chosen more effectively. Development of the expert system, therefore, began on VP-Expert, which was found to be an adequate platform for the intended application. Although, VP-Expert did have some minor limitations, the product was found to be well-suited to the purpose for which it was employed. From a literature evaluation of many PC-based expert system shells, VP-Expert was also found to be one of the best tools available for the PC and the most cost-effective (Harmon, 1990; Harmon et al., 1988; IEEE Expert, 1987).

4.3 Expert Systems Development Procedure

The methodology used to build expert systems involves a number of stages. Identification and definition of the problem is a critical initial step. Development of the system is the next major task and includes the following sub-tasks: 1) knowledge acquisition and domain familiarity and 2) creation of an initial implementation.

4.3.1 Task analysis

The scope of the problem is the management of radioactive metal waste given certain decontamination technologies for waste minimization, waste management regulations, and costs. The program input and the desired output were initially specified by the definition of the project as was the analysis to be performed by the system. Metal waste characteristics are entered by the user to be analyzed by the system. The expert system output provides the user with a list of recommended decontamination technologies applicable to the specified waste as well as possible waste management strategies and a cost-analysis of these strategies (see Figure 4.1). Ideally, the expert system should be capable of choosing between several decontamination processes applicable to a given radioactive metal waste and evaluating the costs associated with decontamination versus the cost of simply disposing of the waste.

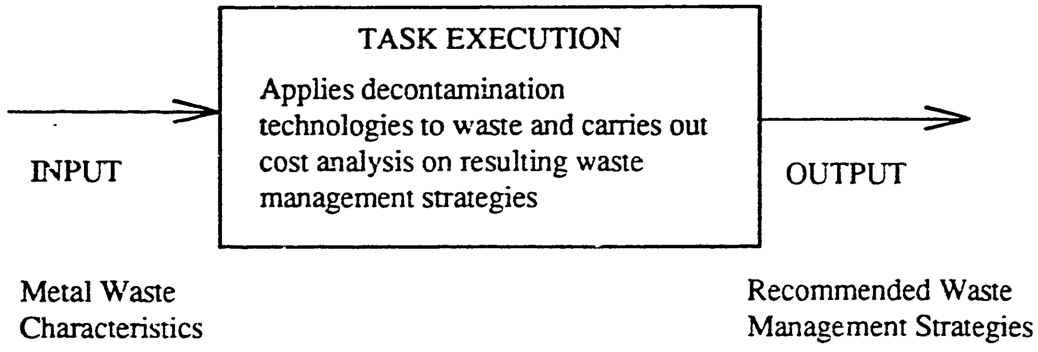

Figure 4.1 Expert system task analysis

Although the recommendations generated are cost-based, providing a ranking of the waste management strategies according to cost-effectiveness, the expert system also furnishes qualitative information on attributes associated with the technologies so that the user can make decisions based on their own priorities.

Problem definition helps give an idea of the design framework, taking into account the probable user community and suitable knowledge representation schemes. The intended users of the system are 1) waste managers who require assistance in decision-making for the identification of waste management strategies and applicable decontamination technologies, 2) technologists who are looking to develop new technologies in any area of waste management, 3) regulators who can use the system to assess the impact of regulatory change on waste management, and 4) interested members of the public who want insights into waste management options available and those chosen by waste generators.

Suitable representation of the knowledge must also be carried out. It was expected that the knowledge could be represented as an ordered set of logical clauses and that more complex structures, such as frames, objects, inheritance hierarchies, or semantic networks were not needed. A rule-based approach was determined to be compatible with this knowledge representation scheme.

4.3.2 System development

After the task was outlined, the actual development of the expert system began. At this stage the "expert" knowledge (facts, relationships, and reasoning strategies) was to be encoded. Development of the prototype system involved the following tasks:

1. Learning more about the domain and task
2. Developing an initial implementation

4.3.2.1 Learning about the domain

Having identified the scope of the problem, the knowledge of the domain of interest must be encoded. Becoming familiar with the radioactive metal waste management domain involved extensive review of the relevant literature and contact with knowledgeable personnel. The knowledge base was then developed using information derived from published reports and conversations with experienced personnel on radioactive waste management, regulations, decontamination technologies, and cost estimating. The knowledge acquisition process involved five main tasks:

1. Waste characteristic data specification
2. Selection of technologies to be evaluated
3. Detailed review of decontamination technologies
4. Determination of applicable regulations
5. Cost analysis data collection

Waste characteristic data specification To determine the specifications for the input data to be analyzed by the system, several aspects of the domain were examined. Included in this study was a technical feasibility assessment of decontamination technologies, an initial review of applicable regulations, a determination of the required cost-related data, and a survey of the existing characterization of metal waste from government and commercial generators.

Waste characteristic data serve to distinguish the applicability of one decontamination technology from another. Surface materials, decontamination situation (in/

ex-situ), contamination type, waste class, and metal type and source are all important considerations. The following characteristics were selected for use with the knowledge base to recommend certain technologies for application to a waste and disqualify others:

1. surface contamination
2. loose contamination
3. smearable contamination
4. fixed contamination
5. oxides or corrosion layers
6. paint, grease, or oils
7. embedded material
8. metal source type
9. in-situ decontamination requirements

Waste character data entries are also used to establish waste management strategies and should therefore match some format requirements of the regulations and guidelines set forth for radioactive metal waste management. Radionuclide type and contamination level are the key attributes of concern in this area for both bulk and surface-contaminated waste materials. For surface-contaminated materials, the average, fixed, and smearable contamination are used and for bulk-contaminated waste, the activity per unit mass is the measure of the extent of contamination.

To produce waste management recommendations, some cost-related data is required of the user. To calculate the costs of decontamination and disposal, volumes, masses, and metal types are required attributes.

A compromise was also reached between the requisite input data described above and the metal waste character data that were available or reasonably obtainable. Review of the radioactive metal waste data from DOE and commercial generators and the data provided by WINCO helped establish the overlap of the level of detail in the characterization of documented metal waste inventory data with the minimum data needed to carry out the pre-defined analysis using the expert system.

The final listing of attributes chosen to characterize the data for use by the expert system is divided into two categories as follows:

surface materials:

- embedded material
- oxides
- paint, grease, or oil
- metal source
- metal type
- metal volume
- metal mass
- specific area
- number of parts

contamination:

- waste class
- contamination depth
- loose contamination
- radionuclide
- average surface contamination
- fixed surface contamination
- smearable surface contamination
- bulk contamination

Selection of the technologies to be evaluated Establishing the set of decontamination technologies to be evaluated by the system was the next phase of the knowledge acquisition process. The most important criteria were the applicability to metal materials and the availability of pertinent literature. Since development of the expert system was going to depend mostly on the literature, selection of the technologies was based on availability and suitability of information on these technologies for the purpose of knowledge acquisition of the expert system.

Most of the information compiled from literature and personal contacts focused on approximately ten technologies used for metal waste decontamination. The final list used in the system included:

1. abrasive jetting
2. carbon dioxide pellet decontamination
3. chemical decontamination
4. electrochemical decontamination
5. freon cleaning
6. high pressure water
7. laser decontamination

8. melting
9. ultra high pressure water
10. vibratory finishing

Some modifications were made from the original list to create the final list of ten. These included narrowing the broad area of chemical decontamination down to acid chemical decontamination and listing high pressure water decontamination as two separate technologies.

Because it is more effective, having a shorter process time and generating less secondary waste, acid chemical decontamination was more competitive with the other technologies being considered than non-acid chemical decontamination. However, it should be noted that acid chemical decontamination is still, itself, a category encompassing a wide range of chemical solutions.

High pressure water decontamination was divided into high pressure water and ultra high pressure water due to the fact that ultra high pressure water demonstrates a different set of attributes than high pressure water. The dividing line between the two is around 20,000 psi of pressure (HPW<20000 psi and UHPW>20000 psi).

Two basic groups evolved from the list of technologies, those that were suited for surface decontamination (all of the technologies) and those suited to bulk decontamination techniques (melting and laser decontamination). This list can be expanded to include technologies currently in development and those that are not currently evaluated by the expert system.

Detailed review of decontamination technologies Once the list of decontamination technologies had been finalized, a more detailed study of each technology's features was conducted. Technical applicability to different waste types, advantages and limitations, and the levels of decontamination achievable were all examined to determine the effectiveness of a technology under different conditions. A detailed discussion of decontamination technologies contained in the knowledge base is found in Chapter 5.

Determination of applicable regulations To establish the possibility of reuse, recycle, or reclassification of a given waste, a familiarity with the regulations was required. The regulations for unrestricted release of surface-contaminated materials, as given by the U.S. Atomic Energy Commission in Regulatory Guide 1.86 (U.S. Atomic Energy Commission, 1974) and U.S. DOE Order 5480.11 (U.S. Department of Energy, 1988), are shown in Table 4.1. These are a function of radionuclide type and residual fixed, smearable, and average contamination measured in disintegrations per minute (dpm) per 100 cm^2. These regulations were widely quoted in the literature and by personnel in the DOE involved in recycling and decontamination efforts (International Atomic Energy Agency, 1988b; Kesinger, 1993; Thomson, 1993; Adams, 1989; Health Physics Society, 1986; McVey et. al., 1981; Oak Ridge National Laboratory, 1991). The application of the expert system to the waste management of surface-contaminated metal was determined, in part, by these regulations, which were entered into the knowledge base.

Currently, in the U.S., no regulations exist for the release of bulk-contaminated materials for unrestricted reuse. There are, however, ongoing efforts to establish a de minimis limit as concern mounts about the large volume of future wastes and the increasing costs of disposal. Scientific rationality also plays its part in support for these regulations. It is argued that if this waste can be decontaminated to, at least, natural background radiation levels it should be permitted to be recycled, if not for general use, then within the nuclear industry. As a result of these efforts, some guidelines have been proposed that suggest bulk contamination levels that might be used to release materials for reuse (International Atomic Energy Agency, 1988b; Kennedy, 1987; Kennedy et. al, 1988) These guidelines along with release regulations that exist in Europe (International Atomic Energy Agency, 1988b; Hock et. al, 1988) for bulk-contaminated materials were used as references to create rules in the knowledge base to determine possible waste management strategies for a given waste.

Cost analysis data collection The final stage of knowledge acquisition involved the compilation of cost information for the decontamination processes and for land disposal

Table 4.1 Regulations for release for unrestricted use of surface-contaminated materials (U.S. Atomic Energy Commission, 1974)

	ACCEPTABLE SURFACE CONTAMINATION LEVELS		
NUCLIDE[a]	AVERAGE[b c]	MAXIMUM[b d]	REMOVABLE[b e]
U-natural, U-235, U-238, and associated decay products	5000 dpm α/100 cm^2	15000 dpm α/100 cm^2	1000 dpm α/100cm^2
Transuranics, Ra-226, Ra-228, Th-230, Th-228, Pa-231, Ac-227, I-125, I-129	100 dpm/100 cm^2	300 dpm/100 cm^2	20 dpm/100 cm^2
Th-natural, Th-232, Sr-90, Ra-223, Ra-224, U-232, I-126, I-131, I-133	1000 dpm/100 cm^2	3000 dpm/100 cm^2	200 dpm/100 cm^2
Beta-gamma emitters (nuclides with decay modes other than alpha emission or spontaneous fission) except Sr-90 and others note above.	5000 dpm β-γ/100 cm^2	15000 dpm β-γ/100 cm^2	1000 dpmβ-γ/100cm^2

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[a] Where surface contamination by both alpha- and beta-gamma-emitting nuclides exists, the limits established for alpha- and beta-gamma-emitting nuclides should apply independently.

[b] As used in this table, dpm (disintegrations per minute) means the rate of emission by radioactive material as determined by correcting the counts per minute observed by an appropriate detector for background, efficiency, and geometric factors associated with the instrumentation.

[c] Measurements of average contaminant should not be averaged over more than 1 square meter. For objects of less surface area, the average should be derived for each such object.

[d] The maximum contamination level applies to an area of not more than 100 cm^2.

[e] The amount of removable radioactive material per 100 cm2 of surface area should be determined by wiping that area with dry filter or soft absorbent paper, applying moderate pressure, and assessing the amount of radioactive material on the wipe with an appropriate instrument of known efficiency. When removable contamination on objects of less surface area is determined, the pertinent levels should be reduced proportionally and the entire surface should be wiped.

of the waste. Cost data was divided into two categories: general costs and costs specific to each decontamination technology. General cost components include labor cost, waste packaging, transportation, and disposal costs, salvage value, and contingency. Cost-related information specific to decontamination technologies include process times, secondary waste volumes, and capital and operating costs.

Summary Building the knowledge base consisted of recording the expert problem solving knowledge about the chosen domain in terms of domain facts, domain relationships, and knowledge about how to combine the facts and relationships to solve the problems.

4.3.2.2 Developing an initial implementation

Developing the expert system required:

1. Capture of the domain knowledge in the expert system
2. Expert system refinement and structure modification
3. Development of the User Interface

The development of an expert system is an iterative process and the final product is a result of moving through one stage of development to another and then back again. Refinement of the knowledge base and associated interfaces (the database, external files, and the user) is also continuous. Since development of an expert system must allow for iteration, detailed specification can not precede system building.

Capture of the domain knowledge in the expert system The initial programming of the expert system involved capturing the basic knowledge of the domain. As part of this process, the structure of the dialogue between the user and the system was established and the desired overall system design attributes were incorporated.

Interface between the user and the system takes two forms. For entry of the metal waste characteristics, data can be read from a dBASE datafile or entered directly from the keyboard by the user as prompted by the program. Keyboard-entered data is then automatically saved in a dBASE datafile for future reference by the user.

In design of the overall system, attempts were made to create a model that was as flexible as possible. This was done to facilitate modification of the system and to allow for the possibility of extending use of the system to other issues in waste management. Flexibility was incorporated by extensive use of dBASE files, database rules, and through the use of ASCII text files. dBASE files were used both to house knowledge manipulated by rules in the program as well as to store results generated during a consultation. Database rules were employed to consolidate several similar rules. In developing the expert system, many rules used to select decontamination technologies for a given waste shared a similar attribute structure. These rules were replaced by a single general rule (database rule) that accessed database records to retrieve different sets of values. Using Table 4.2 as data, the following generalized rule can be employed in place of several similar rules to locate technologies applicable to the user-entered waste characteristics:

```
GET decontamination technologies for which
    user-entered value for surface_contam_only=table value AND
    user-entered value for embedded_contamination=table value AND
    user-entered value for fixed_contamination=table value AND
    user-entered value for oxides=table value AND
    user-entered value for paint_or_oils=table value AND
    user-entered value for in-situ_decontamination=table value AND
    user-entered value for metal_source_type=table value
```

Allowing rules to be derived from the database in this way streamlines the program and makes it run more effectively. ASCII text files were also used to provide a "paper trail" of references for the knowledge that was encoded as rules.

Expert system refinement and structure modification Refinement of the expert system to make the system run more smoothly was carried out by manipulating the structure of the expert system program and by using appropriate control strategies for "reasoning" with the encoded knowledge.

A modular approach to design of the expert system's structure was taken to reduce run-time, expedite debugging and modification, and facilitate comprehension of how the

Table 4.2 Decontamination technology matrix used with database rules in the expert system to determine applicable technologies

	Surface Contam Only	Embedded Contam	Fixed Contam	Oxides	Paint or Oils	In-Situ Decon	Metal Source Type
Abrasive Jetting	YES	YES	HEAVY	YES	YES	YES	pipes, ducts, tanks, sheet metal, equipment
CO2 Pellet Decontamination	YES	NO	LIGHT	YES	YES	YES	pipes, ducts, tanks, sheet metal, elec equip, tools
Acid Chemical Decontamination	YES	YES	HEAVY	YES	YES	YES	pipes, ducts, tanks, sheet metal, equipment, tools
Electrochemical Decontamination	YES	YES	HEAVY	YES	NO	YES	tanks, sheet metal, tools, elec equip
Freon Cleaning	YES	NO	LIGHT	NO	YES	YES	pipes, ducts, tanks, sheet metal, equipment
High Pressure Water	YES	YES	NONE	YES	YES	YES	pipes, ducts, tanks, sheet metal, equipment
Laser Decontamination	NO	YES	HEAVY	YES	YES	YES	pipes, ducts, tanks, sheet metal,
Melting	NO	YES	HEAVY	YES	YES	NO	pipes, ducts, tanks, sheet metal, equipment, tools
Ultra-High Pressure Water	YES	YES	HEAVY	YES	YES	YES	pipes, ducts, tanks, sheet metal, equipment
Vibratory Finishing	YES	YES	NONE	YES	YES	NO	pipes, ducts, tanks, sheet metal, tools

knowledge is represented by the program. Seven linked modules make up the system with each module functioning like an individual knowledge base. System modules:

1. Determine applicable decontamination technologies
2. Present the user with advantages and limitations of each applicable technology
3. Further evaluate the technical feasibility of the applicable technologies according to waste character details
4. Calculate the decontamination achievable for each applicable technology
5. Determine possible waste management strategies according to regulations and guidelines
6. Perform cost analyses on possible waste management strategies
7. Provide a ranked list of waste management strategies for the identified waste

The control strategy used by the inference engine of the rule-based expert system determines the rules in the knowledge base that are to be executed and in what are order they are to be executed. This is the "reasoning" mechanism of the system that uses logical manipulation of the “if-then” rules to reach a conclusion.

In an expert system prototype there are two major issues of control. These are the related goals of reaching accurate conclusions and asking reasonable questions that aid in the interpretation. The two principal types of control that exist are forward chaining and backward chaining. Usually goal-directed control is used in conjunction with backward chaining while data-driven questioning is used with forward chaining.

Forward chaining, also known as data-driven control, is a control strategy that begins without assumptions and follows where the evidence leads. When a finding is discovered, the program goals are then expanded to those that are potentially supported by the evidence. Figure 4.2 illustrates this concept.

Backward chaining, or goal-directed control, focuses on a set of hypotheses and asks questions related to that set of hypotheses. Figure 4.3 serves to demonstrate this method of control.

Like most small expert system building tools, VP-Expert, contains a built-in backward chaining inference engine. The rule programming of VP-Expert, however,

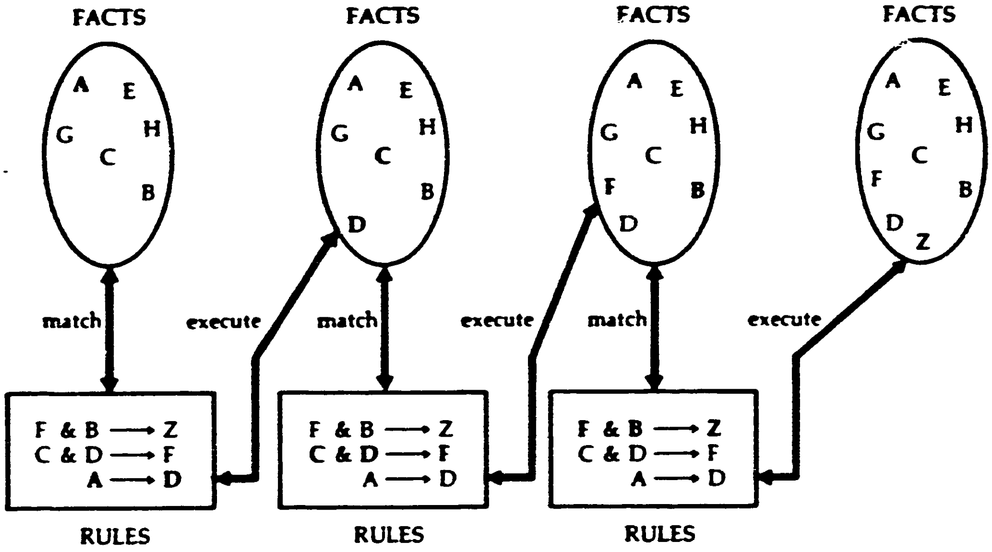

Figure 4.2 An example of forward chaining (Waterman, 1986).

allows forced forward chaining in certain situations. This built-in inference strategy is usually sufficient for most smaller applications, however, to expand the control strategy and system, techniques such as rule ordering can be used.

VP-Expert, like most inexpensive shells, lacks a rule priority system. Instead the inference engine begins with the first rule in the knowledge base and works down trying the first rule it comes across. By ordering the rules in the knowledge base, a certain amount of control can be exerted over the way a consultation will run. Modularity of the system as discussed before is also a means of ordering the rules so that the system runs with increased efficiency because only rules in a certain section of the entire system are searched.

Backward chaining involves gathering data throughout the expert system consultation whereas forward chaining reviews input data, analyzes the material, and then makes recommendations. The basic function of the metal waste management expert system is to analyze the characteristics of metal wastes input by a user and produce a recommendation for the treatment of that waste. This would tend to imply the use of

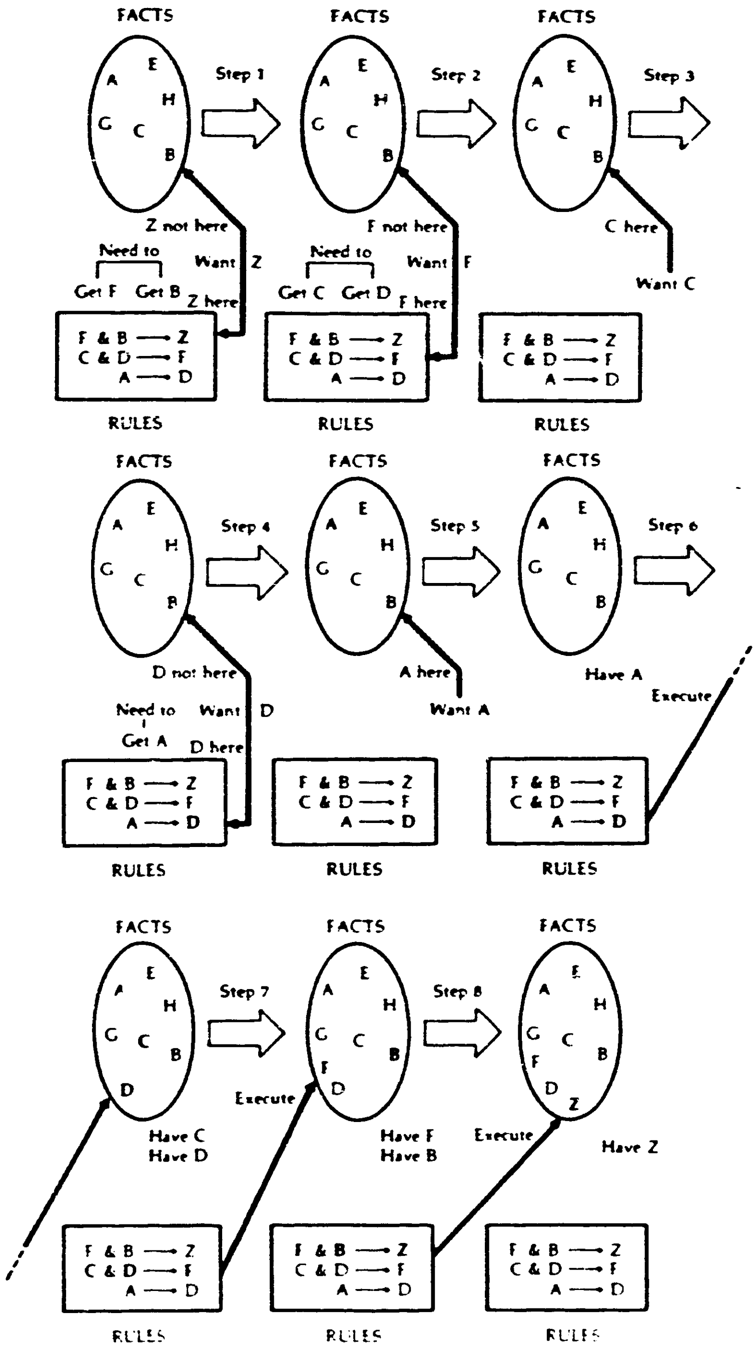

Figure 4.3 An example of backward chaining (Waterman, 1986)

forward chaining. However, given that a dialogue is carried out between the system and user, especially in the initial modules, to determine waste characteristics and additional details given those characteristics, use of backward chaining might also be implied. A combination of backward and forward chaining techniques are, therefore, applied for control of reasoning in the system.

Development of the user interface Development of the interface involves assuring that the system works as designed for the end users. Demonstration of the in-progress expert system to personnel at ISU, Ames Laboratory, and WINCO provided feedback on the user-interface and other features of the program. Suggestions that were implemented to improve the system are itemized below.

1. Allowing the user to request the reason(s) for disqualification of a decontamination technology in the initial expert system module
2. Allowing the user to move back and forth between screens especially for the user displays of the advantages and limitations of the decontamination technologies
3. Displaying post-decontamination contamination levels to the screen for user review
4. Provision of an on-line flow chart of the entire expert system
5. Allowing request for a "paper trail" of references that establish the source of information leading to a given decision made by the expert system
6. Create a programming feature to accept dimensions and metal type of waste to calculate mass, volume, and specific area
7. Allow the user to enter a reasonable cost value (i.e. for disposal). This can be used to help analyze the effects of future increases or decreases in some cost components (discount rate, contingency, package, transport, disposal)
8. Display advantages and limitation for decontamination technologies at the end of the program along with cost analysis of the waste management strategies
9. Allow the user to generate a printed report of various results that the program has generated during a consultation
10. Allow the user to view and compare the values, for a given attribute, for each applicable decontamination technology.

The resulting expert system includes modules related to decontamination technology applicability, decontamination technical features (strengths and weaknesses), regulations, and cost estimation. This expert system program can combine database files of information about waste stream characteristics and treatment technologies with expert knowledge about treatment selection and cost estimation calculations into one application. A more detailed description of the functioning of the system is provided in the next section.

4.4 Overview of Final Expert System Function

The expert system is divided into a series of modules related to each of the subject domains of analysis carried out to generate the desired output (see Figure 4.4). The first module shown in the flow chart in Figure 4.4 generates a list of decontamination technologies applicable to a given waste based on general criteria (contamination characteristics, surface materials, etc.). The user may enter waste characteristics directly from keyboard or have them read from a datafile. Keyboard-entered data is saved to a datafile for future reference. The waste data record is assigned a unique identification number to distinguish it from other waste records and to facilitate future reference of the information. The criteria used to determine applicability of the decontamination technologies to the waste include whether they are surface or bulk-contaminated, whether in-situ decontamination is required, the source of the metal (pipes, tools, etc.) and the presence of loose contamination, fixed contamination, paints, oils, embedded materials, and oxides.

The second module provides the user with information about the advantages and limitations of each applicable decontamination technology generated in the initial module. The attributes that are provided for user consideration include secondary waste volume, the possibility of remote operation, the potential for worker exposure, labor intensity, how easily operators can be trained, the ability to penetrate crevices, the degree of disassembly required, surface damage, and whether pre-treatment is required. Additional details are also available for some technologies.

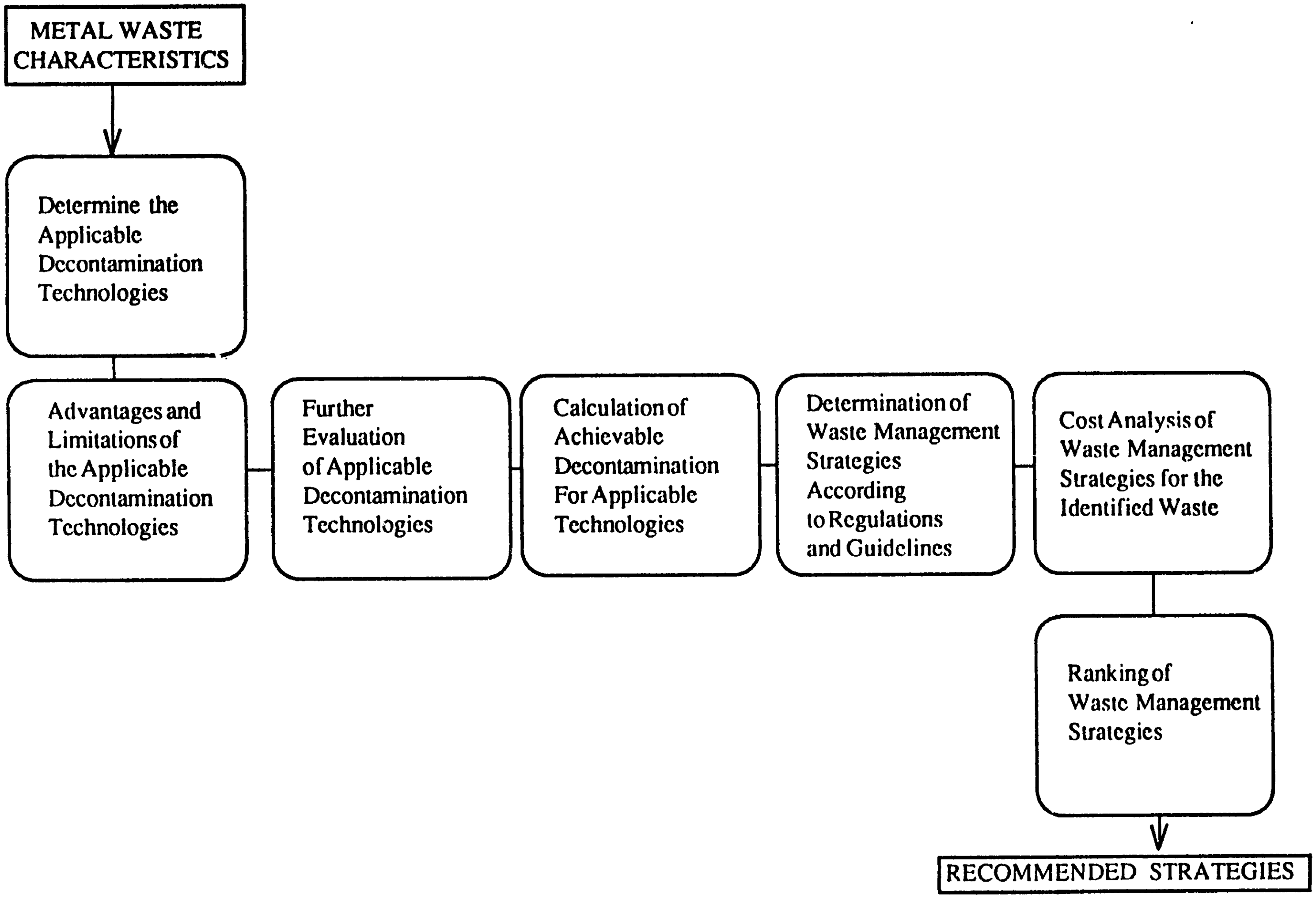

Figure 4.4 Expert system flow chart

The next module carries out a further evaluation of the applicable decontamination technologies based on more specific criteria than were used in the first module. For example, if the metal waste is identified as piping and laser or carbon dioxide pellet decontamination were found to be applicable, the pipe diameter becomes an important characteristic due to the fact that both of these technologies require a minimum inner diameter to carry out decontamination. Evaluation of the technologies has been divided into two modules to restrict the entries required from the user and to save time in carrying out the analysis. This evaluation may result in certain technologies being disqualified based on further examination of the characteristics of the waste.

Calculation of the decontamination achievable for each applicable process, given the characteristics of the waste, takes place in the fourth module of the expert system. Decontamination factors and other decontamination information is used to generate post-decontamination contamination levels of the waste for each technology. These contamination levels are then stored in the database.

In the fifth module possible waste management strategies are determined according to government regulations and guidelines for the given post-decontamination contamination levels of the waste for each applicable decontamination technology. Possible strategies include reuse, recycle, re-classification from TRU to LLW, disposal as TRU waste, and disposal as LLW. The disposal option implies that no decontamination has been carried out. These strategies will be cost analyzed in the next module of the expert system. Further decontamination is also a suggested strategy if release for reuse or recycle is not achieved by a single technology. The same or another decontamination technique can subsequently be applied and analyzed by the system.

The final two modules cost analyze the waste management strategies generated in the previous module for each of the applicable technologies and advise the user. Recommendations, in the form of a ranked list of waste management strategies based on cost-effectiveness, are then provided for the user.

A summary of the interaction of information that takes place in the expert system, involving both the knowledge-base and the database, is illustrated in Figure 4.5. This diagram provides an overview of the inputs and outputs of the system.

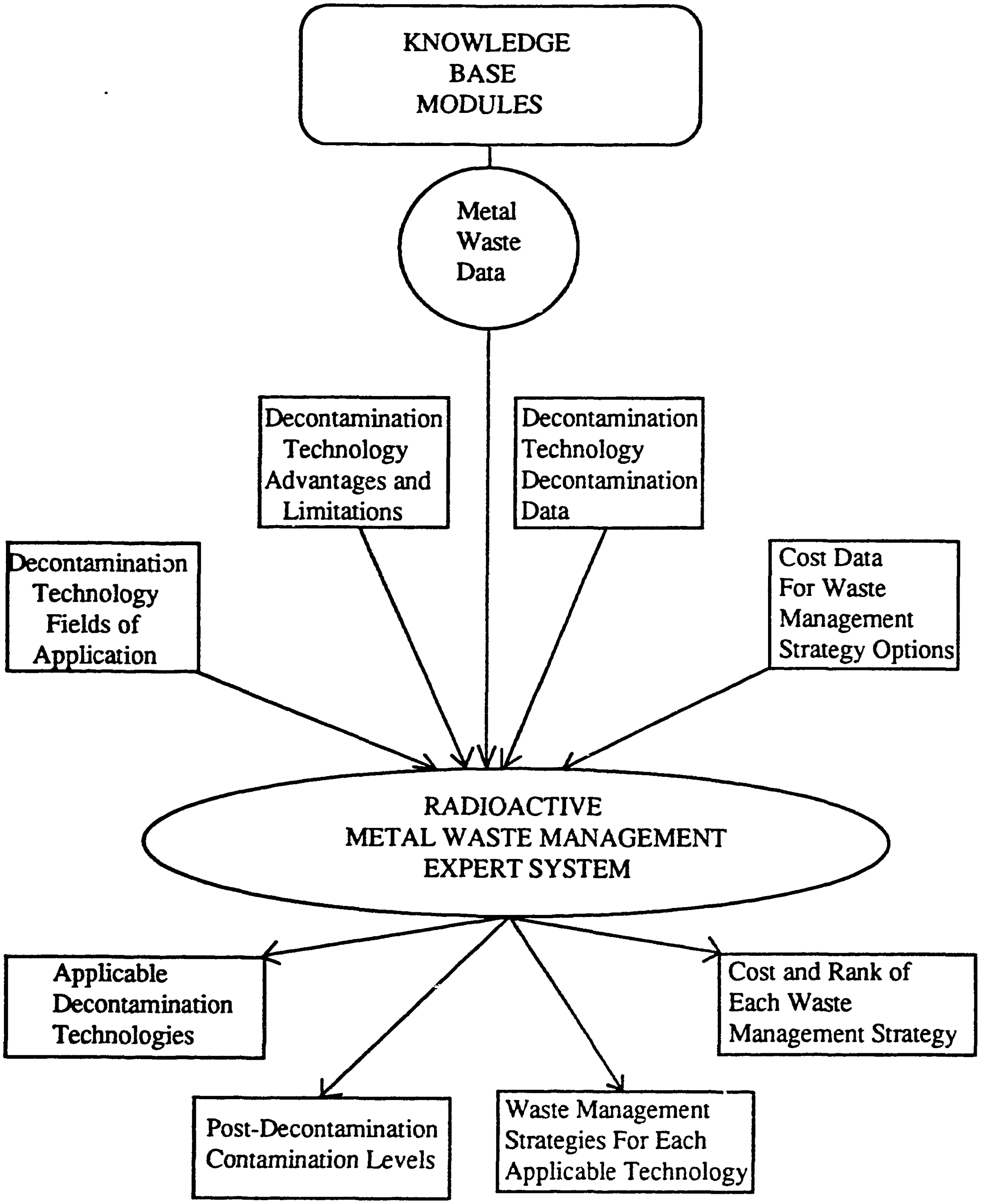

Figure 4.5 Radioactive metal waste management expert system design

5. RADIOACTIVE METAL WASTE DECONTAMINATION TECHNOLOGIES

5.1 Introduction

Decontamination of radioactive metal wastes to the point where they can be reused, recycled, or reclassified to be managed as a less hazardous waste, is technically feasible and is becoming increasingly economically desirable. Several technologies exist for the decontamination of metal waste, some of which are under development or in the demonstration phase, and others, in practical use. To critically determine the most efficient application of decontamination technologies to the minimization of metallic waste volumes that require disposal, an examination of their technical features and advantages and limitations was conducted.

Decontamination objectives may differ for decommissioning operations versus maintenance operations. For the routine decontamination of systems and components during the operational life of nuclear facilities, when reuse is intended, the goal is to limit damage to the substrate and seals (welds). In decommissioning work, when salvage or reclassification of the waste is intended, the main priority is typically to obtain the most effective decontamination without concern for the substrate. The overall goal of decommissioning decontamination is to remove the contamination from the substrate sufficiently to reduce waste volumes sent for disposal.

The specific objectives of a decontamination campaign are safety related, waste management related, and economic in nature. These are itemized below:

Radiation Safety-

1. to minimize public exposure to radioation from nuclear waste
2. to minimize occupational exposure
3. to reduce the residual radiation source at the site to minimize potential hazard to public health and safety
4. to remove loose contamination on structural surfaces or within systems to improve work area habitability or prepare for long term protective storage

Waste Management-

1. to reduce waste volume
2. to concentrate the residual radioactive contamination for placement in a permanent storage container

Economic-

1. to reduce the overall cost of waste management
2. to salvage materials for reuse or recycle
3. to restore a site and/or facility for restricted or unrestricted access and use

Decontamination technologies can be categorized in two ways: based on the depth of contamination (contamination contained in surface layers or penetrating deeper into the bulk of the material) or the type of energy used to remove contaminants (chemical, mechanical, or thermal). Most decontamination is accomplished by removal of contaminants from waste surfaces or by removing the top layers of the substrate along with the embedded contaminant. Removal of contaminants residing in the bulk of the material requires different techniques such as incineration, smelting, or leaching. Many procedures and reagents used to decontaminate equipment and facilities in the nuclear industry were adopted from cleaning techniques used in nonnuclear plants for decades.

The selection of a decontamination process for application to a metal waste is a complex matter involving consideration of many variable factors associated with the features of these processes. Factors influencing selection of a decontamination process are listed below.

Waste Related

1. required degree of decontamination
2. material type and geometry
3. contamination characteristics
4. plant operating history

Technology Related

1. destructive/non-destructive
2. decontamination effectiveness (DF)
3. secondary waste generated
4. secondary waste processing requirements
5. process duration
6. process cost, including waste processing

Application Related

1. methods of application (in/ex-situ, remote/automatic vs. manual)
2. process temperature
3. occupational exposure (due to method)
4. industrial safety
5. impact on component integrity during use (damage to welds, resulting surface finish)
6. use of existing waste processing facility or need for new facility (in-situ vs. ex-situ)
7. impact of effluent releases on general public and environment
8. environmental, safety, and health considerations
9. operability/simplicity

Decontamination efforts may vary in their needs. Organizations intending to perform decontamination often have differing priorities and will use criteria listed above accordingly. In the expert system cost-based recommendations were provided for the user, but other qualitative considerations were provided to allow decontamination technology selection based on other priorities.

This chapter provides a detailed examination of each of the ten decontamination technologies evaluated in the expert system (abrasive jetting, acid chemical decontamination, carbon dioxide pellet decontamination, electrochemical decontamination, freon cleaning, laser decontamination, melting, high pressure water, ultra high pressure water, and vibratory finishing).

5.2 Acid Chemical Decontamination

5.2.1 Introduction

Chemical decontamination involves treatment of a waste with solutions or sprays that wash the surface with chemical solutions. Treatment of metal surfaces is usually accomplished by immersing the waste item in a bath, by spraying, wiping, or by internal circulation in piping systems or tanks. Radioactive contamination is removed by partial or complete dissolution of surface materials and/or metal layers containing the contaminants. This is a process that has been used in the nuclear industry in manual cleanup operations for more than 20 years. Chemical decontamination processes can be divided into two groups based on the strength of active reagents: low concentration and high concentration, with the dividing line at about 1% concentration of the active reagent. The main purpose of low concentration chemical decontamination is contaminant removal without attack on the base metal. Chemical decontamination using high concentration reagents is a more aggressive approach which includes removal of some of the base metal surface.

5.2.2 Fields of application

Acid chemical decontamination is currently used for the surface decontamination of wastes and will remove smearable and fixed contamination and most surface materials including paints, grease, oils, oxides, and embedded substances (International Atomic Energy Agency, 1988; Bennett and Taboas, 1980). Most metal waste can be decontaminated either in-situ or ex-situ using acid chemical decontamination. This process, however, is not applicable to motors or electrical equipment. Low concentration decontamination is generally applied to items that are to be reoperated, such as entire reactor coolant circuits and metal liners for hot cells (Feraday, 1989). High concentration chemical solutions are employed mainly to decontaminate reactor coolant circuits, items that can be immersed in a tank, and transport containers.

5.2.3 Advantages and limitations

Secondary waste: The generation of secondary waste is a major drawback of this method. The high volumes of liquid waste resulting from acid chemical decontamination must be neutralized. These large quantities of corrosive wastes containing the removed contaminants require treatment and disposal as a mixed waste. However, one of the waste products from the use of nitric acid, uranyl nitrate, is used in the first step in conversion of U to U_3O_4 (thus nitric acid is commonly used in uranium recovery processes) (Oak Ridge K-25 Site, 1993).

Labor: This is the easiest of decontamination technologies to operate and requires only a low degree of disassembly of waste items. However, it is a manual process that is labor intensive and there exists a high potential for worker exposure due to the fact that the removed contamination is difficult to contain.

Waste character: This process is destructive and can cause physical degradation of the metal substrate. Concentrated chemicals tend to be corrosive to carbon steel, aluminum, and plated surfaces. Concern exists for damage to welds and the possibility of localized or selective corrosive attack. However, good results have been achieved in the use of acid chemical solutions on stainless steel (International Atomic Energy Agency, 1988, Bennett and Taboas, 1980).

Decontamination efficiency and effectiveness: Process times can run from 20 minutes to 100 hours with a typical range of one to ten hours (Nuclear Energy Agency Group of Experts, 1981; International Atomic Energy Agency, 1988). Decontamination factors (DF), defined as the ratio of activity present before decontamination to that present after decontamination (LeSurf and Weyman, 1983), range from 5 to >100 (Oak Ridge K-25 Site, 1993) Low concentration chemical solutions generally produce the lower DFs and require longer process times whereas more highly concentrated solutions result in high DFs and shorter process times. Decontamination effectiveness can be increased by increasing the reaction time and temperature.

Summary: Generally speaking, low concentration chemical solutions require smaller chemical inventories. These result in a lower cost and easier disposal due to the possibility of ion exchange cleanup. With high concentration solutions large chemical inventories are required. These come at a high cost and cause greater difficulties in waste disposal efforts.

Most chemical decontamination technologies developed to allow for reuse are slow processes, result in relatively low DFs, and generate large secondary waste volumes. In a recent assessment of decontamination technologies (Oak Ridge K-25 Site Technical Division, 1993), the recommendation was made to the DOE to pursue the use of aggressive chemical decontamination methods such as cerium(IV)nitric acid, sulfuric acid, perchloric acid, and ozone. However, solution recycle techniques are in need of development for these reagents.

The potential of worker exposure, labor intensity and mixed waste generation are the biggest disadvantages of this decontamination technology.

Chemical reagents can also be used in combination with other decontamination technologies that use water to improve the effectiveness of these techniques. Some chemicals are also used as pre-treatments in multi-step decontamination processes.

5.3 Vibratory Finishing

5.3.1 Introduction

Vibratory finishing combines a mechanical scrubbing action with chemical cleaning. A rapidly vibrating tub filled with loose abrasive ceramic or metallic media mechanically scrubs contamination and other surface material such as paint, tape, corrosion layers, and soil from most metallic and nonmetallic surfaces. The dislodged loose and embedded surface contamination is rinsed from the vibrating bed by a recirculating flow of filtered cleaning solution (often based on sodium hydroxide diluted with water) and collects in the filters or settling tank.

5.3.2 Fields of application

Vibratory finishing is a technique used for the surface decontamination of wastes. Smearable contamination is reduced to non-detectable levels but there is little effect on fixed contamination (Allen, 1985; Allen et. al.,1984) This process removes contamination contained in corrosion layers or embedded in other surface materials. These include oxides, non-epoxy paint, dirt, and tape. Epoxy paint cannot be removed. This technique can not be applied in-situ.

This process can efficiently convert large volumes of TRU contaminated waste to LLW by removing TRU contamination from many metals and from a wide range of surface-contaminated nonmetallic TRU waste (Allen et al., 1984). Vibratory finishing is an excellent decontamination technique for tools and large quantities of small items but larger components require extensive disassembly and sectioning.

5.3.3 Advantages and limitations

Secondary waste: The secondary waste volume generated as result of this process is low. The same abrasive action that decontaminates the parts also keeps the media at reasonably low contamination levels, which minimizes the volume of media that must be sent for disposal (Allen et al., 1984). Recirculation of the cleaning solution keeps the waste volume down as does concentration and solidification of the final wastes. Filters collect the contaminants as the solution is reciriculated. Vibratory finishing produces less secondary waste than electropolishing (Allen et al., 1984).

Labor: The vibratory finishing process can be operated automatically and remotely to minimize labor needs and worker exposure. A major disadvantage is that items that are processed are limited to a maximum size of about 8-12 inches (Allen, 1993) which means that sectioning and disassembly needs cause labor requirements to become significant.

Waste character: This technology can decontaminate a variety of materials of different sizes and shapes at the same time. This is an important advantage because the waste does not require sorting. Both metallic and nonmetallic components of differing sizes and shapes can be processed in the same batch at the same time.

Decontamination efficiency and effectiveness: Vibratory finishing rapidly decontaminates both metallic and nonmetallic waste to levels (0.2 nCi/g) well below the limit defining TRU waste (100 nCi/g) but will not decontaminate to the non-detectable levels obtainable with electropolishing. Process times are a function of the desired decontamination level: one hour to achieve approximately 0.2 nCi/g and ten to 15 minutes to bring contamination levels down to less than 100 nCi/g (Allen, 1993). Typically, the decontamination time is about one hour (Hazelton and McCoy, 1982). However, an additional rate limiting factor is the sectioning required.

Summary: Vibratory finishing is effective and easy to use for the decontamination of surface-contaminated metallic waste. It is also effective as a pre-treatment technique for removing surface materials, corrosion products, and gross contamination from metallic waste to produce a surface that is ideal for subsequent handling or decontamination to non-detectable levels using electropolishing. The biggest disadvantage associated with this technology is the sectioning required, which affects the process time and labor requirements and therefore, the cost of decontamination.

5.4 Electrochemical Decontamination

5.4.1 Introduction

Electrochemical decontamination is a process that uses anodic dissolution to remove surface contamination on or in metal surfaces by the controlled removal of a thin layer of material, including corrosion films, that would otherwise be difficult to remove. Any radioactive contamination on the surface or entrapped within surface imperfections is removed and released into the electrolyte by the dissolution process. The object is then removed from the electrolyte and rinsed in hot water. The most common electrolytes are phosphoric, sulfuric, and oxalic acid. Electropolishing, the most commonly used technology in the class of electrochemical decontamination techniques, employs phosphoric acid as an electrolyte and a high current density to produce a smooth surface. If the item is not to be reused, nitric acid can be used at a low current density. This results in a rougher finish. Electropolishing is the electrochemical decontamination technology that is evaluated by the expert system.

5.4.2 Fields of application

Electropolishing can be applied either in an immersion mode or as an in-situ technique. The immersion mode is most commonly used and involves immersing removed components or tools in a bath. The in-situ technique uses remotely operated movable cathodes for the insides of tanks, pumps, and large pipes, and the exteriors of large components but is difficult to apply (Allen, 1985; Feraday, 1989; Bennett and Taboas, 1980; International Atomic Energy Agency, 1988a). Relatively complex components can be decontaminated without disassembly by the use of auxiliary electrodes.

Electropolishing can remove any conductive surface materials, including embedded materials and some oxides. However, waste surfaces that are to be decontaminated by electropolishing must be pre-treated to remove paint, dirt, grease and other non-conductive materials.

5.4.3 Advantages and limitations

Secondary waste: Contaminated electrolyte solution is a product of this process. Although the volume of this liquid secondary waste is relatively low, it may require chemical treatment before disposal. The aqueous waste from the cleaning operations and the electropolishing rinse solutions are concentrated using an evaporator system. The spent phosphoric acid electrolyte from the electropolishing decontamination process is solidified for disposal.

Labor: Operation of the electropolishing process is relatively complex and often requires high quality instrumentation and well-trained operating personnel. This technique is labor intensive and worker exposure can be a concern unless the equipment is adapted for remote operation.

The amount of component pre-treatment, disassembly, and sectioning required, other than the removal of nonconductive parts and nonconducting surfaces, is a function of the method (in-situ or immersion) and the size of electropolishing system. For immersion, components are restricted to the tank size.

Waste character: Although auxiliary electrodes can be used to decontaminate components with more complex geometries, it is difficult to remove contamination from crevices. Cracks, crevices, and areas out of reach of the electrode will not be decontaminated (International Atomic Energy Agency, 1988a; Oak Ridge K-25 Site, 1993).

Decontamination efficiency and effectiveness: The major advantage of electropolishing is the ability to rapidly decontaminate to very low or even non-detectable levels. The amount of surface removed is proportional to factors such as current, time, and voltage (Oak Ridge K-25 Site, 1993) The amount of metal surface that must be removed to carry out decontamination is a function of surface topography and depth of contamination, but generally ranges from 5 to 50 micrometers for surfaces that are not heavily corroded or pitted. This corresponds to process times of 3 to 30 minutes (Cavendish, 1978; Allen et al., 1984). This process is highly effective in removing transuranics and high DFs are usually achieved by the removal of a few tens of micrometers of surface material. Decontamination to background level is possible if sufficient material is removed.

Summary: One of the most significant features of electropolishing is the production of a microscopically smooth surface. For reusable components this surface slows recontamination and facilitates subsequent decontamination operations using other techniques. Other decontamination techniques, high and ultra high pressure water blasting and abrasive jetting, result in a very rough surface that subsequently must be smoothed before reuse can be considered. This decontamination technology is very effective but relatively complex. For reusable items, close control must be exercised to maintain tolerances.

Some development needs have been identified for this process (Oak Ridge K-25 Site Technical Division, 1993). This technique has potentially much wider application than those situations in which it has been tested. In particular, electropolishing large surfaces and complex shapes with electrodes needs to be demonstrated. Although in-situ decontamination has been carried out. it has been recognized in literature (Oak Ridge K-2 Site, 1993; Oak Ridge K-25 Site Technical Division, 1993; Gutterud, 1993) assessing various decontamination technologies, that this is a difficult task that needs additional development.

The second area requiring some work involves the treatment of the liquid secondary waste and development of an electrolytic solution recycle process. The cleanup principles for waste treatment are well established (ion exchange and filtering) but design and demonstration have yet to be carried out.

5.5 Abrasive Jetting

5.5.1 Introduction

Abrasive jetting refers to several different decontamination methods based on the propulsion of abrasive media against the surface of a contaminated object. The abrasive may be driven against the surface by centrifugal force or by a high velocity fluid or the abrasive may be carried in a viscous matrix and rubbed against the surface (abrasive-slurry cleaning) to remove the surface layer. The three most common methods include dry blasting, where the abrasive is propelled by a jet of air, wet blasting, where the abrasive is propelled by a jet of water, and the air-slurry technique, where a slurry composed of water and abrasive is propelled against the contaminated surface by a jet of compressed air.

Typical abrasive media include sand, alumina, metals, metal oxides, glass beads, and sawdust. Sand is the most common because it is economical and a good scouring agent. Effective cleaning requires air pressures of approximately 1 MPa or water pressures similar to those used in high pressure water systems. A final rinse after cleaning to remove excess abrasive media from the metal surface is also needed.

5.5.2 Fields of application

Abrasive jetting can be applied to a wide range of materials including metal, wood, rubber, and plastic. It does not require any pre-treatment because it effectively removes both loose and fixed contamination, paint, grease, oil, oxides, and embedded materials from the surface of a contaminated object. It is a destructive process and is, therefore, able to remove some of the metal surface layers that may have become contaminated.

This technology can be applied to pipes (>2" diam) and tank internals but not motors or electrical equipment (International Atomic Energy Agency, 1988a; Allen, 1985; Gutterud, 1993). According to one source (International Atomic Energy Agency, 1988a), abrasive jetting cannot be applied to tools but another (Allen, 1985) claims the opposite is true. The versatility of this technology is illustrated by the following list of item decontaminated by this process: painted iron-pipe supports, lead shielding, turbine blades, gas cylinder dollies, hydraulic jacks, chain falls, wooden transport carts, and charging pump impellers and rotors (Allen, 1985).

5.5.3 Advantages and limitations

Secondary waste: The secondary waste generated is a function of the type of approach used. Wet abrasive jetting generates more secondary waste than dry blasting, but facilitates recycling of the abrasive materials. However, if the abrasive material becomes contaminated, it adds to the material that must be stored or disposed of. Spent abrasive can be readily separated from the water to facilitate individual processing and disposal operations. This can help minimize secondary waste generation. Wet or dry blasting may also generate mixed wastes.

A disadvantage of this technology and other abrasive cleaning methods is the generation of large secondary waste volumes when processing highly contaminated items. Waste volume could be minimized by the use of recirculation technologies. Waste would be spent media containing abraded substrate and removed contaminants plus filter. The waste production rate will depend upon the substrate being decontaminated but is expected to be in the range of 0.005 to 0.1 lbs/ft^2 decontaminated (Oak Ridge K-25 Site, 1993).

Labor: No pre-treatment is required for the waste materials, however, a medium degree of disassembly is necessary (pipe must be sectioned). Abrasive jetting is a hazardous, labor intensive process, the operators are not easily trained, and worker exposure can be a problem, but the equipment can be remotely controlled. Operators are usually required to wear respiratory equipment, wet suits, hard hats, face shields, rubber boots and rubber gloves, and the air supply system is protected by filters. Another disadvantage is the difficulty in containing the dispersed contamination. However, wet blasting is more effective than dry blasting in reducing airborne contamination. Wet abrasive jetting is also typically found to cause less wear on process equipment than dry blasting (Demmer, 1993).

Waste character: Abrasive jetting is unable to penetrate crevices to remove contamination, therefore, shape complexity must be low for this technology to be applicable. All sizes of objects can, however, be accommodated.

Decontamination efficiency and effectiveness: Decontamination of metal waste by abrasive jetting generally results in a bad surface, with bead blasting being one of the worst media in use, creating a very porous surface. The slurry method (water and abrasive propelled by pressurized air) is best because good control of surface removal can be maintained by control of multiple variables (air pressure, feed rate, water in slurry).

For all abrasive jetting technologies, the rate of surface removal is controlled by the air and/or water pressure, velocity, abrasive material type and size, distance, and nozzle type and angle. This allows adjustment of the removal rate to provide the degree of decontamination required and helps maintain critical tolerances when reuse of the contaminated object is desired.

Decontamination factors have been achieved in the range of ten to 100 (Oak Ridge K-25 Site, 1993) However, achievable decontamination factors are independent of the initial condition of the surface and unlimited decontamination factors can be obtained given enough time and thus, enough surface removal. Adding chemicals can improve the technology's effectiveness. For example, adding nitric acid or oxalic acid removes chromium dioxide (LaGuardia, 1989).

Problems exist with the removal of contaminated abrasive from crevices and other constricted areas and the possibility of excessive erosion or surface roughening. The danger exists that contamination will become further embedded.

Summary: Abrasive jetting is an efficient decontamination method that is commercially available. Limitations of this technique, which also pertains to other abrasive cleaning methods, include surface roughening for components that are to be reused and potential cross-contamination effects.

The following aspects of this technology require further development: 1) More durable, longer life media are needed to reduce waste volumes, 2) Better vacuum systems for collecting media are needed to minimize the spread of contamination, 3) Process automation is needed to improve efficiency, and 4) A system to separate contaminants from media and to package the wastes is needed (Oak Ridge K-25 Site, 1993).

5.6 Ultra-High and High Pressure Water

5.6.1 Introduction

High pressure water decontamination techniques are applicable to surface contaminated waste. These techniques can be divided into two classes: high pressure water (HPW) and ultra-high pressure water (UHPW). HPW involves the use of water jets, at pressures from 3000 to 20,000 psi and flows of 5 to 40 gallons per minute, to remove surface contamination (Allen, 1985; International Atomic Energy Agency, 1988a; Gutterud, 1993; Gardner et al., 1982). UHPW involves the use of pressures of over 20,000 psi, typically 35,000 psi up to 55,000 psi (Allen, 1985; Oak Ridge K-25 Site, 1993; Garner et al., 1982). An ultra high pressure pump pressurizes water and forces it through small diameter nozzles, generating high velocity water jets at speeds up to 3000 ft/s (Oak Ridge K-25 Site, 1993) These nozzles can be mounted in various types of cleaning heads for different surface cleaning applications.

Both of these technologies are commercially available and can be used to clean objects in self-contained units and can also be used in an open area, if care is taken to prevent the spread of contamination from waste items being cleaned. Typically a high pressure water cleaning system consists of a power unit, a high pressure pumping unit, and a water supply tank with a filter at the discharge.

5.6.2 Fields of application

Both techniques remove smearable contamination, embedded material, oxides and can penetrate crevices and constricted areas, to some degree, to dislodge contamination. This technique can be applied to components of all sizes, to components with complex geometries. and, with appropriate modifications, to tank interiors. Some demonstrated applications include small equipment, spent-fuel racks, hot cell interiors, spent-fuel shipping casks, fuel handling equipment, water storage tanks, floor drains, and reactor coolant pumps (Allen,1985). According to Allen (1985) interiors of pipes can be decontaminated using high pressure water techniques, however, another source (Gutterud, 1993) claims that these techniques have limited effectiveness for pipe and duct decontamination. Allen (1985) also states that hand tools have been decontaminated by this means, but another source (International Atomic Energy Agency, 1988a) asserts that this not an area of application for high pressure water methods.

Differences between the application of HPW and UHPW take three forms. HPW is unable to remove fixed contamination unless chemicals are used but fixed contamination is easily removed at pressures of 35,000 psi with UHPW.(Allen, 1985; Gardner, 1982). HPW cannot effectively remove transuranic contaminants. HPW is generally a non-destructive process, causing little or no surface damage, but UHPW has been demonstrated to remove corrosion layers and even base metal.

5.6.3 Advantages and limitations

Secondary waste: A significant disadvantage of HPW and UHPW is the production of large volumes of liquid radioactive waste. Unless a better recycle system is developed, waste for UHPW would be 3 to 5 gallons of water per square foot cleaned (Oak Ridge K-25 Site, 1993). If the water is not or cannot be recycled, the cost of treating or disposing of the large volumes of waste could be high.

Labor: This process requires minimal operator skill, easing training needs, but is generally a manual operation that is labor intensive. Operators are required to wear respiratory equipment, wet suits, hard hats, face shields, and rubber boots and gloves. Prolonged use above 10,000 psi results in operator fatigue and at higher pressures the lance used to apply the water to the waste surface cannot be hand held (LaGuardia, 1989). Remote/manual or an automatic machine must then be used. This technique is amenable to remote operation to alleviate operator fatigue problems, minimize operator exposure, and reduce risk from the hazardous high pressures. No pretreatment of the waste is necessary and only a low degree of disassembly of the waste is required.

Waste character: All sizes and shapes can be decontaminated using high pressure water techniques.

Decontamination efficiency and effectiveness: Decontamination factors from two up to several hundred have been reported. Effectiveness and consistency of decontamination can be increased through the addition of chemical cleaning agents or abrasive media.

Decontamination efficiency is a function of the applicator translation speed. Surface coverage rate for a single UHPW jet is about 1.7 in^2/minute with a corresponding water use rate of 0.7 gal/in^2 of decontaminated surface (Allen, 1985) The cleaning rate for HPW was rated as generally quite low compared to other decontamination technologies (Gutterud, 1993).

Summary: The most important advantages of this process include the compatibility of the cleaning medium with materials and radioactive waste processing systems and the versatility of the technology. Chemicals or abrasives can be added, although these additions will complicate management operations for secondary wastes.

Disadvantages are the possible redistribution of contamination and generation of airborne contamination and surface roughening, although this might be minimized by further optimization of the process parameters. HPW causes little or no surface damage, however, care must be taken when using UHPW to minimize damage to the substrate if reuse is intended. Some of the main issues of concern are criticality, the wastewater volumes generated, the prevention of the spread of contamination, and remote operability.

This technique, commercially available and accepted by industry, is often used to reduce overall contamination levels on contaminated surfaces rather than to achieve free release.

5.7 Carbon Dioxide Pellet Decontamination

5.7.1 Introduction

Carbon dioxide pellet decontamination comprises three surface decontamination technologies: centrifugal cryogenic CO_2 blasting, supercritical CO_2 blasting, and compressed air cryogenic CO_2 blasting. Compressed air cryogenic blasting is the approach that is evaluated in this study because, unlike the other two technologies, it has been successfully demonstrated and is commercially available.

Carbon dioxide blasting is similar to the abrasive jetting decontamination method except that the media are rice-sized solid carbon dioxide pellets. Liquid CO_2 is converted into solid pellets that are then propelled onto a surface by an air gun at high pressure using compressed air or other gases. The pellets collide with the surface, thereby generating heat that causes sublimation. The surface is flushed and contaminants are lifted away by the expansion of the carbon dioxide gas as the pellets return to the gas state. As in abrasive jetting, the surfaces to be decontaminated must be accessible to the blast nozzle.

5.7.2 Fields of application

Carbon dioxide blasting can remove smearable contamination and grease and oils (Gillis, 1992; Oak Ridge K-25 Site, 1993). Fixed contamination removal depends upon the nature of the bonding. Non-epoxy paint and loose rust can be removed but this non-destructive technology is not aggressive enough to remove epoxy paint, substrate surface layers, or hard oxides (Ishikura, 1993; Archibald, 1993).

This technology has been used at various nuclear facilities to decontaminate hand tools, tanks, metal sheets, and electrical and non electrical equipment (Knight, 1993; Gillis, 1992). Pipes (with inner diameter greater than three inches) and ducts can also be decontaminated. However, one source (Gutterud, 1993) found CO_2 decontamination to have limited effectiveness for piping and ducts.

5.7.3 Advantages and limitations

Secondary waste: Since the dry ice pellets evaporate on contact and the contamination removed from the surface is collected via vacuum and filtration systems, the secondary waste volumes are limited to the HEPA filters used to remove contaminants. The resulting waste volume is very low, since the HEPA filter is generally replaced only once per month of operating time (Knight, 1993; Gillis, 1992).

Labor: Decontamination is typically carried out manually, with a technician operating the pellet gun. Operation of the device causes operator fatigue so that either a remote (manipulator) or frequent rest periods would be required for large tasks or continuous use (Oak Ridge K-25 Site, 1993). Automation has not been commonly used for this process because of the large variety of items to be decontaminated and the expense of implementation (Gillis, 1993).

Although the operators are easily trained for this process, problems have been encountered with maintaining adequate oxygen levels in the cleaning room due to the rise in carbon dioxide gas that accompanies use of this technique (Knight, 1993).

Waste character: This process can clean small items, such as tools, as well as large items weighing up to 4000 lbs (Gillis, 1993).

Decontamination efficiency and effectiveness: The cleaning rate varies with the contaminant, contamination level, surface material, and size of the object to be decontaminated. One reference cites process times ranging from 1 to 20 minutes, depending upon the item cleaned (Gillis, 1993). Decontamination factors have been cited from 8-250 (Gillis, 1992) up to 5000 (Knight, 1993). Problems exist, for some commercially available equipment, with the rate of production of carbon dioxide pellets keeping pace with the cleaning rate.

Summary: Although tests using a carbon dioxide pellet decontamination system are limited, demonstrations have shown this process to have generally good processing rates. Many items have been efficiently decontaminated to meet release criteria and allow salvage of the metal waste (Knight and Blackman, 1992; Gillis, 1992).

The non-destructive feature of this technology is useful for items that are intended for reuse, but tends to limit the effectiveness of cleaning more adherent surface materials and removing contamination from substrate layers. Improvements are required to increase the kinetic energy of the pellets for a more aggressive cleaning action (Oak Ridge K-25 Site Technical Division, 1993).

Low-level waste has been decontaminated in demonstrations of this technology. Applicability to transuranic waste has yet to be established.

5.8 Freon Cleaning

5.8.1 Introduction

A system has been developed that uses commercial Freon (trichlorotrifluoroethane) cleaning solvents to decontaminate radioactively contaminated waste. Liquid Freon is applied at pressures up to 3000 psi through a spray nozzle to dislodge contamination particles. These systems operate in a recirculation mode that carries the contaminant-laden Freon to a filter which allows the Freon to be recovered, purified and reused.

5.8.2 Fields of application

Freon cleaning techniques can remove smearable contamination, grease, and oil. However, fixed contamination, embedded material, and oxides are not removed. A low viscosity and surface tension facilitate penetration into crevices for use on complex shapes. This method can be applied within an enclosed area to contain the Freon for recycle, or in situ by using a vacuum return attached to the spray nozzle to collect the Freon.

Freon cleaning has been successfully applied to aluminum generator dams, stainless steel shafts, welding cables, hoses, electric motors, hand tools, and communication equipment (International Atomic Energy Agency, 1988a, Allen, 1985; McVey et al., 1981). Freon is chemically inert and non-abrasive which permits its use on many types of electrical and other equipment without damaging delicate parts.

5.8.3 Advantages and limitations

Secondary waste: The use of Freon cleaning results in minimal secondary waste due to the use of distillation and filtration for recovering the cleaning fluid. The only wastes generated are the filter cartridges used to trap the contaminated surface material removed by the solvent. Soluble contaminants are removed by distillation. Freon fumes can be removed from the atmosphere by use of charcoal as adsorbents and can subsequently be reclaimed for reuse.

Labor: This procedure is not labor intensive and does not result in high personnel exposure. However, operators are not easily trained and some pre-treatment is needed to remove oxides and embedded material. For some applications, containment of the contamination may be difficult. A demonstration of this system indicated that Freon cleaning required 1/4 to 1/3 the amount of time that chemical solution decontamination required (McVey, et. al, 1981).

Waste character: Freon cleaning can be applied to components of all sizes and most shapes.

Decontamination efficiency and effectiveness: Processing rates depend upon the size and intricacy of the item of concern. Cleaning times for tools ranged from two to five minutes. In one demonstration, from 82 to 100 percent decontamination was achieved.

Decontamination factors ranged from two to 1.2 million with an average DF of about 30. Ninety percent of the items were cleaned to free release (McVey, et al., 1981).

Summary: Freon decontamination is particularly applicable to electrical equipment and cables. Many items have been decontaminated to release levels. However, Freon techniques are non-destructive which limits their applicability to waste items that have surface oxides or contamination contained in their metal surface layers.

Regulation of chlorofluorocarbons (CFC) by the U.S. Environmental Protection Agency (EPA) is serving to curtail the use of Freon. Freon-cleaning systems that were very effective in removing radioactive contamination from metal components can no longer be used at DOE sites because of DOE regulations related to ozone depletion (Oak Ridge K-25 Site Technical Division, 1993). Several substitutes are, however, being pursued industrially and throughout the DOE complex for application in cleaning semiconductors and machined parts to clean room standards.

5.9 Laser Decontamination

5.9.1 Introduction

Laser technologies for the surface and bulk decontamination of wastes are currently under development, with surface decontamination having been successfully demonstrated. Westinghouse Electric Corporation applied for a patent of the surface technique in 1983 from the European Patent Office. Because surface decontamination is farther along in development and has been successfully demonstrated, it will be the focus of evaluation in this section although both technologies are described below.

In the surface decontamination approach, a powerful laser beam is focused on a metal surface where it delivers a very localized and intense burst of energy that results in the ablation of surface material. The resulting contaminated particulates are then collected by HEPA filtration.

Bulk decontamination involves the selective removal of contaminants from bulk-contaminated metal through the use of lasers to ionize the desired radioisotope in the gas phase. The resulting ions can be separated from the bulk of the material which is electrically neutral and unaffected by electrical or magnetic fields. Targeted for removal are long-lived neutron activation products such as Nb-94, Ni-59, Mo-93, Tc-99, and some unfissioned U-235 as well as Co-60 (Pang et. al, 1992; Oak Ridge K-25 Site Technical Division, 1993).

5.9.2 Fields of application

Laser ablation is able to remove smearable and fixed contamination, greases, oils, paint, oxides, and embedded materials (Pang, 1993). Because it is a process that can remove the surface material and base metal and therefore, all traces of radiological contamination, laser ablation is applicable to situations where a very high degree of decontamination is required. This technique can be used to decontaminate both large surface areas and small geometric features (the beam can be focused to cover areas less than one square millimeter) (Oak Ridge K-25 Site Technical Division, 1993). Pipes (diameter not less than six inches), ducts, and tanks can all be decontaminated (Pang, 1993). More complex geometric shapes like tools and motors or electrical equipment will not be efficiently decontaminated by this method.

5.9.3 Advantages and limitations

Secondary waste: The secondary waste volumes generated by this process would be very low and consist of removed deposits, traces of removed substrate, and HEPA filters.

Labor: Laser technologies lends themselves to remote and automated operation. One technician could be capable of overseeing the operation of multiple systems. This will limit labor requirements as well as substantially reduce worker exposure.

Waste character: All sizes of components can be decontaminated by laser decontamination, however, the most efficient use of this method will be on shapes of low complexity.

Decontamination efficiency and effectiveness: The cleaning rate is a function of laser wavelength, laser power, material type, depth of contamination, and material rastering speed. Focus of the beam with cylindrical lenses have resulted in good surface coverage and reduced surface redeposition (Pang et al., 1992). Decontamination rates up to 2 m^2/h have been used to successfully remove contamination from metal surfaces (Pang et al., 1992). Decontamination rates of 1 m^2 in 20 minutes have also been reported (Oak Ridge K-25 Site Technical Division, 1993).

High decontamination factors are achievable with this method, as the process can remove surface materials and base metal to the required depths for complete removal of contamination. Decontamination factors up to 56 were achieved in experiments with aluminum ductwork (Pang, 1993). Recent experiments have demonstrated up to 99.7% removal of cesium contamination and 97.8 % removal of zirconium from stainless steel samples (Pang, 1993).

Summary: Important advantages of this process are its remote capabilities and very low secondary waste generation. The likely conversion of surface organic wastes to carbon and CO_2 is a beneficial feature (Pang, 1993). Additionally, laser ablation does not result in severe surface erosion, as with abrasive jetting and ultra high pressure water, despite its ability to remove metal surface layers. This allows reuse to be a possible option for items decontaminated in this way. Although surface roughening is not a problem, surface cleaning rates comparable to abrasive jetting would be desirable.

Development needs are the integration, into a system, of existing lasers, optics, and vacuum and filtration systems. It is held by one source (Oak Ridge K-25 Site, 1993) that a considerable amount of research is required before a technology demonstration can be contemplated.

Initial tests have successfully demonstrated the utility of this technology. Future experiments should attempt application with a variety of lasers types on a wide range of metals and contaminants. Of particular interest are the very high repetition rate metal vapor lasers being developed today. As industrial laser technology matures, laser decontamination methods will become increasingly cost-effective.

5.10 Melting

5.10.1 Introduction

Surface decontamination methods cannot be used to decontaminate metal waste whose radioactivity has been induced by neutron activation or whose contamination has penetrated to depths for which it is not feasible or efficient to simply remove surface layers. Decontamination needs to be carried out on these bulk-contaminated materials as well as on surface contaminated items. Metals which are activated, contain tritium or other volatile or gaseous radionuclides, or have surface contamination can be partially decontaminated by melting. By melting and fluxing metals, contaminants can be removed to decontaminate radioactively contaminated metal waste. Decontamination occurs during the melting process to the extent that selected radionuclides are trapped in the slag, crucible, furnace liners, or air ducts, or are volatilized.

Melt refining consists of a class of four related technologies: smelt purification, electrorefining, mond (nickel carbonyl) process, and leach/electrowinning. These techniques can also be employed in the purification of contaminated metal. This study will focus on smelt refining since this is a demonstrated process and the remaining three are still under development for decontamination.

Smelt purification refines metals through the use of slags that react with the impurities when the metal is melted. The contaminants are then removed in the slag that separates from the molten metal and floats to the top. These processes are based on the high affinity that actinide oxides have for silicate slags. When contaminated metals are melted using these slags, the actinide oxides will separate to the slag fraction.

5.10.2 Fields of application

These techniques can be used to decontaminate both surface and bulk-contaminated materials, although it likely more effective to clean surface-contaminated item with surface decontamination technologies. For simple volume reduction of metal wastes, this method is universally applicable.

5.10.3 Advantages and limitations

Secondary waste: Secondary waste volume is very small, consisting only of slags, scrubber solutions, chemical trap materials, and HEPA filters and is approximately two weight percent and five to ten volume percent of the original waste (International Atomic Energy Agency, 1988b; Heshmatpour et al., 1983; Kellog et al., 1983; Copeland and Heestand, 1980; Sappok, 1989; Oak Ridge K-25 Site, 1993).

Labor: Because this is a remote, automatic operation, labor requirements and worker exposure are minimized. The radionuclides that remain in the melted metal are distributed homogeneously and immobilized reducing the possibility of the spread of contamination.

However, pre-processing tasks include sorting, if the item is to be recycled, removal, if the item is a system component (tanks, piping, etc.), some disassembly and size reduction to fit in the furnace, and a drying operation to remove oils and water.

Waste character: This method is completely destructive of metal components so that items cannot be reused, however, consolidation of the waste by melting allows measurement of activity levels to be easily performed on large quantities by taking a single melt sample to verify that radioactivity of the scrap meet requirements for bulk-contamination release regulations if and when they are established.

Decontamination efficiency and effectiveness: Smelt purification has been demonstrated on stainless steel, mild steel, nickel, copper, monel, and aluminum (International Atomic Energy Agency, 1988b; Heshmatpour et al., 1983; Kellog et al., 1983; Copeland and Heestand, 1980; Sappok, 1989; Oak Ridge K-25 Site, 1993). The degree of decontamination achieved through melt refining is affected by a number of variables: furnace type, design, size and operating conditions, slagging ingredients used, and the metal. The decontamination efficiency also varies with the radionuclides of concern in the metal waste. Melt refining is only effective for contaminants that are volatile or more soluble (e.g. plutonium) in the slag than the molten metal. A broad range of decontamination factors have been documented in demonstration-scale tests, from 10 up to 1000 (Copeland et al., 1978; Heshmatpour et al., 1983; International Atomic Energy Agency, 1988b).

Melt refining can be used to remove uranium from most metals because the uranium is preferentially converted to an oxide and transferred to the slag. Experiments have demonstrated that uranium-contaminated stainless steel, nickel, and copper can be decontaminated down to about 1 ppm of metal ingot (International Atomic Energy Agency, 1988b). Other results have given a range of 0.01 to 4 ppm for uranium-contaminated stainless steel, mild steel, nickel, copper, and monel (Oak Ridge K-25 Site, 1993). However, no uranium was removed from aluminum components that were similarly contaminated. This treatment has not been effective on aluminum due to its preferential combination with oxygen and the settling, by gravity of the heavier uranium in uranium-contaminated aluminum (Copeland et al., 1978; International Atomic Energy Agency, 1988b; Bennett and Taboas, 1980; Miller, 1987). Removal of Tc-99 produced the reverse results with good removal from aluminum and virtually no removal from the other metals. For steel melting, Cs-137 is easily removed but Co-60 remains in the melt because it is difficult to separate from steel (New Scientist, 1986; Sappok, 1989; International Atomic Energy Agency, 1988b).

The removal of TRU contamination from metal waste is as effective as the removal of uranium (International Atomic Energy Agency, 1988b; Heshmatpour et al., 1983). Melt refining can decontaminate, in a single melt, most TRU metal wastes to the point where they can be reclassified and disposed of as LLW (Bennett and Taboas, 1980).

Aside from the use of slags in melt refining, levels of activity can also be brought down by diluting the metal with inactive scrap. Rates of decontamination for an 8 ton electric induction furnace are estimated at 4 to 6 tons/hr for ferrous metal and 1.6 tons/hr for non ferrous metal (Oak Ridge K-25 Site, 1993).

Summary: Melt refining of ferrous metals has proven successful for some isotopes and less so for others. Additional work is needed to improve fluxing and contaminant removal, especially for Tc-99. Additional tests should be performed on copper, nickel, and aluminum to improve the effectiveness for these nonferrous metals. Even without effective contaminant removal, however, melt refining can be used to simply reduce the volume of metal waste to be sent for disposal.

A final consideration is that, although melting is an effective method to decontaminate metals contaminated by volatile radionuclides, trapping of these contaminants (i.e. Cs-137) can occur in slag crucibles, ducts, and liners and this must be taken into account in an overall assessment of the technology. This secondary contamination can affect cost and doses related to maintenance and decommissioning of the furnace and disposal of residual waste.

5.11 Conclusion

Technologies are currently available that can achieve high decontamination factors when used for specific applications. Prior to launching any decontamination campaign, a realistic program objective must be outlined as a result of detailed characterization of the contamination and waste type. The proposed decontamination techniques should be examined for their feasibility and suitability for the intended decontamination task.

6. ASSESSMENT OF RADIOACTIVE METAL WASTE INVENTORIES

6.1 Introduction

When determining an appropriate waste management strategy for radioactive wastes, all feasible options should be considered. An assessment of radioactive metal waste inventories was conducted to determine the portion of radioactive waste that might be amenable to alternatives to simple disposal. Of all the materials arising as radioactive waste from nuclear activities, including facility operations and decommissioning projects, valuable scrap metal is one of the most likely materials to be reused or recycled.

To determine the utility of decontamination technologies for the minimization of radioactive wastes that exist in the U.S., the extent to which metal makes up this waste was assessed along with the character of the waste. This information was required given that waste volumes affect disposal costs, contamination characteristics affect decontamination technology applicability, and the types of metal and components affect the salvage value of the recovered material.

As mentioned previously, attempts were made to compile detailed inventories of radioactive metal waste first from the literature and then from a survey sent to personnel at DOE sites and commercial generators responsible for waste management. Only one useful response resulted from ten requests for information. It was later discovered that the kind of waste character details that were sought were not generally being documented. This sort of compilation and characterization of radioactive metal waste, was, in fact only just commencing. It was suggested, by a member (Kesinger, 1993) of a nationwide DOE group that is currently involved in taking inventory of these wastes, that this data might be available by 1995. Most of the data that is currently available describes radioactive metal waste location (generator or storage/disposal site), volumes, and, less frequently, metal and component type. Some specific data was obtained from WINCO and used as a case study for analysis by the expert system. This metal waste will be generated as a result of decommissioning activities at the INEL, a DOE site.

Although detailed metal waste data were not available, a compilation of general data showed that a significant quantity of radioactive waste generated and disposed of in the United States is metal waste which might more profitably be reclaimed for recycle or reuse. These wastes result from U.S. DOE and commercial activities, which include nuclear facility operations, the decommissioning of nuclear facilities upon their retirement, and environmental restoration.

Although operations of many facilities require routine decontamination of in-place systems, the focus of this study was on waste intended for disposal that has potential for recycle. The purpose is to show the extent to which decontamination can minimize radioactive waste volumes. This can include waste resulting from operations or decommissioning projects. For operations, options include reuse, recycle, or disposal. For decommissioning, the employment of decontamination will be determined by the intended use of the facility and its components. Possibilities include reuse or recycle of the metal components or structural materials, interim in-situ storage of the facility and its equipment, and permanent off-site storage of contaminated systems.

Data on radioactive metal waste volumes and characteristics were compiled from various sources. The three main categories of waste inventory information that were collected are listed below:

1) Estimates of metal waste accumulated by DOE and commercial operations and projected quantities from the DOE environmental restoration program.

2) Review of metal waste characterization and inventory studies from specific projects. These wastes may be found within commercial and/or government sectors.

3) Decommissioning activities.

6.2 General Characterization of the Contamination

Radioactively contaminated materials can be divided into two classes: those that are surface-contaminated and those that house contamination within the bulk of the material (bulk-contaminated). Bulk-contaminated material is most frequently characterized by radioactivity induced by neutron activation of certain elements in components. This is often the case with reactor components such as the pressure vessel and adjacent structures. The radioactive material deposited on the internal and external surfaces of various out-of-core systems produces surface contamination. Both activation and fission products are possible contaminants.

In most non-reactor facilities and for most parts of a reactor complex, the contamination occurs on surfaces of metal components. Although this surface contamination contains only a small portion of the total radioactivity in a nuclear power plant, it results in the largest occupational exposures because it is distributed over many readily accessible areas (IAEA, 1988a).

6.2.1 Surface contamination layer characteristics

The nature of the contamination that forms on the surfaces of metal components in nuclear facilities determines the most applicable approaches to decontamination. For primary reactor systems the major source of radioactive contamination results from deposits containing activated isotopes, dissolved elements, and fission products and transuranics from the reactor coolant. The oxide layer that forms on the inside of piping contains these deposits and over extended periods of time the radionuclides in this layer can diffuse into the metal. This oxide layer is typically composed of an adherent inner layer formed by corrosion of the base metal and a loose outer layer formed by deposits and precipitation from the coolant. Depending upon the reactor type, the composition and form of these layers will vary.

In pressurized-water reactors (PWRs) where circuit piping is mainly stainless steel, the inner adherent layer is composed mainly of chromium oxides, some of which are very insoluble. A loose outer layer, formed from the circulating water deposits will likely contain iron and nickel oxides. In boiling-water reactors (BWRs), oxide layers generally consist of magnetite (Fe_3O_4), a black oxide and hematite (Fe_2O_3), a red oxide.

In fuel reprocessing facilities, the formation of an oxide layer and radionuclide deposition is inhibited but heavy deposits of uranium and plutonium can form in pipes and tanks. These deposits are typically very difficult to remove.

In hot cells and mixed oxide fuel fabrication plants, high levels of contamination can exist in process vessels and cells as a result of normal operation. Lower levels of activity are present in UO_2 fabrication plants from normal operations. Where fuels are processed as dry powders, material will settle onto horizontal surfaces and accumulate in crevices not accessible to routine cleaning operations.

Loose contamination is prevalent in ventilation systems although oils can increase the adherence of contamination. Contamination in both ducts and piping tends to accumulate in section where the direction or velocity of the fluid changes and also for piping systems in horizontal runs, dead legs, valves, pumps, and heat exchangers. Loose, airborne contamination can contaminate motors and instrumentation. If the contamination is accessible it can generally be removed.

6.3 Department of Energy and Commercial Operations Waste

The metal wastes from DOE and commercial generators include low-level waste (LLW) and transuranic (TRU) waste from operations and environmental restoration activities. A discussion of the sources and waste quantities follows.

6.3.1 LLW from DOE and commercial nuclear facility operations

LLW is generated as a result of nuclear power generation, uranium enrichment operations, defense activity, the Naval Nuclear Propulsion Program, environmental restoration projects, and various research and development activities.

The commercial nuclear fuel cycle accounts for approximately 75% of the LLW volume shipped to commercial disposal sites; 55% from nuclear power plant operations and 20% from other fuel cycle operations. The remaining 25% of the waste results from institutional and industrial activities (Oak Ridge National Laboratory, 1991).

Dry LLW represents between 30-40% of the total waste volume in the fuel cycle and 40-50% of institutional wastes shipped for disposal (Kibbey and Godbee, 1979). This dry solid waste emerging from nuclear reactor operations is expected to have an estimated composition of 48% plastic, 25% paper, 20% metal, and 7% miscellaneous dry solids (wood, cloth, and rubber) (Tyron-Hopko, 1988).

Given that the total volume of commercial LLW accumulated at disposal sites from 1962 through 1990 is 1.38 million cubic meters as given in Table 6.1, the portion of this waste that is metal can be estimated as follows:

Given that-
75% of commercial waste is from the nuclear fuel cycle
35% of nuclear fuel cycle waste is dry waste
20% of dry waste from the nuclear fuel cycle is metal
Metal waste from the nuclear fuel cycle
= (0.2)*(0.35)*(0.75)*(1.38 x 10^6 m^3)
= $\underline{73,624\ m^3}$ (1.5 million ft^3)

Table 6.1 Total volume of disposed commercial LLW through 1990 (Oak Ridge National Laboratory, 1991)

Site	Accumulated Volume (10^3 m^3)
Barnwell, SC	638.30
Beatty, NV	118.30
Maxey Flats, KY	135.30
Richland, WA	326.60
Sheffield, IL	88.30
West Valley, NY	77.10
TOTAL	1383.90

DOE waste accruing since 1962 can be estimated similarly. Assuming equipment and tools mainly consist of metal parts, a total accumulated DOE/Defense metal LLW volume sent for disposal can be conservatively estimated as the low-level contaminated equipment volume of 390,500 m^3 (8.1 million ft^3) as given in Table 6.2.

Table 6.2 Total volume of disposed DOE/Defense LLW through 1990 (Oak Ridge National Laboratory, 1991)

Site	Accumulated Volume (10^3 m^3)	Percent of Total Volume For All Sites That Is Contaminated Equipment *
LANL	209.90	0.92
INEL	144.00	2.15
NTS	408.40	0.11
ORNL	207.20	0.64
HANF	573.80	0.07
SRS	612.80	8.86
OTHER**	563.50	1.61
TOTAL	2719.60	14.36

Total Volume of Contaminated Equipment that is LLW: **390,500 m^3**

** Ames, BNL, K-25, LLNL, PAD, PORTS, SLAC, SNLA, FMPC, Y-12

The total from both government and commercial activities accumulated through December 1990 is 464,124 m^3 (9.5 million ft^3) of radioactive metallic waste. Approximately 26% of this total, 122,600 m^3 (2.5 million ft^3), is waste resulting from light water reactor (LWR) operations (Oak Ridge National Laboratory, 1991). These accumulated waste volumes have been accruing since 1962. Projected annual generation of LLW for LWR operations is expected to be approximately 16,480 m^3, of which approximately 20% (3296 m^3, 13,608 ft^3) may be metal waste.

The metallic LLW volumes currently at DOE sites are given in Table 6.3 with a total of 35,303 m^3 (contaminated equipment only). Assuming that some portion of decontamination and decommissioning debris is metal, the volume of metal waste is likely a larger total from these sites. Projected for 1991 was a total of 33,674 m^3 of metal waste with a potential additional contribution from decontamination and decommissioning debris. It might be noted also that for the waste at DOE sites for 1990 (generated on-site, stored, and buried), approximately 26% of the total waste, by volume, was contaminated equipment compared to an estimated 14% for wastes characterized from 1980 to 1984. It is unclear whether this indicates a trend, however, if the percentage of waste sent for disposal that is metal equipment is, in fact, on the rise, then it may be increasingly cost effective to recycle or reuse this portion of the waste volume.

Table 6.3 LLW volumes currently at DOE sites (Oak Ridge National Laboratory, 1991)

	Volumes in cubic meters 1990	1991 #
Generated On-Site		
Contaminated Equipment	18350	19427
Decontamination Debris ##	3325	5376
Stored		
Contaminated Equipment	1223	1218
Decontamination Debris ##	2433	4381
Buried		
Contaminated Equipment	15730	13029
Decontamination Debris ##	3827	11110
TOTAL		
Contaminated Equipment	35303	33674
Decontamination Debris ##	9585	20867

Projected volumes
Wastes from decontamination and decommissioning, consturction debris, etc. (unknown percentages of metal)

DOE waste volumes are notably greater than the commercial accumulation and generation of LLW. The given projections of waste volumes imply that commercial waste, in general, will decline in the future and DOE waste will tend to rise. This may be attributed to increasing attempts to reduce waste by compaction and/or decontamination in the commercial sector. The DOE is also implementing waste volume reduction techniques, however, significant quantities of waste will be generated from DOE decommissioning operations and environmental restoration activities in the future which may give rise to higher waste generation rates. Decommissioning of commercial reactors is not expected to generate as large volumes of waste as DOE decommissioning activities.

6.3.2 DOE TRU operations waste

TRU waste contains elements with atomic numbers greater than 92 and activities greater than 100 nCi/g of waste material. Most TRU waste is trash such as rags, coveralls, rubber gloves, equipment, and tools that become slightly contaminated with transuranic elements during the nuclear fuel cycle. Most of this waste is alpha-emitting and designated as contact-handled TRU waste. Approximately two and a half percent, however, contains beta, gamma, and neutron radiation (>200 mR/h) and must be remotely-handled (Oak Ridge National Laboratory, 1991).

In 1970, when the policy of retrievable storage for TRU waste was initiated, TRU waste was defined as a waste material containing at least 10 nCi/g of TRU radionuclides. In 1984, this limit was increased to 100 nCi/g and now waste currently in retrievable storage is composed of wastes stored under both criteria. Consequently, wastes currently in storage containing less than 100 nCi/g of TRU nuclides are now considered LLW. Forty percent (39,197 m^3) of the current total volume of retrievably stored DOE TRU waste through 1990 (60,600 m^3) is expected to be designated as LLW (Oak Ridge National Laboratory, 1991). The amount of this waste that is metal is not directly available but approximations were generated from current estimated percentages of non combustible waste and the portion of that waste that is metallic.

Table 6.4 shows the estimated total volume of metallic TRU waste at DOE sites through December 1990 at 45,800 m^3 (945,000 ft^3). Note that this total does not include newly generated waste. The total metallic volume accumulated in retrievable storage through 1990 for both types of TRU waste is also given in Table 6.4 at 17,800 m^3 (367,000 ft^3). Another source estimates the volume of existing TRU metal waste in interim storage at 19,350 m^3 (399,000 ft^3) (Bennett and Taboas, 1980). The approximate composition by metal type of this waste is 90% stainless steel, 5% mild steel, 2% lead, 2% copper, and 1% other metals. Projected generation of TRU metal wastes for 1990-2000 is estimated to be 17,525 m^3 (365,000 m^3) (Fischetti, 1986).

6.3.3 Environmental restoration wastes

The DOE environmental restoration activities include four areas of operations; 1) the Uranium Mills Tailings Remedial Action Program (UMTRAP), 2) defense-funded Remedial Action (RA) and Decontamination and Decommissioning (D&D), 3) non-defense-funded RA and D&D, and 4) the Formerly Used Sites Remedial Action Program (FUSRAP). Only the latter three are likely to generate significant quantities of radioactive metallic waste.

Remedial action involves the evaluation and remediation of inactive sites and is primarily concerned with contaminated soil and groundwater. The D&D program objective is the dismantlement and removal or isolation of excess DOE facilities formerly associated with the government's defense efforts and those surplus facilities formerly associated with civilian projects. These will be discussed again in more detail in a separate section of this chapter. FUSRAP is concerned with sites formerly used to support the nuclear activities of DOE's predecessor agencies, the Manhattan Engineering District (MED) and the U.S. Atomic Energy Commission (AEC).

Transuranic and low-level wastes generated through the activities of the DOE's environmental restoration program will conceivably contain significant quantities of metallic waste that could be reused or recycled rather than buried or stored.

Table 6.4 TRU metal waste at DOE sites through December 1990 (Oak Ridge National Laboratory, 1991)

RETRIEVABLY STORED WASTE

	Contact Handled			Remotely Handled		
Site	Total Volume (m^3)	Non-Combustible % of Total	*Metal Volume (m^3)	Total Volume (m^3)	Non-Combustible % of Total	*Metal Volume (m^3)
HANF	7670	48.00	3130	201.0	4	6.83
INEL	37400	35.00	11100	49.9	80	33.93
LANL	7550	45.00	2890	27.5	50	11.69
ORNL	667	35.00	198	1307.0	14	155.53
TOTAL	53900		17600	1585.4		208.00

BURIED WASTE

Site	Total Volume (m^3)	Non-Combustible % of Total	*Metal Volume (m^3)
HANF	52300	48.00	21300
INEL	57100	10.50	5100
LANL	14000	13.00	1550
ORNL	6200	unknown	unknown
TOTAL	130000		28000

Total Volume of Stored Metal TRU Waste:	17800 m^3
Total Volume of Buried Metal TRU Waste:	28000 m^3
TOTAL VOLUME OF METAL TRU WASTE:	45800 m^3

*Volume % of glass, metal, or similar non-combustibles is taken as 85% metal (Anderson, 1992)

Defense-funded project waste Defense-funded projects supported defense-related activities such as nuclear weapon component fabrication. There are a total of 23 defense-funded RA and D&D activities located in 13 states. The volumes of TRU and low-level metal waste projected are expected to total 67,600 m^3 (1.4 million ft^3) (Oak Ridge National Laboratory, 1991). About 75% of this will be LLW (49,882 m^3, 1 million ft^3) and 25% TRU waste (17,739 m^3, 366,000 ft^3). The last project is scheduled for completion in 2030, although most of the projects will be completed by 2021. Most of the waste is expected to be disposed of on the site at which it was generated. Of the 23 sites, only 14 had recorded waste data. It is possible that a significant increase in the projected volumes of DOE metal waste could result from those sites that have not yet documented their waste volumes.

Non-defense-funded project waste Non-defense-funded projects are those projects which supported civilian nuclear power applications such as the design and operation of small test reactors. The 22 non-defense-funded RA and D&D activities are located in 12 states. It is expected that 55,002 m^3 (1.1 million ft^3) of low-level metal waste and 762 m^3 (15,700 ft^3) of TRU metal waste will be generated (Oak Ridge National Laboratory, 1991). The last project is scheduled for completion in 2020. Nine of the 22 sites listed did not have available information. It is, again, possible that a significant increase in the volumes of metal waste will result from these sites.

Formerly utilized sites remedial action program (FUSRAP) FUSRAP is primarily concerned with sites used formerly by MED and AEC for the research, processing, and storage of uranium and thorium ores, concentrates, and residues. When these sites were no longer required for the nuclear activities of MED and AEC, they were decommissioned in accordance with regulations applicable at the time but do not now meet today's more stringent criteria. For seven of the sites, metal is listed as a principal component of the waste. The total waste volume for all sites is cited to be 36,117 m^3

(752,000 ft^3) of which a significant amount is metal (Oak Ridge National Laboratory, 1991). All listed FUSRAP projects are expected to be completed by 1996.

The total volume of metallic waste projected to be generated from DOE's environmental restoration activities is estimated to be 123,385 m^3 (2.5 million ft^3). This does not include the metallic waste generated by FUSRAP projects as the portion of this waste that is metal is unknown. If the FUSRAP waste is estimated to be half metal by volume the total projected waste from environmental restoration activities increases to 141,444 m^3 (2.9 million ft^3). These wastes are expected to be generated over the next 40 years.

6.3.4 DOE and commercial operations metal waste summary

The total volume of radioactive metal wastes accumulated and expected to be generated from DOE and commercial operations including LLW, TRU waste, and environmental restoration waste comes to 633,309 m^3 (13 million ft^3) (the FUSRAP wastes are not included).

As illustrated by the inventories discussed previously, metal is a major component of the radioactive waste sent for disposal. A significant volume of this metal waste is potentially available for decontamination, reuse, or recycle as alternatives to disposal. The estimated scrap value from the recycle and/or reuse of scrap metal and equipment accumulating at sites may be justification enough for the employment of decontamination techniques over land disposal of these wastes. A breakdown of metal types, quantities, and salvage value is given in Table 6.5 for metal presently in storage at DOE sites. This metal totals approximately 1.8 million tons with an estimated market value of $1.8 billion. The annual scrap metal generated at DOE sites is estimated to be 16,500 tons (Kluk and Hocking, 1992).

Table 6.5 Radioactive scap metal controlled by DOE (Clemens, 1993)

METAL	MARKET PRICE (U.S.$/TON)	QUANTITY (TONS)	MARKET VALUE (U.S.$)
Nickel	6000	245,000	1,470,000,000
Steel	107	1,300,000	140,000,000
Aluminum	600	195,000	115,000,000
Copper	1500	38,000	57,000,000

6.4 Specific Studies of Metal Waste Inventories

The previous discussion tabulated estimates of radioactive metal waste quantities located at DOE and commercial disposal sites and metal waste generated by various nuclear facility operation and environmental restoration work. More specific details as to the source of the metal waste, the metal types, and the radioactive characteristics of this waste are examined in the following review of five independent metal waste inventory surveys. These studies better characterize the types of radioactive metallic wastes generated which allows for a more accurate evaluation of alternative waste management options. Included is a survey of scrap metal stored at Oak Ridge Operations (ORO) Managed Sites, a tools and equipment decontamination experiment, a compilation of volumes of metal waste that are potentially suitable for treatment at the Westinghouse Hanford site, a survey of DOE, Department of Defense (DOD), and commercial radioactively contaminated stainless steel waste inventories, and Westinghouse Savannah River Company heat exchanger data.

6.4.1 Contaminated metal at Oak Ridge Operations sites

Nearly 90,000 tons of contaminated scrap metal are stored above ground at Oak Ridge Operations (ORO) managed sites, primarily uranium enrichment facilities. Although this inventory accumulated over the 30 years from 1950-1980, most was generated during enrichment process upgrading from 1976-1982 (Mack, 1982).

The primary contaminants of the scrap metal are low-enriched to depleted uranium (< 0.711% U-235) and Tc-99. The average uranium enrichment is estimated to be between 1 and 1.5% U-235. Uranium at 1.5% U-235 has a specific activity of 0.36 µCi/g and is health hazard only when ingested or inhaled. Tc-99 is a low-energy beta emitter that can ordinarily be stopped by the outer layers of the skin. Because of the low specific activity of uranium and the very low concentration of Tc-99, the curie content of the contaminated scrap metal is relatively low compared to other waste streams. The concentration levels of these two contaminants vary widely, even on similar components. Uranium concentrations vary from a few ppm up to several thousand ppm. Tc-99 values range from 0.02 to 70 ppm. For most of the metal, U-235 concentrations are estimated to be less than 200 ppm and Tc-99 is expected to be below 5 ppm for 95% of the scrap (Mack, 1982).

The metal waste consists of nickel, aluminum, copper, and steel of which nickel is by far the most valuable. Annual waste generation rates from each of the five ORO sites are given in Table 6.6 along with a breakdown of the metal types and quantities. Roughly 1125 tons of metallic waste is produced by these sites each year. Steel provides the largest percentage of metal (45%) generated by all the facilities, nickel the second largest (30%), copper third (15%), and aluminum the smallest percentage (10%). Given the annual generation rates from each of the five sites, the current accumulated volume of metal waste can be estimated to be approximately 100,665 tons with an estimated scrap value of almost $100 million dollars.

6.4.2 Tools and equipment recycle

A decontamination experiment took place in 1980 at a nuclear power plant which claimed, for reuse, approximately 6000 contaminated tools and equipment (McVey et al.,1981). Approximately 5500 kg of radioactively contaminated aluminum, steel, and other metals with a volume of 110 m^3 were decontaminated through the use of high pressure Freon cleaning and electropolishing techniques. The return of the tools and equipment,

Table 6.6 Oak Ridge Operations radioactive metal waste (Mack, 1982)

METAL WASTE GENERATED

Site	Generation Rate (Tons/Yr)	From 1982-1992 (Tons)	As of 1982	Total (Tons)
ORNL	375	3750	---	3750
Y-12	150	1500	---	1500
ORGDP	200	2000	28278	30278
PGDP	300	2000	23126	25126
GAT	200	2000	31293	33293
NLO	---	---	6718	6718
TOTAL	1125	11250	89415	100665

METAL SALVAGE VALUE

Metal Type	Generation Rate (Tons/Yr)	From 1982-1992 (Tons)	As of 1982	Total (Tons)	Value ($/Ton)	Total Value ($)
Nickel	337.50	3375.0	9300	12675.0	4200	53,235,000
Copper	168.75	1667.5	3468	5155.5	2100	10,826,550
Steel	506.25	5062.5	71151	76213.5	300	22,864,050
Aluminum	112.50	1125.0	5496	6621.0	1300	8,607,300
TOTAL	1125	11230	89400	100665		95,532,900

worth approximately $1.5 million (1980 dollars), reduced the volume of waste by a factor of 40.

The contamination of the metal tools and equipment before treatment is shown in Table 6.7. Smearable contamination ranged from 200 (disintegrations per minute) dpm to just over one million dpm with fixed contamination at similar levels.

6.4.3 Westinghouse Hanford metal waste

Westinghouse Hanford Company currently has metal wastes in storage at the Hanford Site that could be candidates for treatment technologies under development (Hay, 1992). The metal types are characterized as copper, steel, aluminum, wire, and equipment. The metal waste is classified as LLW, mixed LLW, TRU waste, and mixed TRU waste as shown in Table 6.8. This table also contains values for the average dose rate of the metal waste. Mixed wastes include mixtures of radioactive materials and EPA listed hazardous wastes. The largest waste class, by volume, is the mixed LLW followed by TRU waste, mixed TRU waste, and finally LLW. Steel is the greatest component of the waste (208 m^3), followed by equipment (1.34 m^3), copper (0.25 m^3), aluminum (0.07 m^3), and wire (0.04 m^3).

6.4.4 DOE, DOD, and commercial stainless steel waste

Significant quantities of stainless steel having moderate radioactive surface contamination are generated at various DOE, DOD, and commercial sites (Rosenberg and Stucki, 1989). The level of contamination of the stainless steel waste inventories compiled by Rosenberg and Stucki (1989) met certain contamination criteria. These criteria, required for the safe contact handling of the contaminated metal, follows:

1. Average beta-gamma radiation fields on contact can not exceed 10 mR/h. Up to 50 mR/h may be acceptable in certain cases.
2. Localized radiation fields (hot spots) up to 100 mR/h will be considered on a case-by-case basis.
3. Surface alpha contamination will not exceed 20 dpm/100 cm^2.
4. Smearable beta/gamma contamination shall be less than 40,000 dpm/100 cm^2.

Table 6.7 Metal tools and equipment contamination (McVey et al., 1981)

Item	Quantity	Activity Level (smearable) (dpm/100 cm^2) Minimum	Maximum
aluminum generator dams	32	200000	1200000
aluminum steam generator tracks	16	5000	70000
dam clamps	100	4000	75000
stainless strongback - steam generator	4	40000	95000
stainless turnbuckles	8	20000	60000
stainless braces	29	5000	50000
dam brace	1	300000	300000
NDT test equipment	10	3200	42000
probe pusher	6	1800	425000
electric pump	1	2500	2500
electric drills and grinders	48	200	4500
electric adapters	7	200	5000
large stainless shaft	1	500000	500000
1" hose	*	14000	14000
welding cable	*	3500	3500
electrical cord	*	3000	3000
miscellaneous hand tools	**		15000
stainless generator brackets	23	17000	800000
relief valve	1	300000	300000
miscellaneous electrical equipment	32	200	3900

* record of actual feet not maintained

** drill bits, putty knives, files, levels, hammers, channel locks, scissors, saw blades, crowbars, crescent wrenches, rotary hammers, wire wheels, hand saws, "C" clamps, pliers, torque gauges, torque wrenches, 3 ton chain falls, pulleys, pipe cutters, etc.

Table 6.8 Westinghouse Hanford metal waste potentially suitable for treatment (Hay, 1992)

	Weight (kg)	Weight (kg)	Volume (m^3)	Average Dose Rate (mR/h)
LLW:				
Copper	4.54	10.00	0.0042	0.5000
Galvanized/Iron/Sheet	31.50	69.38	0.7017	1.9900
Sub-Total	36.04	79.38	0.7059	
Average Dose Rate				1.6175
MIXED LLW:				
Aluminum	3.73	8.22	0.06588	0.7667
Copper	106.76	235.15	0.21200	0.5682
Equipment	287.20	632.60	0.76020	0.0140
Galvanized/Iron/Sheet	15965.89	35167.16	167.38053	16.4455
Wire	8.00	17.62	0.04200	0.0400
Sub-Total	16371.58	36060.75	168.46061	
Average Dose Rate				13.1623
TRU WASTE:				
Aluminum	1.00	2.20	0.00210	1.0000
Equipment	131.23	289.05	0.57750	5.1000
Galvanized/Iron/Sheet	5215.96	11486.90	34.80056	1.6181
Sub-Total	5348.19	11780.15	35.38016	
Average Dose Rate				2.6341
MIXED TRU WASTE:				
Aluminum		0.00	0.00210	6.000
Copper		0.00	0.03150	3.8100
Galvanized/Iron/Sheet	824.95	1817.07	4.99984	3.2096
Sub-Total	824.95	1817.07	5.03344	
Average Dose Rate				3.2096
TOTAL METAL WASTE:	22580.76	49737.36	209.58011	

5. Metals internally contaminated with transuranic nuclides exceeding 0.1 nCi/g will not be acceptable.
6. Any induced radioactivity shall be less than 0.2 mR/h.

An inventory of this metal waste was taken in 1989 at DOE, Department of Defense (DOD), and commercial facilities. Table 6.9 and Table 6.10 show the total stainless steel quantities within DOE and at commercial facilities, respectively. The DOE metal waste mass totals almost 3300 tons of stainless steel, however, an additional 25,000 tons of low-level contaminated carbon steel and 5340 tons of contaminated nickel are also available for potential recycle or re-use.

Table 6.9 Total stainless steel waste at DOE facilities (Rosenberg and Stucki, 1989)

	Tons of Stainless Steel	
Facility	Stainless Steel < 10 mR/h	10 mR/h < Stainless Steel < 100 mR/h
Hanford	1050	
ORNL	220	900
INEL	430	135
Other	170	373
TOTAL	1870	1408

Table 6.10 Potential amounts of stainless steel at commercial facilities (Rosenberg and Stucki, 1989)

Item	Tons of Stainless Steel
Reactor Piping	600+
Fuel Racks	2000
Decontamination & Decommissioning	13050
TOTAL	15650

Commercial stainless steel waste has three main sources: 1. BWR cracked piping, 2. water-spaced fuel rack replacement, and 3. D&D of commercial nuclear power plants. Stress corrosion cracking of main reactor coolant piping and other systems necessitates replacement of this piping and produces about 50 tons of contaminated stainless steel per reactor lifetime. Water-spaced fuel racks used to physically separate fuel elements for criticality control are being replaced with fuel racks with neutron absorbers. Replacement of these racks will generate an estimated 200 tons of stainless steel waste per facility. D&D of commercial nuclear power plants will produce approximately 150 tons of contaminated stainless steel per facility. Given that 70 commercial nuclear power plants are scheduled to be shut down and 17 have been shut down permanently and are expected to undergo D&D, approximately 13,050 tons of contaminated stainless steel could be generated within the next 20 to 30 years. This quantity will, however, depend upon whether the plants are granted operating life extensions and whether decommissioning is deferred.

The DOD expects 100 of its naval nuclear vessels to be retired in the years 1984-2000. Each vessel is expected to generate 100 tons of recyclable contaminated stainless steel. Normally, this waste is sent to Hanford for burial. In addition to the stainless steel waste, the DOD generates 5000 to 10,000 ft^3 (20 to 40 tons) of low-level contaminated carbon steel waste each year.

Table 6.11 compiles radioactive waste inventories from DOE, DOD, and commercial facilities to give a total of 28,928 tons of stainless steel waste. Most of this waste is expected to be generated through the year 2000, with the exception of the commercial D&D waste which will be generated through 2020. The scrap value of the stainless steel is estimated to be $8.68 million. The total scrap value of the stainless steel plus the additional metal (carbon steel and nickel) that is also potentially available comes to approximately $31.73 million.

Table 6.11 Total stainless steel from DOE, DOD, and commercial facilities (Rosenberg and Stucki, 1989)

Source	Tons of Stainless Steel
Department of Energy	3278
Department of Defense	10000
Commercial	15650
TOTAL	28928

6.4.5 Savannah River Company stainless steel heat exchangers

Westinghouse Savannah River Company has plans to decontaminate and reuse stainless steel heat exchangers located at its facility (Westinghouse Savannah River Company, 1992). All of the heat exchangers are radioactively contaminated with an estimated 50% having a dose rate of less than 10 mR/h, 40% between 10 and 50 mR/h, and 10% between 50 mR/h and 150 mR/h. None of the heat exchangers will have transferrable external contamination. Internal contaminants may include typical fission products, activation products, tritium, uranium, and transuranic isotopes. The 68 heat exchangers each hold nearly 9000 one-half inch outer-diameter tubes. Given that each unit weighs approximately 100 tons, approximately 6800 tons of stainless steel contained in the equipment is potentially available for reuse or recycle. At an estimated salvage value of $0.10/lb, this material has a scrap value of $1.36 million.

6.4.6 Summary

A more detailed look at metal waste characteristics from a small cross-section of inventories reveals that many of these wastes have fairly small amounts of contamination that might feasibly removed using decontamination techniques. Large volumes of metal wastes intended for disposal due to minimal amounts of contamination could potentially recovered from the waste stream through decontamination.

6.5 Decommissioning Activities

Commercial U.S. and international decommissioning projects will also have the potential to contribute significantly to radioactive metallic waste inventories. Decontamination and decommissioning of DOE facilities will likely generate more material to be disposed of than all DOE operations to date (D&D Integrated Demo Technical Support Group, 1993). The radioactive scrap metal arising from decommissioning of DOE gaseous diffusion plants, alone, is shown in Table 6.12 and totals 707,900 tons. It is expected that the volume of ferrous metal alone (1 million tons, much of which is stainless steel or nickel-lined steel), from decommissioning operations of these facilities will exceed the national capacity for radioactive waste disposal (Oak Ridge K-25 Site Technical Division, 1993).

Table 6.12 Radioactive scrap metal arising from decommissioning gaseous diffusion plants (Decontamination and Decommisioning Integrated Demonstration Technical Support Group, 1993)

	(Estimated material quantities, in thousands of tons)				($1000)
Category	K-25 Site	PGDP	PORTS	TOTALS	Estimated Value**
Ferrous metals/steel***	103.7	74.0	91.4	269.1	24.2
Aluminum/copper	8.5	6.1	7.6	22.2	26.5
Copper wire/tubing, valves	17.6	11.7	15.0	44.3	75.3
Monel pipe/valves	1.7	1.2	1.5	4.4	18.8
Nickel	22.1	15.9	19.8	57.8	350.0
Misc. electrical/instrumentation equipment and housings	123.2	81.9	105.0	310.0	?

* Stream quantities derived from an analysis by Ebasco Services, Inc. 1991

** Estimated values as clean scrap, based upon 1992 average scrap metal prices for iron/steel, aluminum and copper; nickel valued at $3.00 per lb

*** Excludes some structural steel assumed left in place in decontaminated building structures

Decommissioning includes all those activities that begin once operation of a nuclear facility has ceased. The intention of decommissioning is to place the facility in a condition that provides protection for the health and safety of the decommissioning worker, the public, and the environment.

The objectives of decontamination in decommissioning include the reduction of radiation dose to the work force performing the decommissioning operations, equipment and material salvage, waste volume reduction, restoration of the site to unrestricted use, reduction of the magnitude of residual radioactive source, and the removal of loose contamination.

Recycling and reuse of contaminated equipment and materials for unrestricted use is not as widely practiced as reuse within nuclear facilities. Restricted reuse within nuclear facilities may be more economical and more easily realized as problems can arise when attempts are made to confirm that inaccessible surfaces have been decontaminated to acceptable levels for unrestricted use. The reuse of large pieces of equipment such as cranes, motor-pump sets, and turbines may be limited because of the availability of a suitable market and obsolescence after more than 40 years of service. However, it may be possible to use some equipment as a source of otherwise unattainable spare parts for similar units still in operation.

6.5.1 Nuclear facilities

As of 1988 over 130 nuclear facilities in 16 countries, 49 of which were in the U.S., were listed in the International Atomic Energy Agency's (IAEA) inventory of decommissioning projects either completed, in progress, or planned (International Atomic Energy Agency, 1988b). Actual decommissioning schedules may be significantly different from those approximated here due to the possibilities of the extension of reactor operating lifetimes and deferring decommissioning to allow for radioactive decay.

Most nuclear power plants in the U.S. are licensed by the NRC to operate for 40 years, although there is no absolute age at which they become unsafe or uneconomical to operate. It may be possible to economically extend the operating lifetime of many reactors by replacing aging internal components. Postponing decommissioning will have a large effect on the timing, mix, and volume of components and materials arising from decommissioning operations. Table 6.13 shows the effects of delayed decommissioning on the LLW generated by commercial nuclear power plants in the U.S..

Table 6.13 Effects of delayed decommissioning on the LLW generated by commercial nuclear power plants (Office of Technology Assessment, 1989)

Plant Type [1.175 GW(e)]	No Delay	30 Year Delay	50 Year Delay
Radioactivity of all LLW in thousands of curies:			
Boiling-water reactor	6600	180	140
Pressurized-water reactor	4900	210	160
Volume of all LLW in thousands of cubic feet:			
Boiling-water reactor	670	670*	60*
Pressurized-water reactor	630	630*	65*

*Includes wastes from both preparation for storage and decommissioning

Two reasons exist for delaying decommissioning once a reactor has been shut down:

1) Overall radioactivity of the LLW generated will decrease by a factor of 30 to 45, if decommissioning is deferred five decades. This will reduce worker risks and dismantling costs.

2) The volumes of Class A, B, and C LLW generated from immediate decommissioning can be reduced by about 10 times if decommissioning is deferred five decades. This can be seen in Table 6.14 for boiling water reactor (BWR) decommissioning and Table 6.15 for pressurized water reactor (PWR) decommissioning.

6.5.2 Metal waste volumes and characteristics

The four component parts of a nuclear installation can be defined as materials, equipment, buildings, and sites, any or all of which could be recycled or reused for restricted or unrestricted use after decommissioning.

2 of 3

Table 6.14 Radioactive waste from BWR decommissioning (Oak et al., 1980)

		Waste Class Assignment[a]			
					Exceeds Class C
		Class A	Class B	Class C	Limits
Decommissioning Alternative	Burial Volume (m³)	Volume (m³)	Volume (m³)	Volume (m³)	Volume (m³)
DECON	18949	18476	373	53	47
30 Year SAFSTOR[b]	18949	18616	233	53	47
50 Year SAFSTOR[b]	1783	1450	247	39	47
100 Year SAFSTOR[b]	1673	1340	247	39	47
ENTOMB	8042	7569	373	53	47

[a] Based on limiting concentrations of long- and short-lived radionuclides given in Table 1 and Table 2 of 10 CFR 61.55

[b] Includes radioactive wastes from both preparations for safe storage and deferred decontamination

Characterization of the wastes arising from decommissioning is as follows:

Neutron-Activated Waste Materials

1. Structural Materials
   carbon steel, stainless steel, aluminum, reinforced concrete
2. Shielding Materials
   lead, heavy/light concrete
3. Internal Materials
   zirconium,silver,cadmium,graphite,boron

Contaminated Waste Materials (equipment, metal, and concrete surfaces):

Contaminated waste material results from the deposition of radioactive material in or on the surfaces of facility components or structures.

1. ventilation/electrical duct work
2. surfaces of buildings and structure
3. surfaces of concrete walls
4. soil regions

Process Waste:

1. filter media
2. pool or cavity liners
3. misc. items (rags, plastic, clothing)

Five U.S. LWRs are scheduled to be decommissioned by the year 2000 and 33 LWRs by 2010. The total capacity for all 38 LWRs is 30,810 MW(e) (Nuclear Energy

Table 6.15 Radioactive waste from decommissioning an 1175-MW PWR (Fischetti, 1986)

		Radioactivity Class			
Waste Type	Total Burial Volume m^3	Class A Volume m^3	Class B Volume m^3	Class C Volume m^3	Exceeds Class C Limits Volume m^3
Dismantlement					
Neutron-activated	1192	962	60	17	133
Contaminated	16078	16078			
Radwaste	615	461	154		
Total	17885	17521	214	17	133
30 Year Mothball					
Neutron-activated	1192	1036	6	17	133
Contaminated	16078	16078			
Radwaste	618	501	117		
Total	17888	17615	123		
50 Year Mothball					
Neutron-activated	1192	1036	6	17	133
Contaminated	100	100			
Radwaste	538	429	109		
Total	1830	1565	115	17	133
Entombment					
Neutron-activated	471	261	60	17	133
Contaminated	1974	1974			
Radwaste	615	461	154		
Total	3060	2696	214	17	133

Agency Group of Experts, 1986). The estimated metal waste volumes for decommissioning a reference 1175 MW(e) PWR and a reference 1155 MW(e) BWR are given in Table 6.16 (created from Murphy, 1984; Oak et al., 1980; U.S. Environmental Protection Agency, 1989). Given these figures, the total metal waste volume resulting from decommissioning the 38 reactors is expected to exceed 380,000 m^3 (7.8 million ft^3), assuming approximately 14,000 to 15,000 m^3 per LWR (approximately 12.5 m^3 per MW(e) capacity).

Table 6.16 LWR decommissioning metal waste volumes

Waste Type	Class A m^3	Class B m^3	Class C m^3	Class GTCC m^3	Total m^3
1175 MW(e) PWR					
Neutron-activated waste	275	60	13	133	485
Contaminated material	13666				13666
Process waste	39	18			57
Total					14208
1155 MW(e) BWR					
Neutron-activated waste	23	15	53	47	138
Contaminated material	14629				14629
Process waste	94	42			136
Total					14903

Some materials from nuclear reactors, accelerators, and fusion facilities have induced radioactivity. However, the largest fraction of materials from these and other nuclear facilities, such as fuel fabrication plants and reprocessing plants, have only surface contamination that can be removed by decontamination techniques. Of the contaminated and activated metals arising from decommissioning, it has been calculated that about 4800 metric tons of steel from a 1000 MW(e) PWR would have activity concentration at or below one becquerel per gram (International Atomic Energy Agency, 1988b). This concentration limit is being examined as a possible limit for steel recycling for unrestricted use in the European Community.

6.5.3 Decommissioning waste summary

If decommissioning wastes are controlled based on ad hoc procedures and release criteria the regulatory agencies and the licensee will be faced with a difficult task in future years. This problem could be magnified if recycled metals enter into the international market. It is desirable that internationally acceptable criteria be developed for the separation of active from inactive wastes and for the release for recycle or reuse of components arising from decommissioning.

6.6 Conclusion

From the inventories of metallic waste that have been compiled in this report, it is clear that there is a significant amount of waste that could potentially be recycled as scrap metal or reused as equipment if adequate decontamination can be carried out. However, much of the radioactive metallic waste information was limited with regard to the contamination level, localization of contamination, depth of contamination, and type of contamination. This information is essential to accurately determine the applicability and cost effectiveness of potentially viable decontamination technologies to radioactive metallic waste. According to LaGuardia (1989).

> "Once this characterization data has been analyzed radiologically, chemically, and mechanically (for adherence to the surface), a realistic program objective can be developed. The management decision can then be made whether it is feasible to achieve complete decontamination to release the material for unrestricted use and disposal in local landfills or recycling, or whether to reduce radioactivity levels to minimize exposure to workers performing operation or maintenance activities.
>
> There have been far too many decontamination and decommissioning projects where decontamination projects were started based on random and inadequate characterization data. The project had to be stopped, re-characterized, planned, and re-started at additional cost never factored into the original budget."

Further study of the characteristics of radioactive metal waste will lead to a more precise evaluation of the costs and benefits of the waste management options of recycle and disposal.

7. COST ANALYSIS OF WASTE MANAGEMENT ALTERNATIVES

7.1 Introduction

A cost analysis of waste management alternatives is carried out by the expert system to compare the cost-effectiveness of employing different technologies to decontaminate radioactive metal waste with simply sending it for disposal. This chapter will discuss the cost components considered in the analysis, the significance of these components in the overall cost of decontamination, and the variability and uncertainty associated with performing this type of analysis.

7.2 Components of the Cost Analysis

Cost calculations in the expert system, carried out in a single module of the program, make use of data stored in two dBASE datafiles, one for globally applicable costs and one for costs associated with specific decontamination technologies. The overall cost of a waste management strategy is broken down into the following components in the expert system analysis:

preparation cost
labor cost
material cost
utilities cost
maintenance and repair cost
equipment cost
facility cost
waste disposal cost
capital and operating costs
contingency
salvage value

These overall costs were derived from cost-related data in the two categories mentioned above: costs specific to each decontamination technology and costs that could be applied "generically" to all waste management strategies.

7.2.1 Costs applicable to all waste management strategies

Costs applicable to all waste management strategies include labor, transportation, packaging, and disposal cost. Salvage value (tools, equipment, scrap metals) is also calculated for subtraction from the total cost of waste management. For these cost components, the literature reviewed provided a range of values. Table 7.1 shows this range and the value selected for use in the expert system. A value was chosen either because it was most frequently quoted, selected from a range in another cost analysis, or because it falls in the middle of the range. LLW transportation cost is given as the cost to transport waste a representative distance of 390 miles from the reference facility to the disposal site. This cost was established by averaging the one way distance from nuclear power plants to the existing LLW disposal sites (Allen, 1989). For TRU waste this cost has been established by averaging the one way distance from nuclear facilities to the Waste Isolation Pilot Plant (WIPP), the intended final destination for all TRU waste (Schafer and Schleuter, 1992). Salvage values are prices quoted from Bell Metal Salvage (1993) and are listed in Appendix A.

7.2.2 Costs specific to decontamination technologies

Information used to cost-estimate radioactive metal waste management using decontamination technologies is itemized as follows:

number of workers
process times or volume, mass, or area processed per unit time
facility cost and life
equipment cost and life
material cost
utilities cost
preparation time and cost
secondary waste volume or volume reduction factor
secondary waste processing cost
overall capital costs
overall operating costs

Different formats of cost information from reference materials resulted in a proliferation of fields in the database storing this data. Some sources provided only capital

Table 7.1 General costs used in expert system cost analysis

COST COMPONENTS	RANGE	SYSTEM VALUE	REFERENCES
LABOR-Technician	$15-78/hr	$25/hr	(Manion et al.,1980; Staggs and Mathison, 1992; Knight, 1993; Voit, 1984; Hazelton and McCoy, 1983; Nuclear Energy Agency, 1991; Krantz, 1988)
LABOR-Supervisor	$15-78/hr	$30/hr	(Manion et al.,1980; Staggs and Mathison, 1992; Knight, 1993; Voit, 1984; Hazelton and McCoy, 1983; Nuclear Energy Agency, 1991; Krantz, 1988)
DISPOSAL-LLW	$10-577/cu.ft.	$105/cu.ft.	(Staggs and Mathison, 1992; Demmer, 1993; Knight, 1993; Schafer and Schleuter, 1992; Nuclear Energy Agency, 1991)
DISPOSAL-TRU Waste	$150-740/cu.ft.	$740/cu.ft.	(International Atomic Energy Agency, 1988b; Schafer and Schleuter, 1992; Nuclear Energy Agency, 1991)
TRANSPORT-LLW	$1-2.94/cu.ft.	$1.74/cu.ft.	(Staggs and Mathison, 1992; Demmer, 1993; Knight, 1993; Schafer and Schleuter, 1992; Nuclear Energy Agency, 1991)
TRANSPORT-TRU Waste	$16.15-32/cu.ft.	$16.15/cu.ft.	(International Atomic Energy Agency, 1988b; Schafer and Schleuter, 1992; Nuclear Energy Agency, 1991)
PACKAGE-LLW	$3.40-19/cu.ft.	$10/cu.ft..	(Staggs and Mathison, 1992; Demmer, 1993; Knight, 1993; Schafer and Schleuter, 1992; Nuclear Energy Agency, 1991)
PACKAGE-TRU Waste	$28/cu.ft.	$28/cu.ft.	(International Atomic Energy Agency, 1988b; Schafer and Schleuter, 1992; Nuclear Energy Agency, 1991)

and operating costs with no breakdown of these costs, where others gave more detailed information.

Difficulty in locating cost data on the application of decontamination technologies to metal waste prevented the consideration of a range of values for almost all cost-related data associated with these technologies. Most cost values were taken directly from the only source available and entered into the expert system cost database (see Appendices A and B). Exceptions to this include the value for the work year in hours used to calculate capital costs for a given process time. This ranged from 1570 to 2080 hrs/yr with a commonly cited value of 1760 hrs/yr (Staggs, 1992; Hazelton and McCoy, 1982). Other assumptions included, where not otherwise indicated, a fixed facility life of 25 years, mobile facility life of 11 years (Hazelton and McCoy, 1982) and an equipment life of approximately 7 years. Cost data and a more extensive list of assumptions used in performing the cost analysis of decontamination as a waste management strategy is available in Appendix B.

Problems with the availability of cost data and cost analyses of decontamination processes led to some gaps in cost information. These were filled by making some fairly broad assumptions. The cost components most frequently neglected in reference material included preparation of the waste for decontamination (size reduction, disassembly, and pretreatments), maintenance and repair for decontamination equipment, cost of the processing facility, if not in-situ, and the cost of processing the secondary waste generated (evaporation, filtration, ion exchange resins, and solidification). Only two sources (Knight, 1993; Wobser, 1984) gave preparation cost information and one other source (Hazelton and McCoy, 1982) spoke of treating pre-sectioned material. No other sources acknowledged the existence of preparations costs although it may have been part of other cost components itemized. Only two sources (Hazelton and McCoy, 1982; Pang, 1992) cited values for maintenance and repair. Despite the fact that several technologies generate secondary waste requiring processing prior to disposal, only one source (Manion, et al., 1980) provided any relevant cost data. Although four sources (Scientific Ecology Group, 1992; Oak Ridge K-25 Site, 1993; Gillis, 1992; Hazelton and McCoy, 1982) gave facility cost information, most omitted the design life expected from the structure.

7.3 Effects of Cost Components on the Cost of Decontamination

Each cost component affects the overall cost of decontamination in a different way. Some of the more significant elements influencing a cost-based selection of decontamination processes include process times, the ability to carry out operations remotely or automatically, the volumes and types of secondary wastes generated, and the metal salvage value.

Labor cost is often one of the largest constituents of processing costs. Therefore, process times and the capability of a technology to be operated remotely or automatically can have an important impact on whether it is more cost-effective to decontaminate the waste than to send it for disposal Process times will be affected by the type, localization and depth of contamination for surface-contaminated items. If the contamination is localized on the surface, decontamination efforts could be concentrated on these specific regions and the process efficiency could be enhanced. Localization of contamination might help offset the decrease in efficiency cause by greater depths of contamination. Remote and automatic operation may enable one technician to operate multiple decontamination systems thus cutting down the overall process time for a given volume of waste.

The generation of secondary wastes also has important implications for cost-based waste management recommendations. If a process generates more waste than it decontaminates, it is unlikely that this process is more cost-effective than simply disposing of the original waste volume unless the metal carries a significant salvage value. Technologies such as high pressure and ultra-high pressure water, electropolishing, abrasive jetting, acid chemical decontamination, and vibratory finishing can produce large volumes of liquid waste that create greater handling problems than solid or gaseous wastes. Liquid wastes require processing prior to disposal that adds to the total process cost. According to the literature, recycle of decontamination solutions has been carried out (Wobser, 1984) but further development is needed to bring waste volumes down to an acceptable level (Oak Ridge K-25 Site, 1993) for processes that generate large liquid waste volumes at a high rate (i.e. abrasive jetting and ultra-high and high pressure water).

The type of metal to be managed will affect the salvage value of scrap metal reclaimed. The type and associated replacement value of tools and equipment to be decontaminated will also affect the total salvage value.

7.4 Variability and Uncertainty of the Cost Analysis

7.4.1 Variability and Uncertainty of Decontamination Costs

There is a large degree of variability and uncertainty associated with carrying out a cost analysis like the one performed as part of this investigation. Some of this variability can be taken into account by considering the assumptions made in establishing cost figures for waste management options. Some reference material described the cost analyses of particular decontamination technologies. Each of these analyses were likely based on completely different sets of assumptions. Some estimates were also based on vendor information that probably included an unspecified profit margin.

Another source of variability lies in the fluctuation, over time and location, of scrap metal salvage values, labor costs, equipment and materials costs, and other decontamination technology cost components. An especially important consideration in the evaluation of a developing technology like laser decontamination is the potential for equipment costs, a significant cost component in the operation of this technology, to decrease and give this process a cost-advantage over alternative technologies and disposal. It is expected that as industrial laser technology matures, costs will decrease and laser decontamination will become an increasingly attractive option for the recovery of radioactive scrap metal. Similar trends may exist for other decontamination technologies.

A considerable amount of uncertainty in the calculation of decontamination process times and associated cost data result from a lack of "across the board" application of decontamination technologies to radioactive metal waste. Most of the available reference material describes successful case-specific decontamination campaigns but carries little information about inappropriate uses of the technologies or more difficult, time-consuming, costly applications. Testing needs to be carried out, for each technology, over a wide range of materials and waste types to determine variances in decontamination factors, process time, cost, equipment, materials, waste generation, and other cost-related elements. The characteristics of contamination will likely have a significant influence on decontamination costs because the difficulty in removing the contamination from the metal will affect this cost. For surface-contaminated materials the localization and depth of contamination will affect process time and thus, costs.

7.4.2 Variability and Uncertainty of Disposal Costs

The alternative to decontamination, simple disposal, also carries with it a fair amount of variability in cost. Some LLW generators are incurring a charge of only \$10/ft^3 for disposal of the same type of waste that costs others up to ten times as much. Predicted future increases in disposal costs, especially for LLW disposal, will probably affect most generators and will also affect the attractiveness of decontamination to manage radioactive metal wastes.

The marked escalation of waste disposal costs in the recent past (Mathison, 1992; Office of Technology Assessment, 1989), shown in Figure 7.1, might be cause for concern in this analysis. This rise is expected to continue into the future for a variety of reasons. First, surcharges on waste disposal will increase before States and compacts develop new disposal facilities (currently only three commercial disposal sites are accepting waste). Second, as waste volumes decrease, unit disposal costs at disposal sites will increase to cover fixed operating costs. Third, unit disposal costs at new disposal facilities may be higher due to more expensive disposal technologies, smaller facilities, and/or more

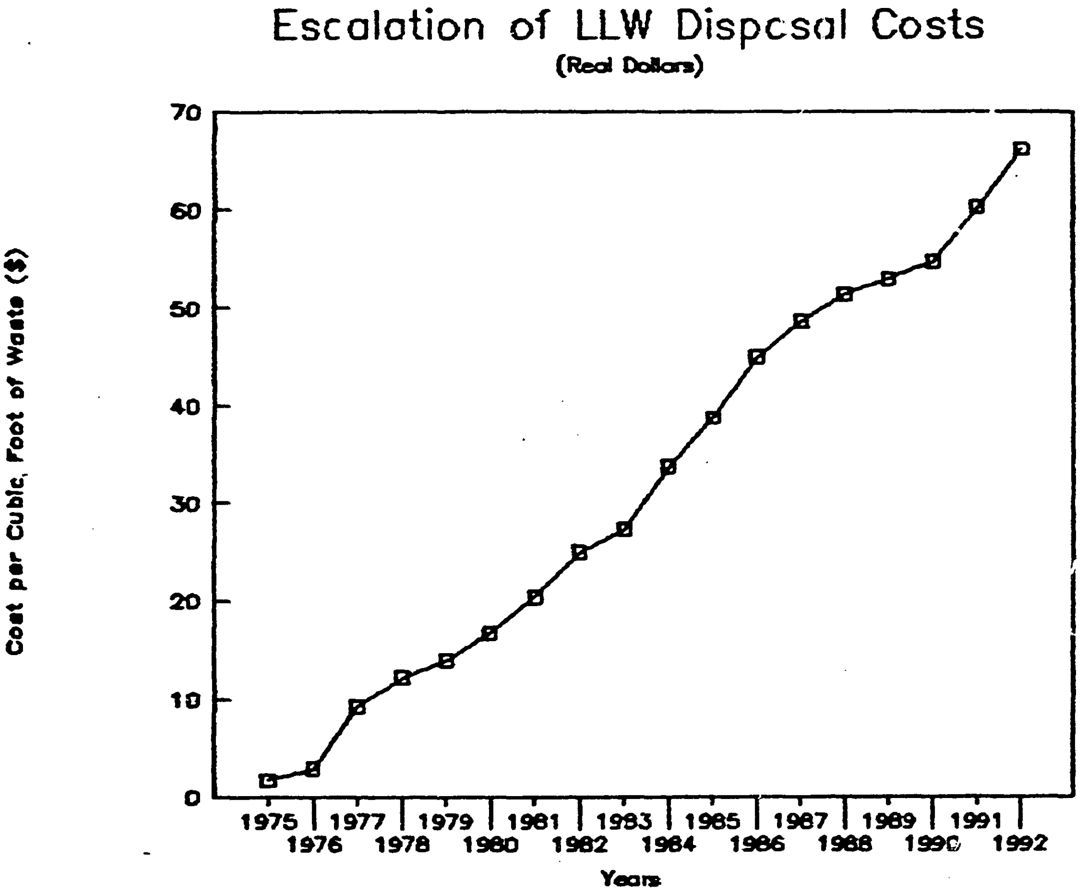

Figure 7.1 Escalation of LLW disposal costs

stringent waste packaging requirements. Finally, disposal costs for more highly radioactive waste and mixed waste may increase due to a need for long-term monitoring and potential remediation. This continued rise in costs may increasingly favor decontamination of metal radioactive waste for recycle as the preferred waste management method.

7.5 Summary

There are many cost components that influence the total cost of a waste management strategy. Although the overall expense incurred from decontamination of a waste is a function of several elements, the components having the most influence over the total cost are the process time, the labor intensity, the secondary waste generated, and the metal salvage value. For direct disposal of wastes there is a concern about the recent sharp rise in disposal costs. This increase could serve to make decontamination an increasingly cost-effective alternative to disposal, although testing of decontamination technologies across a larger range of waste materials is required to carry out an accurate evaluation.

8. RESULTS AND DISCUSSION

8.1 Introduction

The extent to which the research objectives were fulfilled will be discussed in this chapter. This chapter: 1) presents an analysis of the expert system developed as part of this investigation, 2) evaluates theapplicability of several decontamination technologies and presents the WINCO case study results, 3) considers the socio-economic issues not evaluated by the expert system that affect the management of radioactive metal waste, and 4) discusses the impact of metal decontamination on radioactive waste minimization.

8.2 Analysis of the Expert System Design

This section provides an analysis of the expert system designed as part of this study. Both the features and limitations are discussed to illustrate the extent to which creation of a complete and effective radioactive metal waste management decision-making tool has been achieved.

8.2.1 Expert system function

The expert system was developed to analyze, evaluate, and recommend potential waste management strategies for a given radioactive metal waste. Tasks that are performed by the system are itemized below. The expert system:

1) identifies the types of information that need to be obtained and entered to characterize the metal waste
2) generates a listing of technically feasible decontamination technologies to be applied to the identified waste
3) gives a list of disqualified technologies and reasons for disqualification from applicability to the identified waste
4) provides the user with a list of advantages and limitations of the applicable decontamination technologies
5) further evaluates list of applicable technologies based on waste character details
6) calculates post-decontamination contamination levels for the identified waste
7) determines possible waste management strategies for the identified waste, given government regulations and proposed guidelines

8) carries out a cost analysis of each possible waste management strategy
9) recommends waste management strategies for the identified waste

8.2.2 Features of the expert system

Features of the system design include the following:

1) the option of keyboard or dBASE datafile entry of data by the user
2) user access to all results generated (in dBASE)
3) flexibility of the system due to extensive use of dBASE files This facilitates modifications of the system and may permit the extension of this system to other waste management issues.
4) easy access to reference information on which knowledge-base decisions are based and from which rules were derived
5) provides the reason a query is being made and to what conclusion it might lead from a given answer (user option prior to answering a question posed by the system)
6) generates a list of decontamination technologies applicable to a given waste
7) qualitative information regarding decontamination technology attributes are provided to the user so that they can make waste management decisions based on criteria other than cost
8) a list of disqualified technologies for a given waste and the reasons for disqualification
9) the residual level of contamination that remains after a decontamination technology has been applied to a waste
10) waste management strategy possibilities for a given waste matched with an applicable decontamination technology
11) a cost analysis of each possible waste management strategy. (Allows the user to enter a cost value they feel comfortable with for packaging, transport, and disposal of waste as well as a contingency value and discount rate for the amortization of capital.)
12) a recommendation in the form of a cost-based ranking of waste management strategies
13) a report of results from a consultation with the expert system (user option)
14) the application of a series of decontamination technologies to a waste

The assessment of VP-Expert as a platform for carrying out the assigned tasks can be summarized by considering the benefits and drawbacks of the system for the application. Attributes of the system derived from the expert system shell software, VP-Expert, are specified below:

1) Modularization was permitted through the use of a linking feature. Facts (variable values) from each module could also be saved to a text file for use in the subsequent module.

2) Development of a literature "paper trail" was facilitated by VP-Expert's ability to import ASCII text file contents.

3) Creation of generalized rules to replace several similar rules to:
   - i) determine applicability of a decontamination technology to a waste of a given character,
   - ii) provide the user with attributes of each decontamination technology,
   - iii) make the program run more efficiently, and
   - iv) allow for relatively easy expansion of the system to other decontamination technologies without the need for extensive additional programming was made possible by the existence of the database rule feature in VP-Expert.

4) Flexibility of the system for modifications, additions, and storage of data and results generated by a consultation was integrated into the system due to access of dBASE datafiles and the ability to use and manipulate information contained therein through programming code in VP-Expert.

5) The ability to determine during the consultation, prior to answering, the reason a question was being asked by the system was provided by the "WHY?" feature of VP-Expert.

Other features that were useful included the internal text auditor, trace facilities for debugging, windows to debug from, and the ability to make use of both forward and backward chaining control strategies.

Additionally, VP-Expert features that could prove valuable for further development of the system include interaction with spreadsheets and executable programs, induction of rules from a training table of examples, truth thresholds to exercise control over reasoning, and assignment of confidence factors by the user (to input) and developer (to knowledge base rules). These certainty factors are used to express confidence in relationships expressed by the various rules or information being input to the system by the user.

For the intended application, VP-Expert had relatively few limitations. One obstacle was discovered when development of an external executable program (FORTRAN) was desired to carry out volume, mass, and area calculations for metal waste. Problems passing variable values from VP-Expert to the FORTRAN program led to abandonment of the external program approach. The required calculations were, instead, adapted for programming directly into the VP-Expert code.

One of the most significant drawbacks encountered in the use of VP-Expert was the absence of a feature that is characteristic of other expert systems; the capability to change the value of a single variable and re-run the consultation to compare the effects of such a change on the results generated by the system. This feature ("What If") is documented as existing in the software but failed to perform as expected, due to the use in this application of linked knowledge base modules instead of a single complete knowledge base.

Minor development handicaps included the inability to remove records from a database file or to delete a database file from within VP-Expert and the inability to create database rules using data contained in a spreadsheet.

8.2.3 Limitations of the expert system

8.2.3.1 Developmental limitations

The expert system's knowledge base was developed using information from the literature and personnel experienced in the use of decontamination technologies. The resulting system is a prototype that requires validation by human experts and assignment of confidence factors to the knowledge represented within. A complete expert system requires testing with case studies, assignment of confidence factors, and validation of output. Due to restrictions on resources, time, and access to experts willing to donate large amounts of time to the project, this study was confined to development of the prototype. For full development of an expert system, four additional tasks must be carried out: specification of the performance criteria, testing of the implementation with case studies, development of a complete expert system through validation, and assignment of confidence factors by human experts.

Performance standards Performance standards must be established for the expert system. These criteria are used to verify that the knowledge engineer has successfully carried out acquisition of the domain knowledge.

Testing with case studies The system should be tested on a variety of case studies. These tests serve two purposes: 1) they help determine whether the method of knowledge representation is adequate for the tasks posed by the cases and 2) they enable the expert to see how an expert system uses the information being provided to check functioning of the system. Case studies should provide information that can be used as input to the program and also results that can be compared to the system output. One can then determine whether the expert system is successfully performing the task(s) for which it was developed. Initially, it was thought that reference material on decontamination campaigns that had taken place at various DOE sites could be used as case studies for preliminary testing of the system. This was suggested by a source at WINCO (O'Brien, 1993) as a means of performing an initial verification of the system's integrity. Further study of the information revealed that little detailed characterization of the waste prior to or after decontamination had been documented. The pervasiveness of this problem has been cited by LaGuardia (1989) and O'Keefe, Balci, and Smith (1987). In most of this literature, pre-characterization involved defining the class of the waste and, much less frequently, the radioactivity levels before decontamination. Little mention was made of the surface characteristics or materials. Post-decontamination characterization was limited to a statement of whether or not the waste met the regulations for release for unrestricted use or re-classification from TRU to LLW and an estimate of the portion of the waste that met these regulations. Few final contamination levels were provided. Another difficulty in using these case studies to verify output was that, as mentioned previously, few decontamination technologies appear to have been applied across a wide range of materials and waste types. Their results may be confined to a single type of application. This is also a key problem in establishing decontamination factors for technologies applied to various wastes.

To reach the stage of actual implementation, the expert system also requires human expertise for validation of the system and assignment of confidence factors (CF) to the knowledge base.

Confidence factors Personnel at both WINCO (O'Brien, 1993) and Ames Laboratory (Imani, 1992) experienced in expert systems development felt that the assignment of CFs to the knowledge base was fairly arbitrary. Some CFs could be assigned based on statistical information and others from years of experience in a given domain. Given that none of these technologies appear to have been applied to a large variety of wastes, these factors may be very difficult to establish for even a person with decontamination expertise. However, it is expected that at least some of the knowledge will be suitable for assignment of a level of confidence.

Validation Given that an expert system represents human reasoning and knowledge, its representation level must be justified through validation. Validation is the process that evaluates expert system integrity by testing to determine if acceptable levels of performance are achieved. If required, the human expert can then help the knowledge engineer fine tune the expert system to generate better output. Experts, contacted during the development of the expert system, provided some additional knowledge but failed to produce a comprehensive validation of the system. Running test cases through a system and comparing the results against known results is a form of validation. Since suitable case studies could not be obtained, an expert's opinions could instead be compared to system-generated results and a percentage of the system's success rate calculated. Subjective judgement could then be used to analyze and explain expert system failures where test results contradicted expert opinion.

However, problems exist with this approach and that of expert systems validation in general. The final success percentage hinges on the choice of tests and its accuracy relies on the number of test run for comparison to the human expert's knowledge. This expert system validation "quandary" is discussed by Jennings and Heydinger (1989) who state that because these systems are used to solve complex problem normally requiring human expertise, the internal functioning of the systems will often be too complex to anticipate without considerably more than a superficial inspection of the facts. If every possible case could be reasonably (time and resource limitations considered) tested and verified there would be no need for the system in the first place because it would only be applicable to simple problems. Jennings and Heydinger (1989) add that although strategies for validation have been widely debated, the most successful validation strategies are tailored to a specific expert system problem and are carried out as an integral part of system development.

The breakdown of the expert system into modules facilitates testing and validation. Validation may be mainly limited to verifying output rather than actual function, although functioning can be checked in a limited way through the use of the "TRACE" command in VP-Expert which check the order of the execution of the rules.

8.2.3.2 Knowledge base weaknesses

Modules The knowledge base rules are sectioned into seven modules with each module representing a sub-domain in the scope of the task. These sub-domains are listed below with the associated module name and any databases that contain knowledge used to run a consultation.

TASKS	MODULE	DATABASE
Fields of Application	OPTSELEC.KBS	DECONFOA.DBF
Advantages/Limitations	ADVLIM.KBS	DECONAL.DBF
Technology Further Evaluation	FEVAL.KBS	
Decontamination Calculations	DFSA.KBS	DFPROCES.DBF
Strategy Determination	STRAN.KBS	
Cost Analysis	COSTAN.KBS	TECHCOST.DBF GENCOST.DBF
Recommendations	RECOMMND.KBS	

OPTSELEC.KBS: Most of the knowledge encoded in the rules of this module is quite reliable due to fairly extensive coverage, in the literature, of the general applicability of decontamination technologies. Only two major identifiable uncertainties exist. The first is the ability of technologies to remove fixed contamination. The literature made only vague references to removal of fixed contamination in terms of "light", "heavy", or "some" without defining these designations. To distinguish between applicable and non-applicable technologies for this type of contamination, it was assumed that a dividing line could be set at the fixed contamination limit established by regulation for release for unrestricted use. If a technology could only remove "light" or "some" fixed contamination then it would only remove an amount less than or equal to the amount set by this regulation. If it could remove "heavy" fixed contamination then the technology could reduce contamination to below the regulated limit. Also, destructive processes were assumed to be able to remove any fixed contamination whereas non-destructive processes were assumed to have difficulty (Allen, 1993).

The other major weakness in this module is the difficulty of explicitly distinguishing between wastes that have intricate details and complex geometries from those that have simple geometries. The matching of technology to waste with regard to shape complexity is carried out implicitly through the use of a menu of metal sources (sheet metal, tanks, tools, equipment, pipes and ducts). It is assumed in the expert system that equipment and tools have complex shapes and sheet metal, tanks, pipes, and ducts have simple shapes. Technologies that can only handle simple shapes cannot decontaminate equipment or tools and technologies that can handle more complex shapes can decontaminate items such as equipment and tools. This may not always be the case and these assumptions should be reviewed by an expert for validation.

ADVLIM.KBS: Although this module does not carry out any analysis but simply prints information to the screen for the user, the information requires verification by decontamination experts. The decontamination technology attributes are presented qualitatively and some relative values (low, medium, and high) are assigned. This information, taken from the literature, was from various sources using different standards that renders some of the relative values questionable. This is information that can, in future developments, be weighted by experts to help generate waste management recommendations prioritized according to criteria other than costs. Some of the qualitative values shown here are later translated into a quantitative number in other modules to enable comparisons of decontamination technologies. These numbers include secondary waste volumes and process costs.

FEVAL.KBS: The certainty associated with the knowledge encoded in this module is quite high. Development of this module stemmed from specific details about decontamination technologies primarily obtained from conversations with experienced personnel. The first modules determine the general applicability of a technology to a waste, whereas this module disqualifies technologies according to more specific characteristics (pipe diameter, paint type, and oxide hardness) than those examined in the first modules. The importance of this module will potentially increase when information from more extensive testing of decontamination technologies on a wide range of wastes is encoded into the knowledge base.

DFSA.KBS: This module calculates the decontamination achievable when applying each decontamination technology to an identified waste. As mentioned previously, the lack of documented testing of decontamination technologies across a wide range of wastes and the limited amount of pre- and post-decontamination characterization of wastes results in incomplete knowledge and therefore, this module is the weakest and has the least amount of confidence associated with it. In many instances decontamination factors (DFs) were provided in the literature without giving any specification of the wastes or conditions under which decontamination was performed. For surface decontamination, depths removed per pass were given for some technologies, which helped to determine the decontamination achievable. Although DFs are widely cited as measures of decontamination effectiveness for a given technology, according to Allen (1993) they are relatively meaningless because decontamination is a complex function of many factors. Metal type, shape, extent of contamination (surface materials and depth), degree of corrosion, process parameters, and the time that the process is applied to a waste all contribute to the decontamination that is achieved. An expert's knowledge is needed to help encode a more extensive rule-base in this module to cover all elements that influence decontamination for a given technology.

STRAN.KBS: Knowledge in this module was derived from the current regulations for release of surface-contaminated materials and proposed guidelines for release of bulk-contaminated materials. Rules associated with the regulations have a great deal of confidence associated with them, however, those produced from the guidelines are uncertain insofar as they are not currently being applied. Little expertise was required to develop this module because the knowledge was explicitly codified by the regulations.

COSTAN.KBS: Knowledge encoded as rules in this module, for the most part, are calculations that depend on cost values taken from the databases. There is a relatively high confidence associated with the rules themselves. Uncertainty, however, does exist for the calculations of process times and associated costs due to the lack of documentation on the application of technologies to a wide range of wastes. Process times were derived from fairly case-specific uses of the technologies. Other cost uncertainties were previously reviewed in Chapter 7.

A cost component only considered generally in the analysis was preparation cost, a value that, itself, was hard to obtain. Pre-treatment in the form of disassembly and sectioning of different size and shape waste components needs to be accounted for in the cost analysis. These can factor significantly into the overall cost of a decontamination process. Pre-treatment needs to also be considered for waste disposal since sectioning and disassembly is necessary to fit standard disposal containers.

Transportation cost calculations, as discussed in Chapter 7, are based on a representative distance to disposal facilities. This calculation can be handled in more detail by considering the specific distance from each generator to each site and thus, calculate cost on a per mile basis. Some literature (Guenther and Tosetti, 1984) also cites this cost based on the level of radioactivity of a waste. Costs of transportation should also be added to decontamination cost estimates. Due to the uncertainty associated with cost values for both mobile and stationary facilities this cost was not included in the system's analysis. For in-situ decontamination and for the use of a mobile decontamination facility, the transportation cost of the equipment, materials, labor, etc. if not already on-site, should be calculated. If an off-site stationary facility exists both package and transportation costs of the waste should be included in the analysis of this waste management alternative. This expert system module could be expanded to include these costs.

RECOMMND.KBS: This module is based on a sorting algorithm and simply ranks waste management strategies according to costs so there is little uncertainty associated with its execution. The role of this module can be expanded to generate waste management recommendations based on a combination of weighted criteria.

Overall technology knowledge weaknesses Surface laser decontamination has been successfully demonstrated although it is still in development. Therefore, as process parameters are optimized for different waste types, the knowledge base will need to be updated. Bulk laser decontamination is in too early a stage of development to determine applicability to different waste types, DFs, process times, and costs and so, as for surface laser decontamination, the knowledge base needs to be enlarged to accommodate new information about this technology when available. Acid chemical decontamination encompasses a broad range of solutions and the knowledge base could be expanded to evaluate each one.

8.3 Evaluation of Applicable Decontamination Technologies

8.3.1 WINCO D&D waste case study discussion

Decontamination and decommissioning (D&D) is planned for a number of buildings at WINCO located at the INEL. The most near-term D&D operations will likely be carried out on the old Waste Calcining Facility (CPP-633) and the Hot Pilot Plant (CPP-640). CPP-633 was used to calcine liquid waste generated from chemical decontamination activities at the site. CPP-640 contains two headend uranium fuel reprocessing systems. The projected generation of metal waste from decommissioning of CPP-640 served as a case study for analysis by the expert system.

CPP-640 was used to reprocess spent fuel. The ROVER system used a fluidized in-bed combustion process to burn graphite based fuel and the Electrolytic system used high voltage electricity to dissolve stainless steel clad spent fuel rods. D&D is currently planned from 1995 through 2000 and will involve the in-cell and process support equipment but not the building structure.

Metal waste data was collected during a week long visit to the site. The bulk of the information was taken from reports prepared by Engineering Science, Inc. (1991), an engineering consulting firm that provided detailed information about the size and material of most components of the facility. Additional information concerning contamination types and levels was provided by employees of WINCO (Demmer, 1993; Shantz, 1993).

Surface contamination will mainly be due to zirconium and cesium. It is expected that 90% of the contamination problems involve these contaminants. Forty percent of the contamination will be embedded by corrosion and 60% will be dried on the surface (non-embedded). The estimated radiation levels range from low to very high in different areas of the building. Low radiation is assumed to be less than 5000 dpm beta-gamma and 100 dpm alpha radiation and high is greater than 20,000 dpm beta-gamma and 250 dpm alpha radiation. Very high radiation is estimated at greater than 100,000 dpm alpha. Most of the waste volume to be generated will have contamination of low activity as shown in Table 8.1.

The decommissioning operations will generate metal waste in the form of tanks, cell liners, centrifuges, condensers, and heat exchangers. Initial estimates of the mass and volume of this waste are 93,300 lbs and 1938 ft^3 respectively (see Table 8.2). This waste is approximately 94% (by volume) stainless steel with the remaining 6% comprised of Hastelloy-x, carbon steel, and Carpenter 20. The estimated salvage value of this waste is

Table 8.1 WINCO waste volumes by radiation level

Radiation Level	Percent by Volume
Low (4000 dpm beta-gamma, 10 dpm alpha)	84%
Moderate (15000 dpm beta-gamma, 150 dpm alpha)	7%
High (30000 dpm beta-gamma, 500 dpm alpha)	5%
Very High (50000 dpm beta-gamma, 100000 dpm alpha)	4%

Table 8.2 WINCO decontamination and decommissioning waste

	Items	Mass (lbs)	Volume (ft^3)
TANKS			
STAINLESS STEEL	23	35 858	1636
HASTELLOY X	2	2925	62
CARBON STEEL	2	2653	88
CENTRIFUGES			
STAINLESS STEEL	2	547	7
CONDENSERS			
CARPENTER 20	1	196	2
STAINLESS STEEL	1	195	1
HEAT EXCHANGERS			
STAINLESS STEEL	2	2505	45
LINERS/SHEET METAL			
STAINLESS STEEL	4	48821	97
TOTAL		93,300	1938

$11,743. In contrast, at an estimated disposal cost of $80/ft^3, $155,040 would be spent sending the waste for burial. The disposal cost does not include removing the components from the building.

Waste from the decommissioning operations was divided into 21 sub-types according to radiation level (low, moderate, high, or very high radiation levels), waste type (tank, centrifuge, condenser, sheet metal, or heat exchanger), metal type (stainless steel, carbon steel, Hastelloy-x, or Carpenter 20), and whether the contamination was dried on or embedded in the metal. Division of the waste into sections was required for input to the expert system.

Technologies determined by the expert system to be applicable for all 21 waste types included abrasive jetting, laser decontamination, acid chemical decontamination, and ultra-high and high pressure water. For the 60% of the wastes that had dried on contamination, CO_2 pellet decontamination was also applicable, and freon cleaning for those wastes that were sheet metal.

Abrasive jetting consistently came out, for all wastes, as the most cost-effective waste management alternative and ultra-high pressure water was the least cost-effective. This was caused by the large volumes of secondary waste generated by this technique requiring costly disposal. Abrasive jetting's rapid decontamination rate was one of the main reasons for its cost-effectiveness. When freon cleaning could be applied (sheet metal with dried on contamination) it had the second best cleaning rate, otherwise both high pressure water techniques ranked second for this attribute. Acid chemical decontamination, laser decontamination, and CO_2 pellet decontamination followed.

For this case study it was assumed that the work required in-situ decontamination. Most of the other decontamination technologies were disqualified on this account.

One of the primary goals of decontamination of the process equipment at this facility is uranium recovery. Although it is not an attribute considered by the expert system, no liquid decontamination can be carried out prior to the removal of uranium due to criticality control concerns. This means that acid chemical, ultra-high and high pressure water, and wet or slurry abrasive jetting are not feasible, leaving only dry abrasive jetting, laser decontamination, and, for dried on contamination, CO_2 pellet decontamination and freon cleaning.

Recovery of uranium that was left in the system equipment when processing ceased may be further complicated by the use of abrasive media in jetting techniques. It may be difficult to separate the uranium from the media after decontamination has been carried out. Given that freon cleaning is no longer permitted at DOE sites, for this particular case study it could be concluded that laser decontamination is one of the more applicable technologies followed by CO_2 pellet decontamination (for wastes that have no embedded contamination).

8.3.2 Decontamination technology applicability

Due to the difficulty in obtaining detailed characterization of the radioactive metal wastes being generated in the U.S., the applicability and utility of the decontamination technologies can only be discussed generally according to various attributes.

The "ideal" decontamination technology would be a dry process generating low secondary waste volumes that could be operated remotely and automatically. It would have a reasonable processing rate and remove all types of contaminants and surface materials. It would produce a smooth surface finish so components could be reused but would be capable of removing substrate metal that is contaminated. Use of this technology would not require extensive sectioning or disassembly, even for large or complex shaped objects, and could be applied in-situ as well as ex-situ. This technology would also be more cost-effective than simple waste disposal.

The extent to which the decontamination technologies evaluated as part of this study approach the "ideal" is discussed below to illustrate the applicability and effectiveness of these technologies to radioactive metal wastes.

8.3.2.1 Wet decontamination processes

The surface decontamination processes that are applied using water or solutions include ultra-high and high pressure water, electropolishing, abrasive jetting, and acid chemical decontamination. Not only are the large volumes of liquid secondary waste generated a waste handling problem requiring processing prior to disposal, but wet processes, for some applications, are a criticality concern. Use of chemicals also increases the likelihood of generating mixed waste. Newer technologies (CO_2 pellet blasting and laser decontamination) have moved away from processes that produce or use liquid that can become contaminated. Attempts are being made to develop methods of recycling liquid wastes produced by "wet" decontamination processes to improve the utility of these technologies.

Each of the "wet" technologies features fairly good processing rates, is effective, and can remove most surface materials. Electropolishing, however, cannot remove nonconductive materials. All, but high pressure water, are able to remove some substrate metal and, therefore, fixed contamination.

Processing is fairly labor intensive for all of these technologies. Although processing can be adapted for remote operation, it is not commonly done due to the expense. Most of these technologies, therefore, have a relatively high potential for worker exposure. Certain industrial hazards also accompany both high pressure water and abrasive jetting techniques. An advantage that wet decontamination technologies do have over dry processes is the ability to limit the amount of airborne contamination.

Most of the "wet" techniques do not require extensive sectioning or disassembly and can also be applied in-situ. However, complex shapes, in general, pose a problem for radiation monitoring after decontamination by any technology.

Ultra-high and high pressure water decontamination and abrasive jetting result in the poorest quality surface finish of any of the ten technologies examined, preventing reuse of materials. Electropolishing, on the other hand, results in the best finish, leaving the item with a microscopically smooth surface that slows recontamination and facilitates subsequent decontamination operations if an item is reused.

The processing and disposal of large secondary waste volumes coupled with the labor intensity of these technologies make them less cost-effective than some of the alternatives although these factors vary with the waste type, degree of contamination, and actual process used.

8.3.2.2 Vibratory finishing

Vibratory finishing is another wet surface decontamination process, but it consumes less liquid and thus, generates less secondary waste than the rest of this class of technologies due to a well-developed recycling system. This process is operated remotely and automatically to minimize labor requirements and exposure but cannot decontaminate items in-situ. This is a good process for rapidly decontaminating large quantities of small parts of varied shapes and sizes to low levels of radioactivity. It is a non-destructive process that cannot remove much fixed contamination or epoxy paint but does result in a good surface finish. The cost limiting factor and the one that tends to increase any labor requirements minimized by automatic operation of the technique, is the amount of sectioning and disassembly required for the waste.

8.3.2.3 Carbon dioxide pellet blasting

Carbon dioxide pellet blasting is a relatively new surface decontamination technique. It is similar to other high pressure abrasive decontamination technologies (abrasive jetting, high and ultra-high pressure water) except that it is a dry process, is non-destructive, and results in a good surface finish. Because it cannot remove substrate metal, heavy amounts of fixed contamination will likely remain in the surface layers of the waste. Although epoxy paint and hard oxides are unaffected by this technique, most other surface materials can be removed. As with other abrasive techniques, metal surfaces must be accessible to the blast nozzle. Pipes with inner diameters three inches or less cannot be decontaminated without sectioning.

Processing rates are good and secondary waste volumes are very low, restricted to HEPA filters containing the contaminants. This technique can be labor intensive and, like other abrasive techniques, can be hazardous to implement, but the process can be adapted for remote operation. Again, this is not frequently done due to the additional expense and also because decontamination of tools or small parts requires non-routine movements of the blast nozzle.

8.3.2.4 Laser decontamination

Although both bulk and surface laser decontamination technologies are being developed, bulk decontamination is too early in the development stage to evaluate its applicability and effectiveness. Only surface decontamination has thus far been successfully demonstrated and will, therefore, be discussed below.

Surface laser decontamination, like carbon dioxide pellet decontamination, is a dry process generating very low secondary waste volumes (HEPA filters containing the contaminants). Unlike CO_2 blasting, it is destructive, capable of removing substrate metal that holds fixed contamination to a waste surface. The resulting surface finish is reasonably good and should limit concern about tolerances for reusable items. The laser can remove all types of surface material but is currently restricted from decontaminating pipes with inner diameters less than six inches and more complex-shaped items, like tools or intricate equipment. Surface materials that are mixed wastes are expected to be removed using this technology.

The technology is remotely and automatically operated and one technician could operate multiple systems to minimize labor requirements and reduce worker exposure. The current decontamination rate is, generally, not as rapid as some of the other technologies but, given that laser decontamination is still under development, this may increase in the future. Although an excimer laser is currently being used for development of the surface decontamination technology, this laser is not necessarily the most technologically effective one for this process. Other laser types are being considered and the development of more advanced lasers in the future may also increase the effectiveness and efficiency of the application of this technology to radioactive metal wastes. This, along with other process parameters, has yet to be optimized.

Although laser equipment costs are high, they can be amortized over time and may be justified by the reduction in worker exposure, waste volumes, and labor costs. Rate of decontamination will factor into the cost-effectiveness of this technology.

8.3.2.5 Melting

Melting is a decontamination technique that can be used for surface or bulk-contaminated materials. Surface contamination, however, will likely be more effectively removed using surface decontamination technologies. This technology also generates low waste volumes, although these are generally greater than wastes resulting from CO_2 pellet or laser decontamination.

Because this is a remote, automatic operation, labor requirements and worker exposure are minimized. Processing rates are good although decontamination effectiveness varies with radionuclide and metal type. This technology can also be used for simple waste volume reduction even if decontamination effectiveness is low. This technique is completely destructive of components, therefore, reuse is not possible for waste items. Depending on the furnace size, relatively large and intricate parts can be decontaminated without much sectioning or disassembly. In-situ decontamination is not possible, however, measurement of activities is more easily performed than for surface decontamination technologies because the radioactivity level of large quantities of metal can be assessed by taking a single melt sample. Large quantities of waste are required to make this a cost-effective technology.

8.3.2.6 Freon cleaning

Freon cleaning is a good decontamination technology that is particularly applicable to electrical equipment, complex shaped objects, and delicate components. Regulation of CFCs, however, have served to render freon cleaning obsolete. It can no longer be used at DOE sites.

8.4 Socio-Economic Issues and Impacts of Radioactive Waste Management

Although an analysis of the costs and benefits of waste management alternatives has been carried out, there are issues and other costs associated with the various waste management strategies that cannot be so easily quantified. These, nonetheless, deserve at least equal consideration when analyzing the impacts of decontamination versus disposal of radioactive metal wastes.

By minimizing the quantity of radioactive waste sent for burial at disposal sites, both radioactive waste disposal costs and risks to public and environmental health will be reduced. A significant portion of these radioactive wastes consists of radioactive metallic waste which could be, if sufficiently cleaned of radioactivity, reclaimed as scrap metal or reused as tools and equipment. To compare the two types of waste management alternatives, simple disposal and decontamination, a discussion of impacts was carried out.

8.4.1 Impacts of the use of decontamination technologies

The potential impacts on waste generators, decontamination technicians, and the public from the use of decontamination technologies can be categorized as either costs or benefits. Following is a summary of the impacts under each of these headings.

COSTS

Technology Development Costs
  labor, equipment and materials, facility, operation and maintenance
Decontamination Facility Costs
  i) stationary facility waste transportation, packaging, storage, facility, equipment, operation and maintenance, labor, capital
  ii) mobile facility waste transportation, facility transportation, facility, equipment, operation and maintenance, labor, capital
  iii) future decontamination and decommissioning of facility

Concentration of the Waste
  higher risk to public health
Secondary Waste Disposal Costs
Re-Classified Waste Disposal Costs

BENEFITS
I. Waste Minimization:
Reduced Required Disposal Capacity
  reduced potential for public exposure
  reduced risk to public health
  reduced disposal cost (site selection and licensing, land cost, technology cost)

II. Reclamation of Valuable Metals, Tools, and Equipment
Recycle of Valuable Metals
  salvage value of metals decontaminated
  savings from replacement cost of virgin metals
Reuse of Tools and Equipment
  savings from replacement cost of tools and equipment

III. Miscellaneous
Re-Classification of Waste for Lower Security Disposal
  reduced shipping, packaging, and disposal costs
Worker Safety From Remote Operations (if possible)
Reduced Labor Costs Due to Automation (if possible)

8.4.1.1 Metal waste and recycling issues

Although the salvage value of the metal is considered in the cost analysis, cost savings from not having to mine and produce virgin metal from ore were not included. Significant energy savings can be realized by recycling scrap metal rather than smelting new metals from ores. If scrap steel is used rather than virgin iron ore, approximately 75% of energy costs are saved (International Atomic Energy Agency, 1988b) Also, where scrap steel is used instead of iron ore, total wastes are reduced by 90% and air and water pollution are also reduced.

Identifying a use for the decontaminated articles is important. As illustrated by Table 8.3, a large market exists within the DOE and private utilities for metal products used in radiation services. However, in a program to recover scrap metal, additional concerns include the cost of labor and cost equivalent of a radioactive dose accumulated as a result of decontamination operations and the cost of additional monitoring to determine if items meet the regulations for release. Administrative, technical, and personnel costs associated with public acceptance, public relations, license applications, hearings, etc. are also incurred, especially if approval for a recycling program is given on a case by case basis. Cost savings from not having to purchase new equipment and tools that have been decontaminated are an additional consideration.

Table 8.3 Metal products for use in radiation services within the DOE and private utilities (Clemens, 1993)

Product	Material	Quantity		Total Weight (Tons)
Shield Blocks	carbon or stainless steel	300,000	(Tons)	300,000
Vitrification Canisters	stainless steel	30,000		45,000
Universal Dry Fuel Casks	stainless steel	3,000		282,000
Transportation & Disposal Boxes	carbon or stainless steel	1,000,000		500,000
Transportation & Disposal Drums	carbon or stainless steel	50,000,000		1,250,000
Type A Shipping Casks	carbon or stainless steel	30,000		150,000
Reinforcing Bar & Mats	carbon or stainless steel	100,000	(Tons)	100,000
TOTALS				2,627,000

8.4.1.2 Decontamination technology issues

It is expected that certain decontamination processes can be automated in a full-scale operation. Automation of a process will have significant effects on worker safety. Because some decontamination technologies can be remotely operated, the savings from increased worker safety is a real, though relatively intangible, benefit. Automation of the process will further increase the safety of the worker. The value associated with the reduced hazard is difficult to measure, although the Nuclear Regulatory Commission (NRC), in 10 CFR 50, set a value of $1000 per man-rem and another source (LeSurf and Weyman, 1983), states that $5000 to $7000 per man-rem of radioactivity is a commonly used estimate.

Increased worker safety can also mean a reduction in labor costs where this cost contains a component to compensate for the job hazards.

Disadvantages of some decontamination technologies include the use of solvents, and the production of mixed (hazardous and radioactive) wastes, and the production of large volumes of liquid wastes that are more difficult to dispose of and pose greater risk to the environment than solid wastes.

Compaction and metal melting for volume reduction are alternatives to decontamination that might feasibly compete with decontamination technologies for cost-effective waste minimization. These alternatives also do not concentrate the contamination as do the decontamination technologies. Advantages of some decontamination technology applications over these options, however, include the potential ability to decontaminate metal wastes that are mixed wastes and to re-classify more highly radioactive wastes to lower levels so that they can be more easily and less expensively disposed of. Also, simple volume reduction techniques do not recover the metal and gain from the salvage value.

8.4.2 Radioactive waste disposal issues

Under the Low-Level Waste Protection Act (LLWPA), plans to site and construct new commercial low-level waste (LLW) disposal facilities are currently being carried out. The cost of developing these facilities and the projected increase in disposal charges will tend to encourage the use of volume reduction technologies. The issues associated with current and future radioactive waste disposal are addressed in the discussion to follow.

The cost of disposal in the evaluation of radioactive waste management alternatives considers the charge per unit of waste buried. It is unclear whether or not this cost per unit of waste reflects other cost components associated with waste disposal. Related costs include construction of the disposal site which, in turn, depends upon the hazard level of the waste and therefore the security and technology required to construct an adequate facility. Along with the cost of construction comes the difficulty associated with locating an appropriate site and the restriction of land use and monitoring after the site has filled and closed. Mineral resource extraction and exploration will likely be prevented near operating and closed disposal sites. The more sites that are required, the more the potential loss from not exploring and extracting resources. If waste is minimized, fewer sites will be required and reduced loss from not being able to extract valuable natural resources will result. Finally, environmental and public health risks should be examined as a component of radioactive waste disposal cost.

Given that disposal capacity and costs are significant considerations in any radioactive waste management evaluation, the factors affecting them must be further explored. The marked escalation of, specifically, LLW disposal costs in the recent past may be cause for concern. This inflation of disposal costs may not actually reflect real costs but other motives such as encouragement, by the three existing U.S. commercial LLW disposal sites currently accepting waste, for other states to site LLW disposal facilities. These policies, however, also likely reflect the diminishing disposal capacity and the cost increase associated with a scarce resource.

8.4.2.1 History of LLW disposal in the U.S.

Of the original six commercial LLW disposal sites in the U.S. there remain only three that continue to accept waste. To keep up with the rapidly expanding civilian nuclear power industry after ocean dumping was abandoned in the 1950s, a land-based approach to disposal was taken and six commercial sites were developmed and licensed during the 1960s. All sites used shallow land burial as the disposal technology where 55-gallon steel drums were put into 30 foot trenches later backfilled with earth. Between 1975 and 1978, three of these facilities were shut down. Two (Maxey Flats, KY and West Valley, NY) were closed due to mismanagement that led to the release of radioactive contaminants outside the trenches. The third site (Sheffield, IL) was closed when the Nuclear Regulatory Commission (NRC) refused to license additional capacity.

In 1979 the governors of South Carolina, Nevada, and Washington, the states hosting the three remaining facilities, determined that their states could no longer bear the national responsibility for LLW disposal. The benefits of nuclear energy were being broadly distributed throughout society but the costs of dealing with the effluents of this technology (radioactive wastes) were highly concentrated.

In December 1980, Congress enacted, the Low-Level Radioactive Waste Policy Act (LLWPA) to force distribution of the responsibility of LLW disposal among all regions of the U.S.. The Act embodies three principles: 1) state responsibility for providing LLW disposal capacity, 2) encouragement of interstate compacts to carry out this responsibility on a regional basis to produce a more efficient system of LLW disposal, and 3) the right of regional compacts to prohibit disposal at their regional facilities of LLW generated in non-member states. The compacts as of 1989 are shown in Figure 8.1.

The LLWPA allowed five years for the development of the new system of disposal facilities but, as of 1985, the system still had far to go. The Low Level Waste Policy Amendments Act (LLWPAA) was passed in 1985 and provided for the continued use of the three existing disposal sites up until January 1993. The cost of disposal would increase, but generators could continue to ship their waste to these sites for seven more years. Between 1986 and 1993, compacts and states were expected to meet four milestones with penalties, in the form of increased disposal charges, for non-compliance (from English, 1992):

1. By July 1, 1986 each state was required to either join a compact or indicate its intent to site a facility for itself. After this date, all generators other than those in regions with existing sites had to pay a surcharge of $10 per cubic foot, in addition to the regular disposal fee. Missing this milestone resulted in doubling of the surcharge.

2. By January 1988, compacts had to select a host state, and each compact or host state, including each unaffiliated state, had to adopt a siting plan giving procedures and a schedule for selecting a site and preparing a facility license application. On January 1, 1988, the regular surcharge was to be raised from $10 to $20. Missing the deadline gave generators only a one-year grace period, during which time they would have to pay a $40 surcharge for the first six months and an $80 surcharge for the next six months. After the year was up, the sited states could deny access.

3. By January 1990, if the host states failed to file disposal facility license applications, the governor of each noncomplying state, including each state in a noncomplying region, had to certify to the NRC that the state would provide storage or disposal capacity for LLW generated within the state after the 1993 deadline. Failure to meet the milestone could

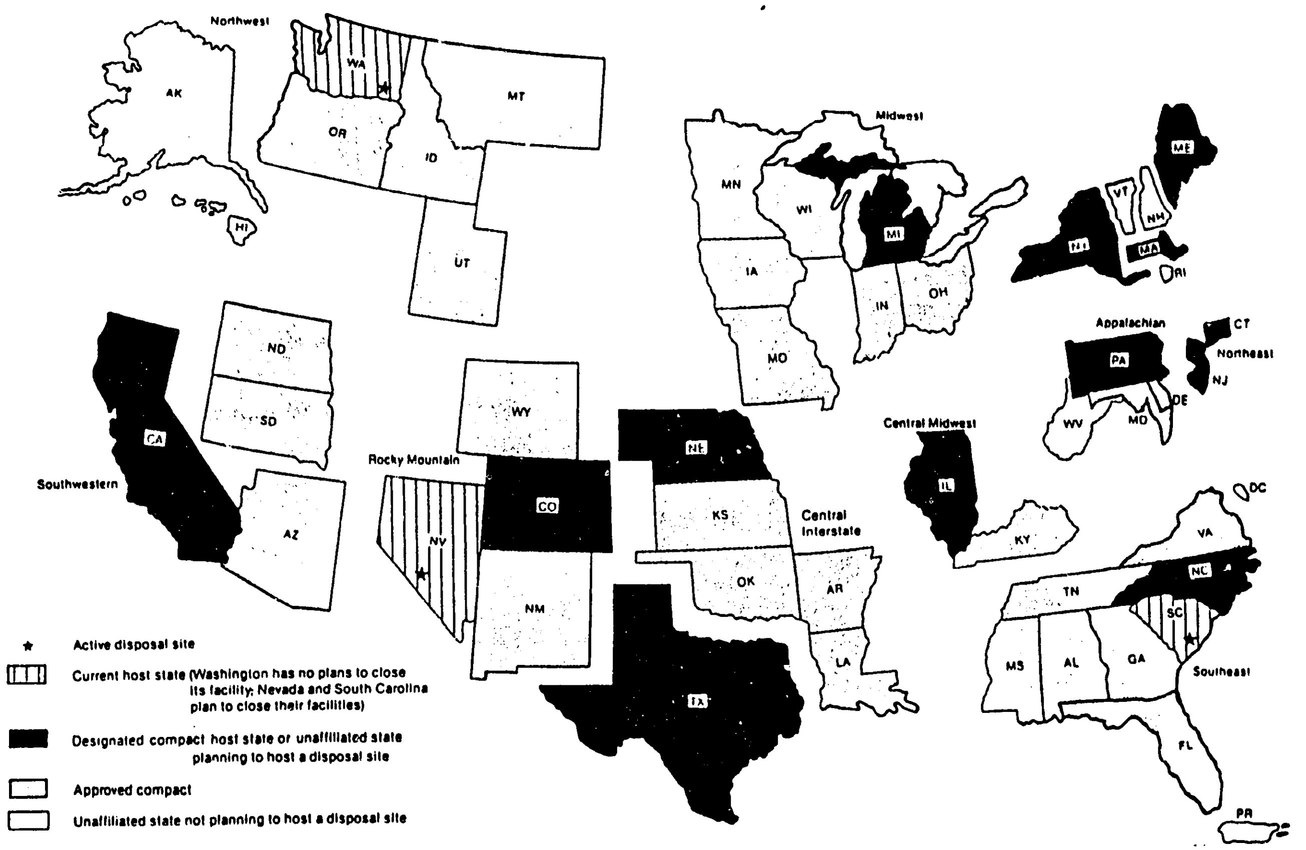

Figure 8.1 Status of compacts and unaffiliated states (Office of Technology Assessment, 1989)

result in denial of access to existing waste disposal sites. On January 1, 1990, the regular surcharge was to be raised from $20 to $40 per cubic foot.

4. By January 1992, a disposal facility license application had to be filed or the governors of sited states could require that for continued access to their disposal facilities, generators from noncomplying regions or states would have to pay a surcharge of up to $120 per cubic foot.

Party states to compacts with existing sites (the Southeast, Northwest, and Rocky Mountain compacts), however, were exempt from having to pay surcharges or meet these milestones. States that arranged for waste disposal by contract with a sited compact and its host state had to pay the surcharges but were not required to meet the milestones even if the contract was only good until 1993.

By January 1, 1993 the new disposal facilities were expected to be up and running. However, of the states and compacts trying to develop new LLW disposal facilities, only California and Nebraska anticipated having facilities open and operational by 1993. The others expected that it would take at least two years beyond the 1993 deadline to have a viable facility. This will mean significant expense in the form of surcharges and/or temporary storage until such time as a facility is operational.

8.4.2.2 Issues in Present and Future LLW Disposal Under the LLWPA

Key issues relating to compact formation and disposal of LLW within the compacts include: 1) LLW definitions, 2) federal waste, 3) disposal technologies, 4) fee structures, liability, and closure, and 5) valuing human health at risk from environmental pollution.

1. The definition of LLW Almost all compacts use LLW definitions which differ from that of the LLWPA's and from each other. Additionally, in a 1984 regulation the NRC changed the limit for transuranic (TRU) radionuclides in LLW from 10 nCi/g to 100 nCi/g. However, most compacts exclude waste containing more than 10 nCi/g of TRU radionuclides. This affects volumes of waste sent and expense. The lower limit means reduced waste and disposal cost for LLW facilities but higher costs for society at large (more TRU waste requires better and more costly barriers from environment).

2. Federal waste Past practice has been that, except for unusual waste, all waste shipped for disposal by non-Department of Energy (DOE) federal agencies has been to commercial disposal facilities. The LLWPA, however, exempts from compacts under the Act, LLW from both "atomic energy defense activities" and federal research and development (R&D) activities. The first term is explicitly defined, however, the term "federal R&D" is not defined by the Act and this lack of clear definition has created some concern.

Most states are reluctant to receive and dispose of waste generated by the Department of Defense (DOD) and other federal agencies. The Northwest and Rocky Mountain states all explicitly exclude federal waste from their respective facilities. However, the DOD does not have or want disposal facilities on its lands. From the standpoint of efficiency, cost-effectiveness, and public health and safety, DOD along with other federal agencies argue that they are better served by use of commercially available sites. Development of waste sites to handle only a small amount of waste would increase disposal costs and represent an undesirable proliferation in the number of LLW sites in the country. Federal non-DOE waste that is currently shipped for disposal at commercial sites is shown in Table 8.4 and totals 2224.38 m^3 annually. This makes up about 5.5% of the total annual LLW volume shipped (estimated at 40,775 m^3) (Oak Ridge National Laboratory, 1991).

3. Disposal technologies To increase the acceptability of LLW disposal and to offer the promise of meeting stringent release standards, disposal technology selection has turned to elaborate, highly engineered facilities. The only facility planning to use the traditional shallow land burial is California's Ward Valley site.

In selecting technologies for disposal of LLW, a principal issue has been the question of retrievability, for those who question the safety of LLW disposal. Generally, there seems to be a public pull for retrievability and monitoring against the view by government and nuclear experts that a disposal technology should contain the waste such that institutional controls are not necessary. Federal definitions of storage and disposal are, in

Table 8.4 Non-DOE federal waste (Choi, 1984)

Organization	Annual Volume (cubic feet)	(cubic meters)	Type
Department of Agriculture	3000	84.90	Lab
Department of Defense			
Army	12200	345.26	Med/Lab
Navy	32000	905.60	Med/Lab/Nuclear Reactor
Air Force	3000	84.90	Med/Lab
Department of Health and Human Services			
National Institues of Health	15000	424.50	Med/Lab
Center for Disease Control	500	14.15	Med/Lab
Food and Drug Administration	1000	28.30	Lab
Environmental Protection Agency	500	14.15	Lab
National Aeronatics and Space Administration	250	7.08	Lab
National Bureau of Standards	150	4.25	Lab/Nuclear Reactor
Veterans Administration	11000	311.30	Med/Lab
TOTAL	78600	2224.38	

fact, based on the absence or presence of institutional monitoring and control. Federal regulations call for reliance on geological barriers in disposal facilities with the intent to prevent inadvertent human intrusion in the event records are lost in centuries to come. The public, on the other hand, demands institutional control and continuous monitoring of a facility designed to allow inexpensive retrieval of the waste if monitoring reveals a problem or if a better alternative to radioactive waste disposal is found.

Regardless of the issue of retrievability, new complex engineered disposal technology will likely result in increased costs. Where disposal costs, as of 1990, were on average about $40 to $50/cu. ft. at the existing sites, they are now projected to rise in the next decade to about $100 to $500 per cu. ft at the new engineered disposal facilities. Very small, highly engineered facilities (i.e. accepting only 10,000 ft^3 annually) are likely to have costs of $500/cu.ft. where large, highly engineered facilities (i.e. accepting 300,000 ft^3 annually) are likely to have costs of $100/cu.ft. (English, 1992).

The economies of scale afforded by a large facility are used as an argument for having fewer sites. Some states have hoped that instead of the compact system, Washington or California might open their doors and allow in waste from the rest of the nation, reasoning that the prospective system of 14 sites is inefficient. It is argued that a few well-run sites, located in arid climates, would be both less costly and much safer. Also, the high cost of finding and developing new LLW disposal sites (fewer expensive screening processes and community benefit packages) could be reduced significantly with a decreased number of sites.

4. Fee structures, liability, and closure It is expected that all states with new facilities will regulate their disposal fees. Fee structures are likely to take into consideration such factors as size and weight of the waste container, form of the waste, radionuclide activity, and surface dose rate. Fees will be set to allow for a profit margin, if the facility is privately operated, and to take into account full costs, from development to post closure, including the cost of liability insurance to cover expenses incurred as a result of an accidental release of such waste during shipment or after reaching a facility. Closure costs alone for a section of one DOE LLW disposal site were estimated at approximately $25/m^3 ($1.21/ft^3) (Westinghouse Savannah River Company, 1991). This does not include monitoring or future liabilities.

5. Valuing human health at risk from environmental pollution Because the disposal, as well as the transportation, of radioactive waste is a threat to the environment and public health, these elements should also make up part of the burial and transportation charges. Two types of measures exist to help categorize health effects for an identified hazard. These are mortality, the loss of life, and morbidity, ill health.

Mortality is defined as "the measure of a change in health as the change in probability of dying, or more specifically, the change in the conditional probability of dying at each age, for an identified group of individuals at risk" (Cropper and Freeman, 1991).

Morbidity is defined by the U.S. Public Health Service as "a departure from a state of physical or mental well-being, resulting from disease or injury, of which the affected individual is aware". Morbidity can be classified according to chronic and acute ill health effects, the degree of impairment of activity, the type of symptom or illness, and based on the number of reported cases of a disease.

Health can be valued according to individual preference, the willingness to pay for a certain level of health or the opportunity costs of ill-health, an individual's discounted lifetime earnings as a measure of value. Environmental pollution that impairs human health can reduce well-being through five channels:

1. medical expenses associated with treating pollution-induced diseases, including the opportunity cost of time spent in obtaining treatment
2. lost wages
3. defensive or averting expenditures associated with attempts to prevent pollution-induced disease
4. disutility associated with the symptoms and lost opportunities for leisure activities
5. changes in life expectancy or risk of premature death

According to the NRC's regulation (10 CFR 61) 25 mrem is the maximum whole body dose that a member of the public may receive annually from a LLW disposal facility. Several host states, however, are adopting more stringent standards (as low as 1 to 2 mrem down to a goal of zero release). The value associated with reduced hazard is difficult to measure although, as mentioned previously, one source (LeSurf and Weyman, 1983) quotes an estimate of $5000 to $7000 per man-rem of radioactivity.

The public health costs incurred by a community hosting a waste disposal site will be fairly site-specific and depend upon a variety of factors such as population and proximity of the site to the community. These issues are discussed in the next section.

8.4.3 Socio-economic issues of radioactive waste disposal

In any analysis of the concerns of radioactive waste management certain socio-economic issues need to be addressed. The number and location of waste facilities will affect the socio-economic and institutional burdens associated with radioactive waste management. Overall management costs will also be sensitive to transportation designs, cask costs, and facility development. Psychological stress occurring at facility sites and along transportation corridors will also be a consideration.

The socioeconomic effects associated with the network of nuclear waste facilities and transportation are fairly sensitive to the number and location of sites (National Research Council, 1984). Factors include transport system complexity, shipping costs, public concern, and institutional burdens on states and localities (regulations and emergency response requirements).

Beneficial and adverse effects and costs of radioactive waste management should be appropriately distributed over generations, geographic regions, and beneficiaries and nonbeneficiaries of nuclear power. Regional siting of disposal facilities (i.e. compacts) might help minimize any interregional inequity. Provisions should also be made to ensure an adequate flow of incentives, impact mitigation, and compensation measures. Adverse socioeconomic effects will likely be strongly site-specific and will be related to the population size and rural qualities of the host region as well as the waste system design. Adverse effects to a host community and region that cannot be reasonably avoided or further mitigated must be adequately compensated with capital provided by the beneficiaries of nuclear power. Funding should also be provided for the mitigation of expected adverse effects. A study carried out on the price effects of landfills on nearby homes might be taken as an estimated lower bound on the extent to which disposal facilities impact communities (Nelson et al., 1992). The study results indicated that home values were adversely affected approximately 12% at the landfill boundary and 6% one mile away. Beyond 2.5 miles adverse effects became negligible. These findings have important implications for the siting of waste disposal facilities.

Perceived risks of the technology by the public will play a significant role in the demands for community compensation in the siting of a radioactive waste disposal facility. Communities may also feel that if they leave future generations a radioactive waste site, they should also leave better schools and/or lower property taxes. The stigma of having a radioactive waste disposal site may also discourage certain industries or corporations from locating in the area. When considering the cost of the facility itself, the cost of centuries of institutional monitoring and control, and payments to compensate for industry not locating in the area, it is not uncommon to hear projected disposal cost estimates exceeding $500 per cubic foot of waste.

8.5 Impact of Decontamination On Waste Minimization

Assuming that almost all radioactive metal waste can be decontaminated or recycled in some way, an examination of these quantities will show the extent to which the overall radioactive waste management problem can be eased by minimizing metal wastes sent for disposal. This section presents: 1) a summary of the quantities of metal waste discussed in Chapter 6, 2) an evaluation of the potential to reduce overall waste volumes, 3) an study of the extent to which overall disposal site lives can be extended, and 4) a study of the effect regulations may have on waste minimization.

8.5.1 Summary of metal waste inventory compilation

Data available on radioactive metal waste can be broken down into two main categories: operations waste and decommissioning waste. Each of these categories has contributions from both DOE and commercial generators. A summary of the data discussed in Chapter 6 follows.

8.5.1.1 Operations waste

Commercial waste The metal LLW that has been accumulating in commercial disposal sites since 1962 now totals approximately 1.5 million ft^3 (Oak Ridge National Laboratory, 1991).

DOE waste The total accumulated metal LLW volume sent for disposal from DOE sites since 1962 is estimated to be 8.1 million ft^3, more than five times that of commercial LLW. Currently the DOE sites have an estimated metal LLW volume of 729,000 ft^3 and projected for 1991 was an additional 695 000 ft^3. From 1980 to 1984, 14% of wastes generated were contaminated equipment whereas in 1990, 26% of these wastes were of this type. If this, in fact, indicates a trend, the portion of waste sent for disposal that is metal may be on the rise. Metal TRU waste from DOE generators has an estimated total current volume of 945,000 ft^3 with a projected generation for the years 1990-2000 of 361,000 ft^3 (Oak Ridge National Laboratory, 1991).

Although no breakdown of commercial radioactive scrap metal has been documented, DOE sites have an estimated 1.6 (Clemson, 1993) to 1.8 (Kluk and Hocking, 1992) million tons in storage and generate approximately 16,500 tons per year (Kluk and Hocking, 1992).

8.5.1.2 Decommissioning waste

Concerns about the waste volumes to be generated from the decommissioning of DOE and commercial nuclear facilities coupled with increasing costs of disposal have been some of the strongest drivers in the push for better decontamination technologies to permit recycling and thus, minimize metal waste quantities.

DOE decommissioning An estimated 276 thousand tons of metal waste will be generated (Decontamination and Decommissioning Integrated Demo Technical Support Group, 1993) from the decommissioning of DOE gaseous diffusion plants alone. For all DOE facilities scheduled for decommissioning it is expected that the volume of ferrous metal alone will exceed the current national capacity for radioactive waste disposal (Oak Ridge K-25 Site Technical Division, 1993). This metal is estimated to total 1 million tons.

Commercial decommissioning Thirty eight U.S. light-water reactors (LWR) will be decommissioned by 2010. The total metal waste volume arising from decommissioning of these reactors is expected to exceed 7.8 million ft^3.

8.5.1.3 Summary

Given that currently scheduled DOE decommissioning projects alone will generate enough metal waste to fill the current national capacity, it could be reasonably argued that decontamination will have a significant impact on minimizing overall waste volumes. A more detailed evaluation of commercial metal waste quantities could provide an even stronger case for metal decontamination. It is unlikely that it would dilute this assertion, as DOE waste volumes, in general, are notably larger than the commercial accumulation and generation of LLW.

8.5.2 Minimizing LLW from decontamination and incineration

In support of the assertion made above, a combination of decontamination and incineration can also make a significant impact on waste volumes sent for disposal. Utility waste, alone, accounted for 58% (840,000 ft^3) of the total U.S. LLW volume sent to commercial disposal facilities in 1988 (1.44 million ft^3), 57% of which was non combustible containing a large amount of metallic material (Office of Technology Assessment, 1989). Assuming, conservatively, that half of the 57% could be decontaminated, 240,000 ft^3 of waste could be added to the 43% (360,000 ft^3) of combustible waste for a total of 600,000 ft^3

of waste volume reduction. This would mean a reduction, by nuclear utilities of 42% of the total LLW volume. This percentage could potentially increase again with decontamination and other volume reduction techniques for LLW from other types of generators.

8.5.3 Impact of waste minimization on disposal site life

Use of waste minimization techniques could help extend the lives of currently operating as well as future waste disposal sites. Table 8.3 shows the status of space available at the DOE and commercial LLW disposal sites as of December 1990 (Oak Ridge National Laboratory, 1991). Assuming an annual commercial LLW disposal rate as given above (1.44 million ft^3) and assuming that 240,000 ft^3 of this waste is metal that can be decontaminated instead of being sent for disposal, the total remaining volume of commercial disposal space given in Table 8.5 (64 million ft^3) will be able to extend its life by 9 years. If volume reduction from combustible waste (6000,000 ft^3) is also taken into account, the original 44 year life of the disposal space will be extended to 77 years. The 47 million ft^3 of current DOE disposal site space could be similarly extended over a greater amount of time. By extending the lives of disposal facilities the need to locate and construct new sites can be postponed, thus deferring the incurring of associated costs. Through waste minimization the required number of future facilities will also likely be reduced resulting in significant cost savings.

8.5.4 Effect of regulations on waste minimization

8.5.4.1 Release of bulk-contaminated metal waste

In the U.S., there is currently no regulatory structure that supports the release of bulk-contaminated material. This waste is usually sent for disposal without any decontamination, except for the removal of loose surface material to facilitate handling. Efforts to develop bulk-contamination release regulations have involved the NRC, DOE, and the Environmental Protection Agency (EPA). These efforts were largely driven by the impending need to deal with the significant waste volumes that are forecast to arise from the large number of decommissioning projects scheduled for the next 20 years and beyond.

Table 8.5 Status of land usage at DOE and commercial LLW disposal sites

DOE	Estimated Total Usable (ha)	Usage Factor (m^3/ha)	Estimated Area Utilized Through 1990 (ha)	Volume Used Through 1990 (m^3)	Area Remaining Through 1990 (ha)	Volume Remaining Through 1990 (m^3)
LANL	37.100	29500	17.000	501,500	20.10	593,000
INEL	35.600	20000	21.200	424,000	14.40	288,000
NTS	*	*	*			
ORNL	10.000	6600	6.000	39,600	4.00	26,400
HANF	235.000	4900	150.000	735,000	85.00	416,500
SRS	72.700	11200	72.100	807,500	0.60	6,720
SNLA	0.412	31000	0.103	3,193	0.30	9,579
SNLL	0.029	*	**			
TOTAL	390.841		266.403	2,511,000	124.44	1,340,000
Commercial						
West Valley, NY (closed 3/11/75)	7.200	20300	3.800	77,140		
Maxey Flats, KY*** (closed 12/27/77)	51.000	13600	10.400	141,400		
Sheffield, IL (closed 4/8/78)	8.100	10900	8.100	8,8290		
Barnwell, SC	60.700	20300	29.800	604,900	30.90	627,300
Beatty, NV	18.600	7400	15.700	116,200	2.90	21,460
Richland, WA	35.400	42200	7.800	329,200	27.60	1,165,000
TOTAL	181.000		75.6000	1,357,000	105.40	1,813,000
Grand Total	571.841		342.003	3,868,000	229.84	3,154,000

* the availability of land that could be used for burial is not available due to the classified nature of the site

** information is unavailable

*** total usage area is less than 51 ha

As decommissioning of reactors begins to take place there will likely be an increase in bulk-contaminated metal entering the waste stream. Not only are new technologies needed to treat this waste, but regulations are required to allow release of this material for recycle, at least within the nuclear industry. These regulations will have a significant effect on the types and quantities of metal waste that can potentially be recycled helping to minimize waste volumes requiring disposal. Europe and Canada have both established de minimis limits for the recycling of bulk-contaminated material and successful metal recycling programs currently exist in Europe (International Atomic Energy Agency, 1988a; Seidler and Sappok, 1987; Sappok and Rettig, 1992).

8.5.4.2 Mixed waste regulation

Another regulatory problem is the handling of wastes that are both hazardous and radioactive, termed mixed wastes. Currently no disposal options exist for this category of wastes. The hazardous components of these wastes are subject to two federal statutes administered by the EPA: the Resource Conservation and Recover Act (RCRA) and the Toxic Substances Control Act (TSCA). The radioactive components of these wastes are subject to the Atomic Energy Act (AEA) which is administered by the DOE for government sources and by the NRC for commercial sources. It has been estimated that about 3 to 10% of the total volume of commercial LLW may be mixed waste, although the metal component of this has not been indicated (Oak Ridge National Laboratory, 1991) For TRU and HLW mixed wastes, the radioactive characteristics alone dictate the method by which they are to be treated and disposed. Mixed wastes are of particular concern in the generation of secondary wastes from decontamination technologies. If decontamination technologies are able to remove mixed contamination components from metal wastes, waste will not only be minimized, but handling problems due to regulation will be greatly simplified even if some contamination remains that is only of one type or the other (hazardous or radioactive).

9. CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

From the results of this study, the following can be concluded about the application of decontamination technologies to radioactive metal waste minimization.

1. Each of the ten decontamination technologies has a unique set of attributes that determine under which conditions it can be applied. These are a function of the characteristics of the metal waste and criteria established by the user.

2. Laser decontamination has a distinct advantage over other decontamination technologies analyzed in this study in that it offers the following combination of features: very low secondary waste generation, remote operation which reduces labor requirements and worker exposure, dry processing which reduces criticality concerns, and the ability to remove substrate metal and, therefore, fixed contamination.

3. Disadvantages of laser decontamination in relation to alternative technologies include its relatively low decontamination rate and inability to clean small and intricate components such as tools or equipment as efficiently as some other decontamination technologies.

4. Use of expert systems to determine the applicability of decontamination technologies to radioactive metal waste is an effective means of evaluating radioactive metal waste management options. The resulting tool provides a comparison of the technical capabilities of decontamination technologies, carries out a cost analysis of possible waste management strategies, and makes cost-based waste management recommendations. The user is also provided with qualitative information on other technology attributes to allow them to make decisions based on their own criteria. This prototype expert system is a model that requires validation by human experts. The system structure design is flexible to facilitate updating, enhancement, and expansion of the knowledge base.

5. Significant socio-economic, policy, and regulatory issues affecting the management of radioactive metal waste in the U.S. include:
    i. radioactive waste disposal issues
        present disposal capacity
        future disposal facility siting and technologies
        monitoring and future liability of waste disposal
        public health effects
    ii. decontamination technologies issues
        worker safety concerns
        the effects of concentrating the waste by decontamination
        recycling issues-
            public acceptance
            regulations affecting the extent to which bulk-contaminated metal
                can be released and therefore the extent to which waste can be minimized

6. The decontamination of radioactive metal waste can make a significant impact on the minimization of radioactive wastes sent for disposal. The magnitude of this impact will increase with the decommissioning of a large number of nuclear facilities in the next 20 years.

9.2 Recommendations

Through this research, attempts have been made to analyze the applicability of decontamination technologies to radioactive metal waste minimization. To improve this assessment, future work should focus on the following areas:

1. Validation of the expert system and assignment of weighting factors to technology attributes by human experts as well as assignment of confidence factors to the knowledge base
2. Expansion of the expert system to consider decontamination technologies and criteria not presently included (mixed waste generation and removal, off-gas considerations, and compatibility of a technology with a waste generating site's present processes)
3. Evaluation of laser technologies when they are more fully developed and process parameters have been optimized
4. Determination of the applicability of all technologies to the types of metal waste being generated by the DOE when detailed characterization of these wastes has been completed (estimated to occur by 1995)
5. Further study of socio-economic and policy issues affecting radioactive metal waste management

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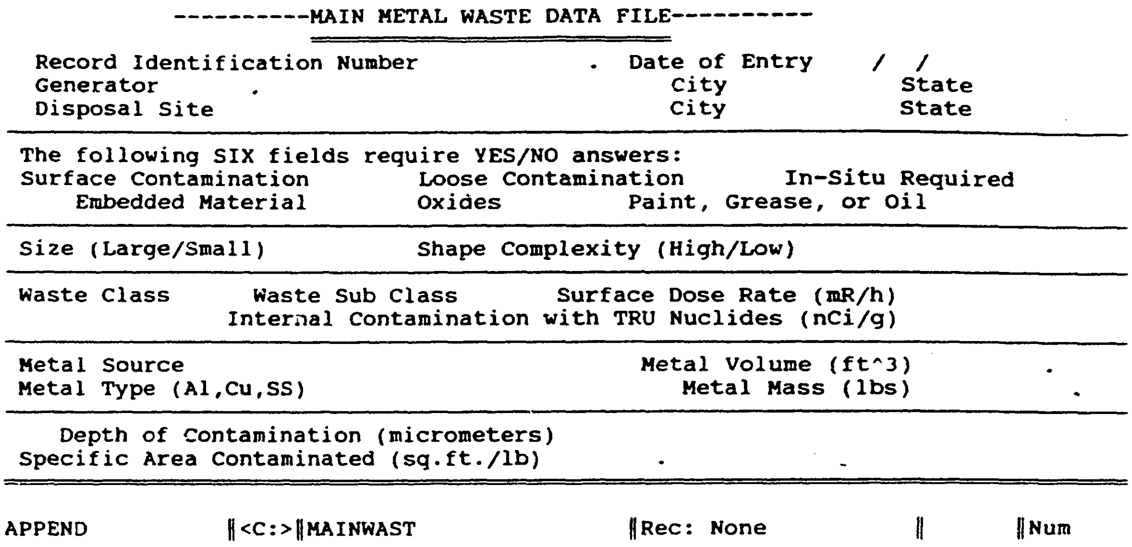
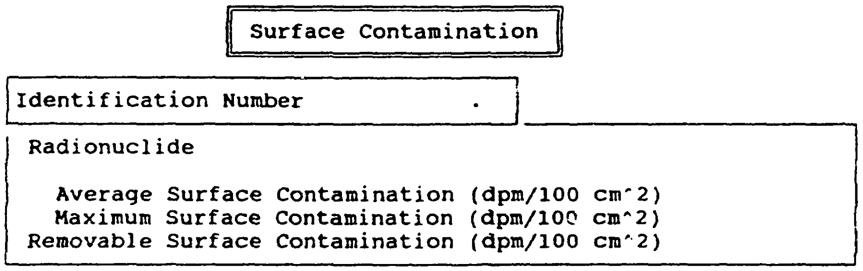
APPENDIX A. DATABASE FILES USED WITH EXPERT SYSTEM



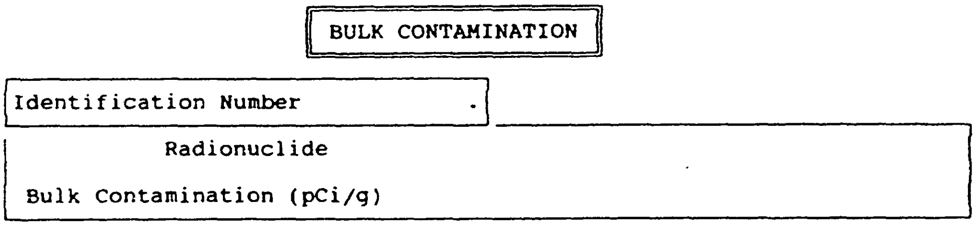
```
----------MAIN METAL WASTE DATA FILE----------
 Record Identification Number          .  Date of Entry    /  /
 Generator      .                            City           State
 Disposal Site                               City           State
--------------------------------------------------------------------
 The following SIX fields require YES/NO answers:
 Surface Contamination       Loose Contamination      In-Situ Required
    Embedded Material        Oxides         Paint, Grease, or Oil
--------------------------------------------------------------------
 Size (Large/Small)          Shape Complexity (High/Low)
--------------------------------------------------------------------
 Waste Class      Waste Sub Class       Surface Dose Rate (mR/h)
               Internal Contamination with TRU Nuclides (nCi/g)
--------------------------------------------------------------------
 Metal Source                                Metal Volume (ft^3)      .
 Metal Type (Al,Cu,SS)                          Metal Mass (lbs)       .
--------------------------------------------------------------------
    Depth of Contamination (micrometers)
 Specific Area Contaminated (sq.ft./lb)       .
====================================================================
APPEND        ║<C:>║MAINWAST              ║Rec: None          ║      ║Num
```



```
                  Surface Contamination

Identification Number                .
 Radionuclide

   Average Surface Contamination (dpm/100 cm^2)
   Maximum Surface Contamination (dpm/100 cm^2)
 Removable Surface Contamination (dpm/100 cm^2)
```



```
                        BULK CONTAMINATION

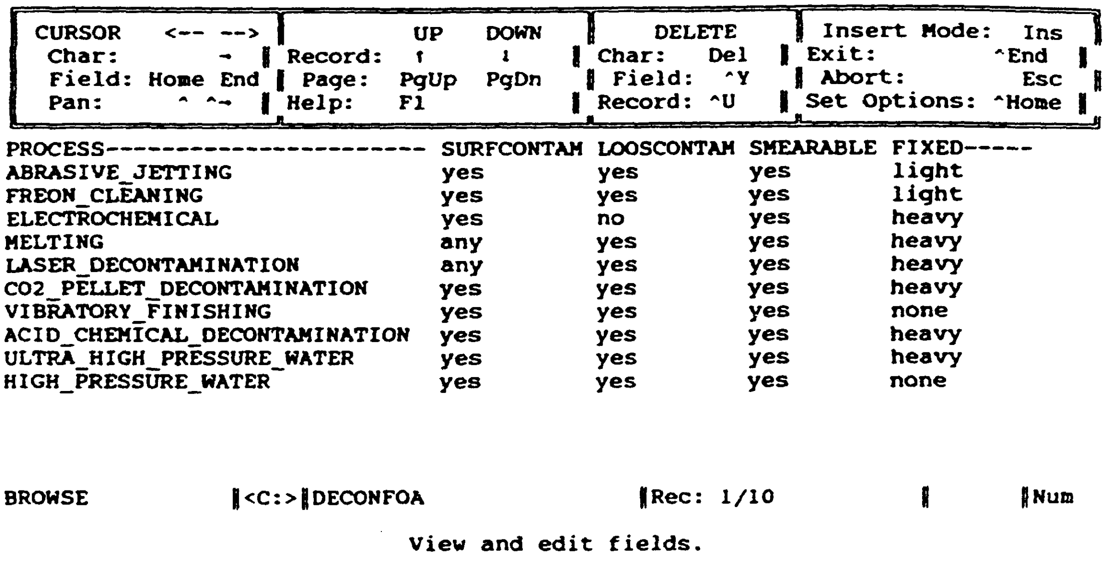
Identification Number              .
            Radionuclide

 Bulk Contamination (pCi/g)
```

```
Structure for database: C:MAINWAST.dbf
Number of data records:       0
Date of last update   : 09/28/93
Field  Field Name  Type       Width    Dec
    1  RINSITU     Character      3
    2  SUBWSTCLSS  Character      4
    3  WSTCLSS     Character      3
    4  IDNUMBER    Numeric       12      1
    5  ENTRYDATE   Date           8
    6  SURFACE     Character      3
    7  LOOSE       Character      3
    8  EMBED       Character      3
    9  OXID        Character      3
   10  PGOIL       Character      3
   11  SIZE        Character      5
   12  SHPCOMPLEX  Character      6
   13  MST         Character     30
   14  MTYPE       Character     20
   15  SURFDOSERT  Numeric        9
   16  ICONTRUNUC  Numeric       10
   17  WSTGENSITE  Character     30
   18  WSTGENCITY  Character     10
   19  WSTGENST    Character      2
   20  WSTDISSITE  Character     30
   21  WSTDISCITY  Character     10
   22  WSTDISST    Character      2
   23  METALVOL    Numeric       10      2
   24  METALMASS   Numeric       12      2
   25  DEPTHCONT   Numeric        6
   26  SPAREACONT  Numeric       10      3
   27  PROCESS1    Character     30
   28  PROCESS2    Character     30
   29  PROCESS3    Character     30
** Total **                     338
```

```
Structure for database: C:BULKNUC.dbf
Number of data records:       0
Date of last update   : 09/28/93
Field  Field Name  Type       Width    Dec
    1  IDNUMBER    Numeric       12      1
    2  RADNUC      Character     35
    3  BULKCONTAM  Numeric        9
    4  PROCESS1    Character     30
    5  PROCESS2    Character     30
    6  PROCESS3    Character     30
** Total **                     147
```

```
Structure for database: C:SURFNUC.dbf
Number of data records:       0
Date of last update   : 09/28/93
Field  Field Name  Type       Width    Dec
    1  IDNUMBER    Numeric       12      1
    2  RADNUC      Character     35
    3  AVG         Numeric        9
    4  MAX         Numeric        9
    5  REM         Numeric        9
    6  CONTAMTYPE  Character     15
    7  PROCESS1    Character     30
    8  PROCESS2    Character     30
    9  PROCESS3    Character     30
** Total **                     180
```



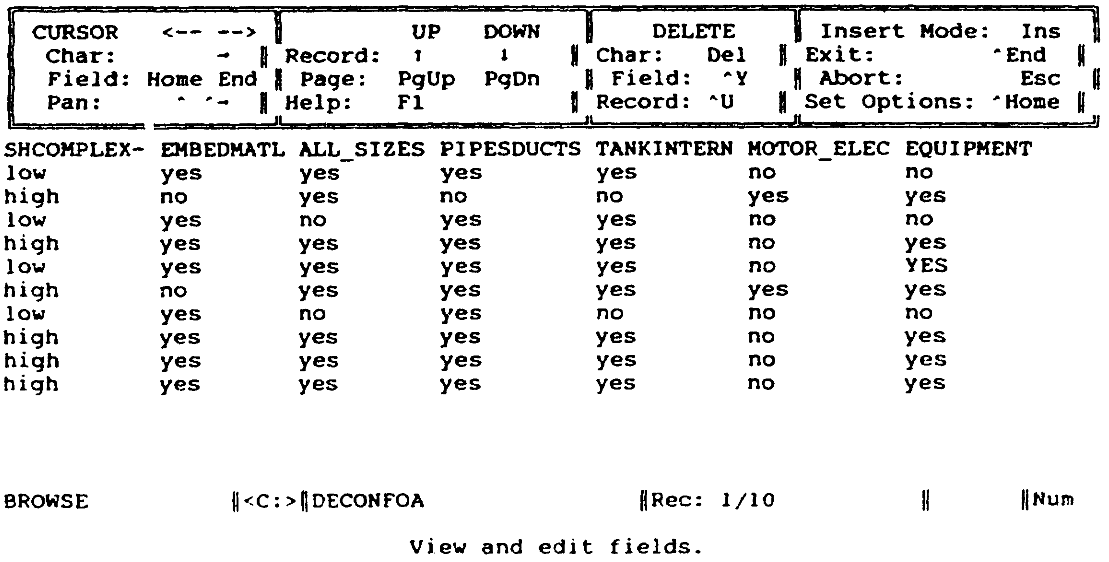
```
CURSOR    <-- -->  ║         UP    DOWN  ║    DELETE      ║ Insert Mode:  Ins ║
 Char:         →   ║ Record:  ↑      ↓   ║ Char:    Del   ║ Exit:        ^End ║
 Field: Home End   ║ Page:   PgUp  PgDn  ║ Field:   ^Y    ║ Abort:        Esc ║
 Pan:       ^ ^→   ║ Help:   F1          ║ Record: ^U     ║ Set Options: ^Home║

PROCESS----------------------- SURFCONTAM LOOSCONTAM SMEARABLE FIXED-----
ABRASIVE_JETTING               yes        yes        yes       light
FREON_CLEANING                 yes        yes        yes       light
ELECTROCHEMICAL                yes        no         yes       heavy
MELTING                        any        yes        yes       heavy
LASER_DECONTAMINATION          any        yes        yes       heavy
CO2_PELLET_DECONTAMINATION     yes        yes        yes       heavy
VIBRATORY_FINISHING            yes        yes        yes       none
ACID_CHEMICAL_DECONTAMINATION  yes        yes        yes       heavy
ULTRA_HIGH_PRESSURE_WATER      yes        yes        yes       heavy
HIGH_PRESSURE_WATER            yes        yes        yes       none



BROWSE         ║<C:>║DECONFOA              ║Rec: 1/10           ║       ║Num

                          View and edit fields.
```



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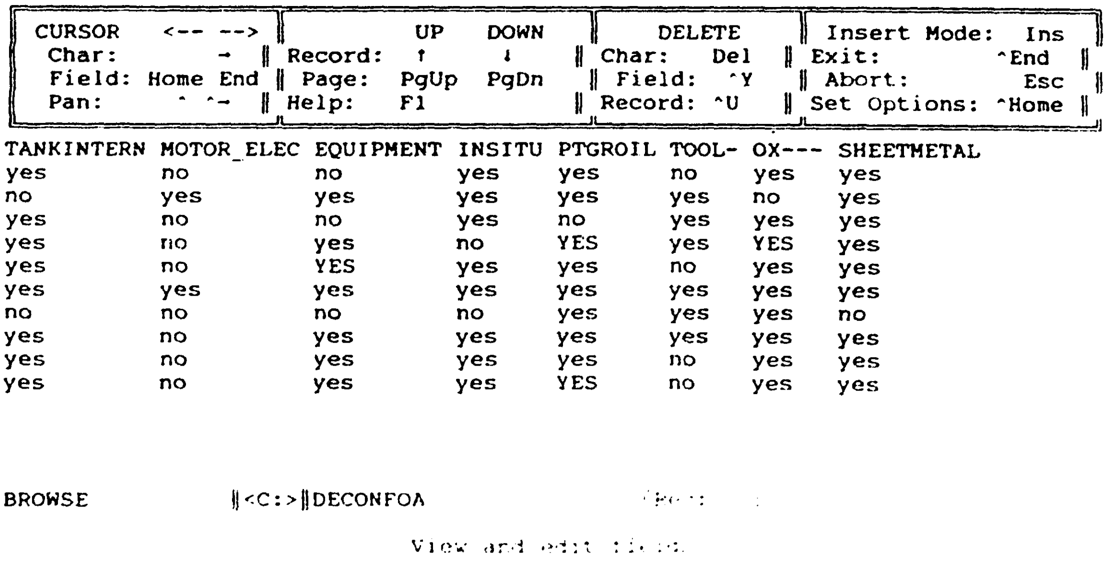
CURSOR    <-- -->  ║         UP    DOWN  ║    DELETE      ║ Insert Mode:  Ins ║
 Char:         →   ║ Record:  ↑      ↓   ║ Char:    Del   ║ Exit:        ^End ║
 Field: Home End   ║ Page:   PgUp  PgDn  ║ Field:   ^Y    ║ Abort:        Esc ║
 Pan:       ^ ^→   ║ Help:   F1          ║ Record: ^U     ║ Set Options: ^Home║

SHCOMPLEX- EMBEDMATL ALL_SIZES PIPESDUCTS TANKINTERN MOTOR_ELEC EQUIPMENT
low        yes       yes       yes        yes        no         no
high       no        yes       no         no         yes        yes
low        yes       no        yes        yes        no         no
high       yes       yes       yes        yes        no         yes
low        yes       yes       yes        yes        no         YES
high       no        yes       yes        yes        yes        yes
low        yes       no        yes        no         no         no
high       yes       yes       yes        yes        no         yes
high       yes       yes       yes        yes        no         yes
high       yes       yes       yes        yes        no         yes



BROWSE         ║<C:>║DECONFOA              ║Rec: 1/10           ║       ║Num

                          View and edit fields.
```



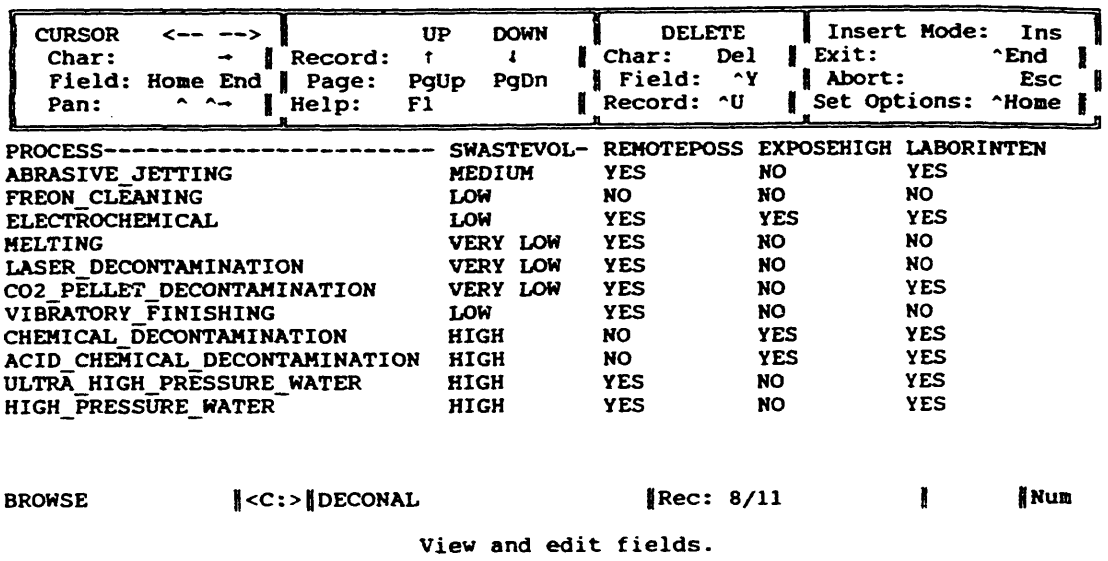
```
CURSOR    <-- -->  ║         UP    DOWN  ║    DELETE      ║ Insert Mode:  Ins ║
 Char:         →   ║ Record:  ↑      ↓   ║ Char:    Del   ║ Exit:        ^End ║
 Field: Home End   ║ Page:   PgUp  PgDn  ║ Field:   ^Y    ║ Abort:        Esc ║
 Pan:       ^ ^→   ║ Help:   F1          ║ Record: ^U     ║ Set Options: ^Home║

TANKINTERN MOTOR_ELEC EQUIPMENT INSITU PTGROIL TOOL- OX--- SHEETMETAL
yes        no         no        yes    yes     no    yes   yes
no         yes        yes       yes    yes     yes   no    yes
yes        no         no        yes    no      yes   yes   yes
yes        no         yes       no     YES     yes   YES   yes
yes        no         YES       yes    yes     no    yes   yes
yes        yes        yes       yes    yes     yes   yes   yes
no         no         no        no     yes     yes   yes   no
yes        no         yes       yes    yes     yes   yes   yes
yes        no         yes       yes    yes     no    yes   yes
yes        no         yes       yes    YES     no    yes   yes



BROWSE         ║<C:>║DECONFOA              Rec:

                          View and edit fields.
```



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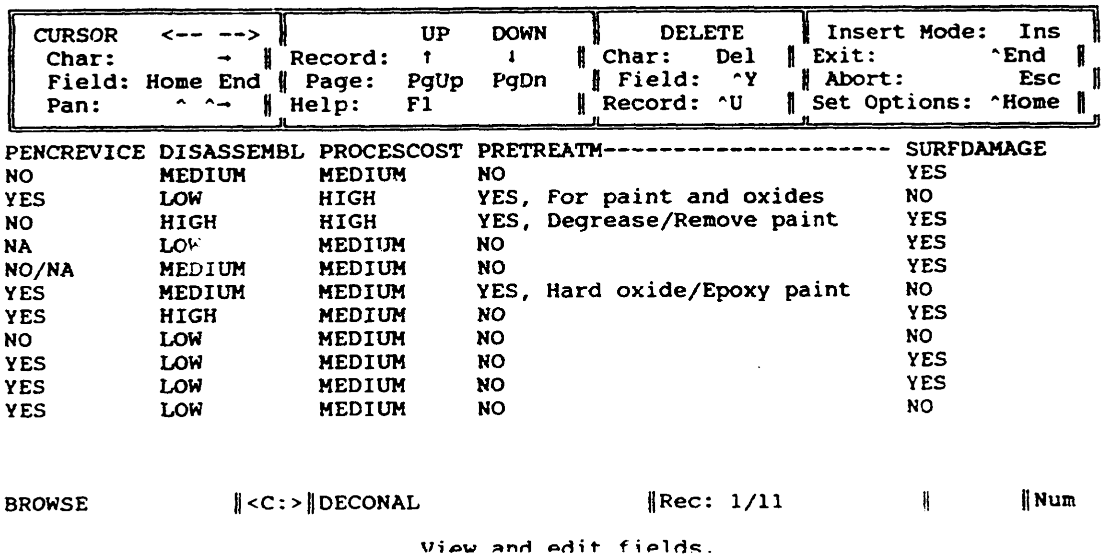
║ CURSOR    <-- -->        ║            UP    DOWN       ║      DELETE        ║ Insert Mode:  Ins       ║
║  Char:           →       ║ Record:    ↑      ↓         ║ Char:    Del       ║ Exit:           ^End    ║
║  Field:  Home  End       ║ Page:     PgUp   PgDn       ║  Field:   ^Y       ║  Abort:          Esc    ║
║  Pan:         ^  ^→      ║ Help:     F1                ║ Record:  ^U        ║ Set Options:  ^Home     ║
╚══════════════════════════╩═════════════════════════════╩════════════════════╩═════════════════════════╝
PROCESS----------------------- SWASTEVOL- REMOTEPOSS EXPOSEHIGH LABORINTEN
ABRASIVE_JETTING               MEDIUM     YES        NO         YES
FREON_CLEANING                 LOW        NO         NO         NO
ELECTROCHEMICAL                LOW        YES        YES        YES
MELTING                        VERY LOW   YES        NO         NO
LASER_DECONTAMINATION          VERY LOW   YES        NO         NO
CO2_PELLET_DECONTAMINATION     VERY LOW   YES        NO         YES
VIBRATORY_FINISHING            LOW        YES        NO         NO
CHEMICAL_DECONTAMINATION       HIGH       NO         YES        YES
ACID_CHEMICAL_DECONTAMINATION  HIGH       NO         YES        YES
ULTRA_HIGH_PRESSURE_WATER      HIGH       YES        NO         YES
HIGH_PRESSURE_WATER            HIGH       YES        NO         YES


BROWSE        ║<C:>║DECONAL             ║Rec: 8/11        ║          ║Num

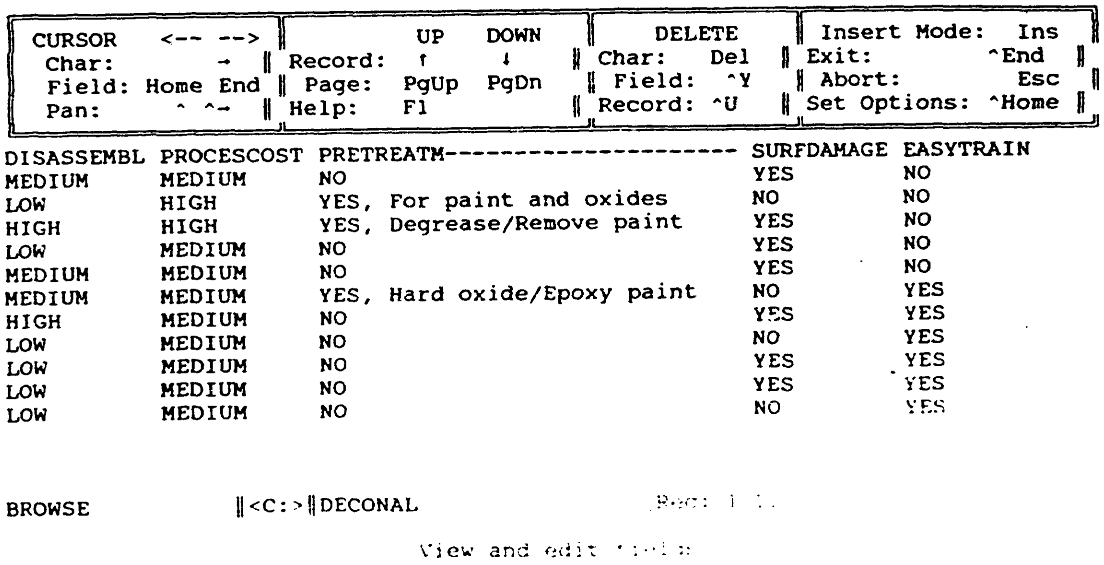
                          View and edit fields.
```



```
╔══════════════════════════╦═════════════════════════════╦════════════════════╦═════════════════════════╗
║ CURSOR    <-- -->        ║            UP    DOWN       ║      DELETE        ║ Insert Mode:  Ins       ║
║  Char:           →       ║ Record:    ↑      ↓         ║ Char:    Del       ║ Exit:           ^End    ║
║  Field:  Home  End       ║ Page:     PgUp   PgDn       ║  Field:   ^Y       ║  Abort:          Esc    ║
║  Pan:         ^  ^→      ║ Help:     F1                ║ Record:  ^U        ║ Set Options:  ^Home     ║
╚══════════════════════════╩═════════════════════════════╩════════════════════╩═════════════════════════╝
PENCREVICE DISASSEMBL PROCESCOST PRETREATM-------------------- SURFDAMAGE
NO         MEDIUM     MEDIUM     NO                            YES
YES        LOW        HIGH       YES, For paint and oxides     NO
NO         HIGH       HIGH       YES, Degrease/Remove paint    YES
NA         LOW        MEDIUM     NO                            YES
NO/NA      MEDIUM     MEDIUM     NO                            YES
YES        MEDIUM     MEDIUM     YES, Hard oxide/Epoxy paint   NO
YES        HIGH       MEDIUM     NO                            YES
NO         LOW        MEDIUM     NO                            NO
YES        LOW        MEDIUM     NO                            YES
YES        LOW        MEDIUM     NO                            YES
YES        LOW        MEDIUM     NO                            NO


BROWSE        ║<C:>║DECONAL             ║Rec: 1/11        ║          ║Num

                          View and edit fields.
```



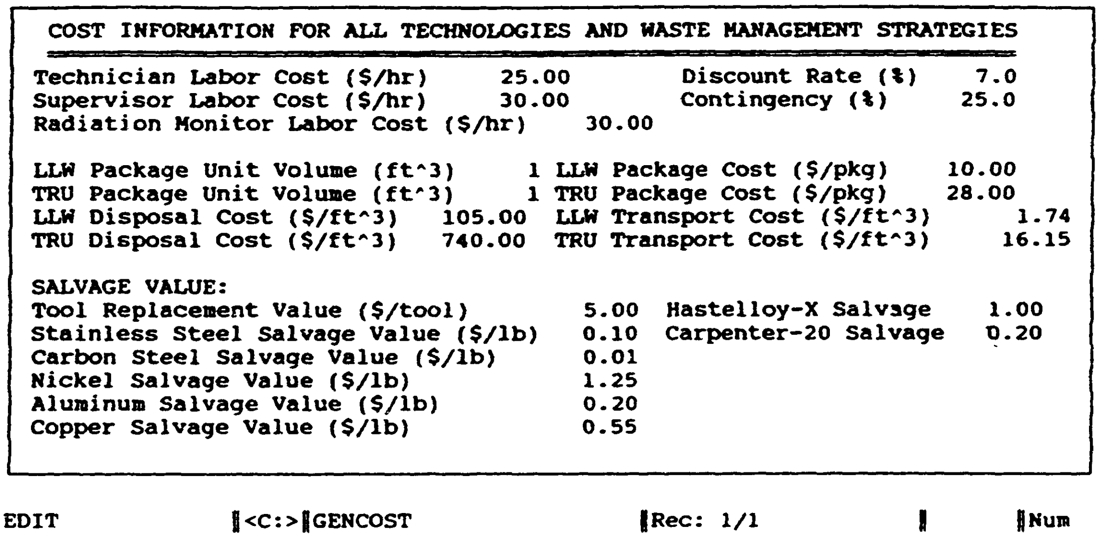
```
╔══════════════════════════╦═════════════════════════════╦════════════════════╦═════════════════════════╗
║ CURSOR    <-- -->        ║            UP    DOWN       ║      DELETE        ║ Insert Mode:  Ins       ║
║  Char:           →       ║ Record:    ↑      ↓         ║ Char:    Del       ║ Exit:           ^End    ║
║  Field:  Home  End       ║ Page:     PgUp   PgDn       ║  Field:   ^Y       ║  Abort:          Esc    ║
║  Pan:         ^  ^→      ║ Help:     F1                ║ Record:  ^U        ║ Set Options:  ^Home     ║
╚══════════════════════════╩═════════════════════════════╩════════════════════╩═════════════════════════╝
DISASSEMBL PROCESCOST PRETREATM-------------------- SURFDAMAGE EASYTRAIN
MEDIUM     MEDIUM     NO                            YES        NO
LOW        HIGH       YES, For paint and oxides     NO         NO
HIGH       HIGH       YES, Degrease/Remove paint    YES        NO
LOW        MEDIUM     NO                            YES        NO
MEDIUM     MEDIUM     NO                            YES        NO
MEDIUM     MEDIUM     YES, Hard oxide/Epoxy paint   NO         YES
HIGH       MEDIUM     NO                            YES        YES
LOW        MEDIUM     NO                            NO         YES
LOW        MEDIUM     NO                            YES        YES
LOW        MEDIUM     NO                            YES        YES
LOW        MEDIUM     NO                            NO         YES


BROWSE        ║<C:>║DECONAL             Rec: 1/11

                          View and edit fields.
```

```
Structure for database: C:DECONFOA.dbf
Number of data records:      10
Date of last update   : 08/05/93
Field  Field Name  Type       Width    Dec
    1  PROCESS     Character     30
    2  SURFCONTAM  Character      5
    3  LOOSCONTAM  Character      5
    4  SMEARABLE   Character      5
    5  FIXED       Character     10
    6  SHCOMPLEX   Character     10
    7  EMBEDMATL   Character      5
    8  ALL_SIZES   Character      5
    9  PIPESDUCTS  Character      5
   10  TANKINTERN  Character      5
   11  MOTOR_ELEC  Character      5
   12  EQUIPMENT   Character      5
   13  INSITU      Character      5
   14  PTGROIL     Character      5
   15  TOOL        Character      5
   16  OX          Character      5
   17  SHEETMETAL  Character      5
** Total **                     121
```

```
Structure for database: C:DECONAL.dbf
Number of data records:      11
Date of last update   : 05/06/93
Field  Field Name  Type       Width    Dec
    1  PROCESS     Character     30
    2  SWASTEVOL   Character     10
    3  REMOTEPOSS  Character      5
    4  EXPOSEHIGH  Character      5
    5  LABORINTEN  Character      5
    6  PENCREVICE  Character      6
    7  DISASSEMBL  Character     10
    8  PROCESCOST  Character     10
    9  PRETREATM   Character     30
   10  SURFDAMAGE  Character      8
   11  EASYTRAIN   Character      5
** Total **                     125
```



```
 COST INFORMATION FOR ALL TECHNOLOGIES AND WASTE MANAGEMENT STRATEGIES
 ════════════════════════════════════════════════════════════════════
Technician Labor Cost ($/hr)      25.00        Discount Rate (%)     7.0
Supervisor Labor Cost ($/hr)      30.00        Contingency (%)      25.0
Radiation Monitor Labor Cost ($/hr)    30.00

LLW Package Unit Volume (ft^3)      1 LLW Package Cost ($/pkg)    10.00
TRU Package Unit Volume (ft^3)      1 TRU Package Cost ($/pkg)    28.00
LLW Disposal Cost ($/ft^3)   105.00  LLW Transport Cost ($/ft^3)     1.74
TRU Disposal Cost ($/ft^3)   740.00  TRU Transport Cost ($/ft^3)    16.15

SALVAGE VALUE:
Tool Replacement Value ($/tool)       5.00  Hastelloy-X Salvage    1.00
Stainless Steel Salvage Value ($/lb)  0.10  Carpenter-20 Salvage   0.20
Carbon Steel Salvage Value ($/lb)     0.01
Nickel Salvage Value ($/lb)           1.25
Aluminum Salvage Value ($/lb)         0.20
Copper Salvage Value ($/lb)           0.55

EDIT            ║<C:>║GENCOST           ║Rec: 1/1         ║      ║Num
```

```
Structure for database: C:GENCOST.dbf
Number of data records:       1
Date of last update   : 08/05/93
Field  Field Name  Type       Width    Dec
    1  CP20SALVGE  Numeric        6      2
    2  HXSALVAGE   Numeric        6      2
    3  TRUTRANSP   Numeric        8      2
    4  LLWTRANSP   Numeric        8      2
    5  TRUPKGCST   Numeric        8      2
    6  LLWPKGCST   Numeric        8      2
    7  LLWPKGVOL   Numeric        5
    8  TRUPKGVOL   Numeric        5
    9  TRUDISPCST  Numeric        8      2
   10  LLWDISPCST  Numeric        8      2
   11  TECHLABOR   Numeric        7      2
   12  SPVISLABOR  Numeric        7      2
   13  RADMNLABOR  Numeric        7      2
   14  DISCOUNTRT  Numeric        4      1
   15  CONTINGNCY  Numeric        4      1
   16  TOOLVALUE   Numeric        6      2
   17  SSSALVAGE   Numeric        6      2
   18  NISALVAGE   Numeric        6      2
   19  ALSALVAGE   Numeric        6      2
   20  CSTSALVAGE  Numeric        6      2
   21  CUSALVAGE   Numeric        6      2
** Total **                     136
```

```
***** COST DATA FOR TECHNOLOGIES *****
TECHNOLOGY  VIBRATORY_FINISHING                         Profit Margin  0.00
Work Year (hrs)  1760   Volume Divisor (ft^3)     8.83
Work Month (hrs)  147   Area Divisor (ft^2)     0.00
No. of Technicians 2.00  Mass Divisor (lbs):   300.00     Ferrous     0.00
No. of Supervisors 0.50                                 Non-Ferrous     0.00
No. of Radiation Monitors 0.50
Capital Costs ($)        0.00 Operating Costs:($/lb)   0.00, ($/ft^2)    0.00
Capital & Operating Cost ($/lb):  Ferrous   0.00  Non-Ferrous   0.00
                                  Rental Facility Cost ($/Mnth)        0
Mobile Facility Cost ($)      588000      Fixed Facility Cost ($)        0
Mobile Facility Life (Yrs)  11         Fixed Facility Life (Yrs)   0
                                         Equipment Life (Yrs)    0
           Material Cost ($/Hr)     24.75     Equipment Cost ($)          0
        Material Cost ($/Mnth)   3630.00  Equipment Cost ($/Yr)      505000
          Utilities Cost ($/Hr)      2.25 Equipment Cost ($/Mnth)      0.00
Maintenance & Repair Cost ($/Hr)    23.86 Preparation:Cost ($/Hr)      0.00
Secondary Waste Processing Cost ($/ft^3)     2.13        Cost ($) 11286.00
Secondary Waste Volume (ft^3/Mnth)     0.00 Prep Time/Vol (h/ft^3)    0.000
Secondary Waste Volume (ft^3/Hr)      0.000  Mass Divisor (lbs)  5000.00
Volume Reduction Factor  67  Melting VRF   0  Mass Reduction Factor    0

EDIT              ║<C:>║TECHCOST              ║Rec: 1/10          ║      ║Num
```

```
***** COST DATA FOR TECHNOLOGIES *****
TECHNOLOGY  ELECTROCHEMICAL                             Profit Margin  0.00
Work Year (hrs)  1760   Volume Divisor (ft^3)    30.00
Work Month (hrs)  147   Area Divisor (ft^2)   247.57
No. of Technicians 2.00  Mass Divisor (lbs):     0.00     Ferrous     0.00
No. of Supervisors 0.00                                 Non-Ferrous     0.00
No. of Radiation Monitors 0.00
Capital Costs ($)        0.00 Operating Costs:($/lb)   0.00, ($/ft^2)    0.00
Capital & Operating Cost ($/lb):  Ferrous   0.00  Non-Ferrous   0.00
                                  Rental Facility Cost ($/Mnth)        0
Mobile Facility Cost ($)      400000      Fixed Facility Cost ($)        0
Mobile Facility Life (Yrs)  11         Fixed Facility Life (Yrs)   0
                                         Equipment Life (Yrs)    0
           Material Cost ($/Hr)      9.64     Equipment Cost ($)          0
        Material Cost ($/Mnth)   1417.55  Equipment Cost ($/Yr)           0
          Utilities Cost ($/Hr)      2.25 Equipment Cost ($/Mnth)  11056.89
Maintenance & Repair Cost ($/Hr)     2.05 Preparation:Cost ($/Hr)      0.00
Secondary Waste Processing Cost ($/ft^3)     2.13        Cost ($) 11286.00
Secondary Waste Volume (ft^3/Mnth)    73.50 Prep Time/Vol (h/ft^3)    0.000
Secondary Waste Volume (ft^3/Hr)      0.000  Mass Divisor (lbs)  5000.00
Volume Reduction Factor   0  Melting VRF   0  Mass Reduction Factor    0

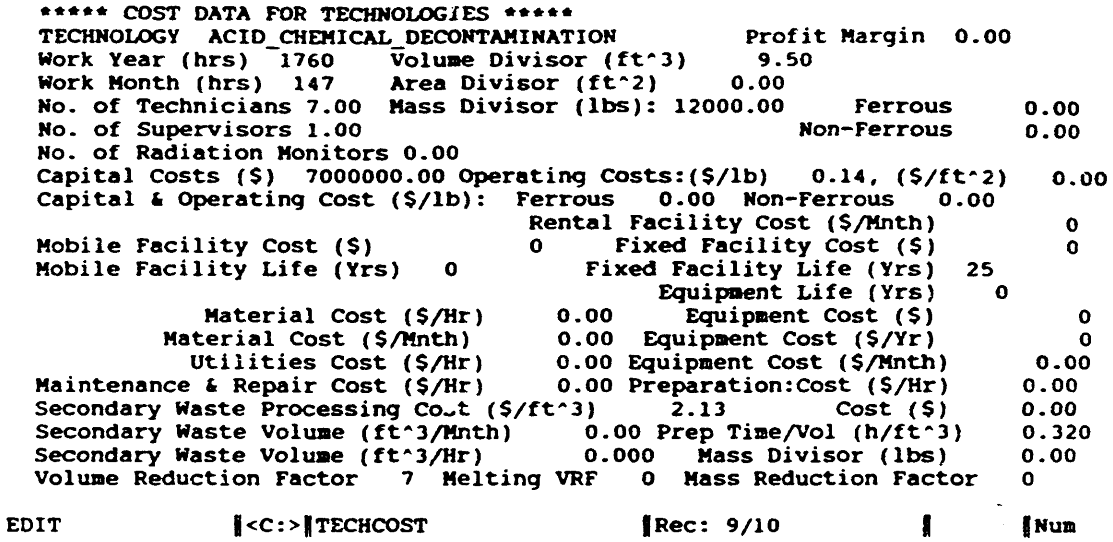
EDIT              ║<C:>║TECHCOST              ║Rec: 2/10          ║      ║Num
```

```
 ***** COST DATA FOR TECHNOLOGIES *****
 TECHNOLOGY  ULTRA_HIGH_PRESSURE_WATER           Profit Margin  0.00
 Work Year (hrs)  1760    Volume Divisor (ft^3)    0.00
 Work Month (hrs)  147    Area Divisor (ft^2)    60.00
 No. of Technicians 2.00  Mass Divisor (lbs):     0.00     Ferrous     0.00
 No. of Supervisors 0.00                                Non-Ferrous    0.00
 No. of Radiation Monitors 0.00
 Capital Costs ($)        0.00 Operating Costs:($/lb)  0.00, ($/ft^2)   0.00
 Capital & Operating Cost ($/lb):  Ferrous   0.00  Non-Ferrous   0.00
                                Rental Facility Cost ($/Mnth)          0
 Mobile Facility Cost ($)      300000     Fixed Facility Cost ($)      0
 Mobile Facility Life (Yrs)  11         Fixed Facility Life (Yrs)  0
                                     Equipment Life (Yrs)  100
            Material Cost ($/Hr)     0.00     Equipment Cost ($)     600000
         Material Cost ($/Mnth)     0.00  Equipment Cost ($/Yr)        0
           Utilities Cost ($/Hr)     3.34 Equipment Cost ($/Mnth)     0.00
 Maintenance & Repair Cost ($/Hr)     2.05 Preparation:Cost ($/Hr)     0.00
 Secondary Waste Processing Cost ($/ft^3)     2.13        Cost ($) 11286.00
 Secondary Waste Volume (ft^3/Mnth)     0.00 Prep Time/Vol (h/ft^3)    0.000
 Secondary Waste Volume (ft^3/Hr)      40.000    Mass Divisor (lbs)  5000.00
 Volume Reduction Factor    0  Melting VRF   0  Mass Reduction Factor    0

EDIT            |<C:>|TECHCOST              |Rec: 5/10        |      |Num
```

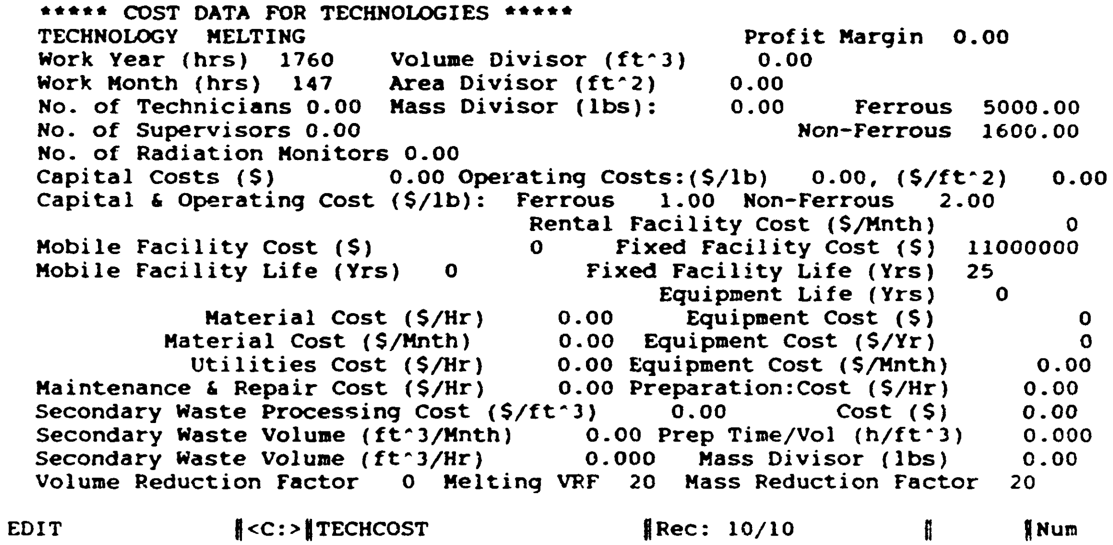
```
 ***** COST DATA FOR TECHNOLOGIES *****
 TECHNOLOGY  HIGH_PRESSURE_WATER                 Profit Margin  0.00
 Work Year (hrs)  1760    Volume Divisor (ft^3)    0.00
 Work Month (hrs)  147    Area Divisor (ft^2)    60.00
 No. of Technicians 2.00  Mass Divisor (lbs):     0.00     Ferrous     0.00
 No. of Supervisors 0.00                                Non-Ferrous    0.00
 No. of Radiation Monitors 0.00
 Capital Costs ($)        0.00 Operating Costs:($/lb)  0.00, ($/ft^2)   0.00
 Capital & Operating Cost ($/lb):  Ferrous   0.00  Non-Ferrous   0.00
                                Rental Facility Cost ($/Mnth)          0
 Mobile Facility Cost ($)      300000     Fixed Facility Cost ($)      0
 Mobile Facility Life (Yrs)  11         Fixed Facility Life (Yrs)  0
                                     Equipment Life (Yrs)    7
            Material Cost ($/Hr)     0.00     Equipment Cost ($)      62500
         Material Cost ($/Mnth)     0.00  Equipment Cost ($/Yr)        0
           Utilities Cost ($/Hr)     3.34 Equipment Cost ($/Mnth)     0.00
 Maintenance & Repair Cost ($/Hr)     2.05 Preparation:Cost ($/Hr)     0.00
 Secondary Waste Processing Cost ($/ft^3)     2.13        Cost ($) 11286.00
 Secondary Waste Volume (ft^3/Mnth)     0.00 Prep Time/Vol (h/ft^3)    0.000
 Secondary Waste Volume (ft^3/Hr)      24.000    Mass Divisor (lbs)  5000.00
 Volume Reduction Factor    0  Melting VRF   0  Mass Reduction Factor    0

EDIT            |<C:>|TECHCOST              |Rec: 6/10        |      |Num
```



```
***** COST DATA FOR TECHNOLOGIES *****
TECHNOLOGY  ACID_CHEMICAL_DECONTAMINATION        Profit Margin  0.00
Work Year (hrs)  1760    Volume Divisor (ft^3)     9.50
Work Month (hrs)  147    Area Divisor (ft^2)     0.00
No. of Technicians 7.00  Mass Divisor (lbs): 12000.00     Ferrous     0.00
No. of Supervisors 1.00                                 Non-Ferrous     0.00
No. of Radiation Monitors 0.00
Capital Costs ($)  7000000.00 Operating Costs:($/lb)   0.14, ($/ft^2)    0.00
Capital & Operating Cost ($/lb):  Ferrous    0.00  Non-Ferrous   0.00
                                   Rental Facility Cost ($/Mnth)          0
Mobile Facility Cost ($)          0      Fixed Facility Cost ($)          0
Mobile Facility Life (Yrs)   0        Fixed Facility Life (Yrs)  25
                                          Equipment Life (Yrs)    0
        Material Cost ($/Hr)      0.00      Equipment Cost ($)            0
      Material Cost ($/Mnth)      0.00  Equipment Cost ($/Yr)             0
        Utilities Cost ($/Hr)     0.00 Equipment Cost ($/Mnth)         0.00
Maintenance & Repair Cost ($/Hr)     0.00 Preparation:Cost ($/Hr)      0.00
Secondary Waste Processing Cost ($/ft^3)      2.13       Cost ($)      0.00
Secondary Waste Volume (ft^3/Mnth)     0.00 Prep Time/Vol (h/ft^3)     0.320
Secondary Waste Volume (ft^3/Hr)      0.000    Mass Divisor (lbs)      0.00
Volume Reduction Factor    7  Melting VRF    0  Mass Reduction Factor    0

EDIT            ▌<C:>▌TECHCOST               ▌Rec: 9/10          ▌      ▌Num
```



```
***** COST DATA FOR TECHNOLOGIES *****
TECHNOLOGY  MELTING                                  Profit Margin  0.00
Work Year (hrs)  1760    Volume Divisor (ft^3)     0.00
Work Month (hrs)  147    Area Divisor (ft^2)     0.00
No. of Technicians 0.00  Mass Divisor (lbs):     0.00      Ferrous   5000.00
No. of Supervisors 0.00                                Non-Ferrous   1600.00
No. of Radiation Monitors 0.00
Capital Costs ($)          0.00 Operating Costs:($/lb)   0.00, ($/ft^2)   0.00
Capital & Operating Cost ($/lb):  Ferrous    1.00  Non-Ferrous    2.00
                                   Rental Facility Cost ($/Mnth)         0
Mobile Facility Cost ($)          0      Fixed Facility Cost ($)  11000000
Mobile Facility Life (Yrs)   0        Fixed Facility Life (Yrs)  25
                                          Equipment Life (Yrs)    0
        Material Cost ($/Hr)      0.00      Equipment Cost ($)           0
      Material Cost ($/Mnth)      0.00  Equipment Cost ($/Yr)            0
        Utilities Cost ($/Hr)     0.00 Equipment Cost ($/Mnth)        0.00
Maintenance & Repair Cost ($/Hr)     0.00 Preparation:Cost ($/Hr)     0.00
Secondary Waste Processing Cost ($/ft^3)      0.00       Cost ($)     0.00
Secondary Waste Volume (ft^3/Mnth)     0.00 Prep Time/Vol (h/ft^3)    0.000
Secondary Waste Volume (ft^3/Hr)      0.000    Mass Divisor (lbs)     0.00
Volume Reduction Factor    0  Melting VRF   20  Mass Reduction Factor   20

EDIT            ▌<C:>▌TECHCOST               ▌Rec: 10/10         ▌      ▌Num
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```
***** COST DATA FOR TECHNOLOGIES *****
TECHNOLOGY  LASER_DECONTAMINATION                 Profit Margin  0.00
Work Year (hrs)  1760    Volume Divisor (ft^3)     0.00
Work Month (hrs)  147    Area Divisor (ft^2)    21.53
No. of Technicians 1.00  Mass Divisor (lbs):     0.00     Ferrous     0.00
No. of Supervisors 0.00                                Non-Ferrous     0.00
No. of Radiation Monitors 0.00
Capital Costs ($)   750000.00 Operating Costs:($/lb)   0.00, ($/ft^2)    1.00
Capital & Operating Cost ($/lb):  Ferrous    0.00  Non-Ferrous   0.00
                                   Rental Facility Cost ($/Mnth)        0
Mobile Facility Cost ($)      550000     Fixed Facility Cost ($)        0
Mobile Facility Life (Yrs)  11         Fixed Facility Life (Yrs)   0
                                          Equipment Life (Yrs)     7
           Material Cost ($/Hr)     1.31     Equipment Cost ($)      57140
        Material Cost ($/Mnth)    191.67  Equipment Cost ($/Yr)          0
          Utilities Cost ($/Hr)     1.04 Equipment Cost ($/Mnth)      0.00
Maintenance & Repair Cost ($/Hr)     2.05 Preparation:Cost ($/Hr)     0.00
Secondary Waste Processing Cost ($/ft^3)     0.00        Cost ($) 11286.00
Secondary Waste Volume (ft^3/Mnth)     0.00 Prep Time/Vol (h/ft^3)    0.000
Secondary Waste Volume (ft^3/Hr)      0.013   Mass Divisor (lbs)  5000.00
Volume Reduction Factor    0  Melting VRF    0  Mass Reduction Factor    0

EDIT           |<C:>|TECHCOST            |Rec: 7/10          |       |Num
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```
***** COST DATA FOR TECHNOLOGIES *****
TECHNOLOGY  FREON_CLEANING                        Profit Margin  0.00
Work Year (hrs)  1760    Volume Divisor (ft^3)    32.00
Work Month (hrs)  147    Area Divisor (ft^2)     0.00
No. of Technicians 7.00  Mass Divisor (lbs):     0.00     Ferrous     0.00
No. of Supervisors 1.00                                Non-Ferrous     0.00
No. of Radiation Monitors 0.00
Capital Costs ($)          0.00 Operating Costs:($/lb)   0.00, ($/ft^2)    0.00
Capital & Operating Cost ($/lb):  Ferrous    0.00  Non-Ferrous   0.00
                                   Rental Facility Cost ($/Mnth)        0
Mobile Facility Cost ($)      400000     Fixed Facility Cost ($)        0
Mobile Facility Life (Yrs)  11         Fixed Facility Life (Yrs)   0
                                          Equipment Life (Yrs)     0
           Material Cost ($/Hr)   634.00     Equipment Cost ($)          0
        Material Cost ($/Mnth)      0.00  Equipment Cost ($/Yr)          0
          Utilities Cost ($/Hr)     2.25 Equipment Cost ($/Mnth)   8000.00
Maintenance & Repair Cost ($/Hr)     2.05 Preparation:Cost ($/Hr)     0.00
Secondary Waste Processing Cost ($/ft^3)     0.00        Cost ($) 11286.00
Secondary Waste Volume (ft^3/Mnth)     0.00 Prep Time/Vol (h/ft^3)    0.000
Secondary Waste Volume (ft^3/Hr)      0.000   Mass Divisor (lbs)  5000.00
Volume Reduction Factor   40  Melting VRF    0  Mass Reduction Factor    0

EDIT           |<C:>|TECHCOST            |Rec: 8/10          |       |Num
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```
***** COST DATA FOR TECHNOLOGIES *****
TECHNOLOGY  ABRASIVE_JETTING                        Profit Margin  0.00
Work Year (hrs)  1760    Volume Divisor (ft^3)     0.00
Work Month (hrs)  147    Area Divisor (ft^2)  1237.85
No. of Technicians 1.00  Mass Divisor (lbs):      0.00     Ferrous     0.00
No. of Supervisors 0.00                                Non-Ferrous     0.00
No. of Radiation Monitors 0.00
Capital Costs ($)       0.00 Operating Costs:($/lb)   0.00, ($/ft^2)   0.00
Capital & Operating Cost ($/lb):  Ferrous   0.00  Non-Ferrous   0.00
                                   Rental Facility Cost ($/Mnth)        0
Mobile Facility Cost ($)      400000    Fixed Facility Cost ($)         0
Mobile Facility Life (Yrs)  11        Fixed Facility Life (Yrs)   0
                                           Equipment Life (Yrs)    0
            Material Cost ($/Hr)     1.54    Equipment Cost ($)         0
         Material Cost ($/Mnth)    226.81  Equipment Cost ($/Yr)        0
           Utilities Cost ($/Hr)     2.25 Equipment Cost ($/Mnth)   9866.15
Maintenance & Repair Cost ($/Hr)     2.05 Preparation:Cost ($/Hr)    0.00
Secondary Waste Processing Cost ($/ft^3)     2.13       Cost ($) 11286.00
Secondary Waste Volume (ft^3/Mnth)      7.40 Prep Time/Vol (h/ft^3)    0.000
Secondary Waste Volume (ft^3/Hr)       0.000   Mass Divisor (lbs)  5000.00
Volume Reduction Factor   0  Melting VRF   0  Mass Reduction Factor   0

EDIT              ║<C:>║TECHCOST                ║Rec: 3/10          ║      ║Num
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```
***** COST DATA FOR TECHNOLOGIES *****
TECHNOLOGY  CO2_PELLET_DECONTAMINATION             Profit Margin 10.00
Work Year (hrs)  1760    Volume Divisor (ft^3)     0.00
Work Month (hrs)  147    Area Divisor (ft^2)     0.00
No. of Technicians 2.00  Mass Divisor (lbs):   130.00     Ferrous     0.00
No. of Supervisors 1.00                                Non-Ferrous     0.00
No. of Radiation Monitors 0.00
Capital Costs ($)   500000.00 Operating Costs:($/lb)   0.00, ($/ft^2)  10.00
Capital & Operating Cost ($/lb):  Ferrous   0.00  Non-Ferrous   0.00
                                   Rental Facility Cost ($/Mnth)     16000
Mobile Facility Cost ($)      200000    Fixed Facility Cost ($)         0
Mobile Facility Life (Yrs)  11        Fixed Facility Life (Yrs)   0
                                           Equipment Life (Yrs)    0
            Material Cost ($/Hr)    40.71    Equipment Cost ($)         0
         Material Cost ($/Mnth)      0.00  Equipment Cost ($/Yr)        0
           Utilities Cost ($/Hr)     3.34 Equipment Cost ($/Mnth)     0.00
Maintenance & Repair Cost ($/Hr)     2.05 Preparation:Cost ($/Hr)    0.00
Secondary Waste Processing Cost ($/ft^3)     0.00       Cost ($) 11286.00
Secondary Waste Volume (ft^3/Mnth)      1.00 Prep Time/Vol (h/ft^3)    0.000
Secondary Waste Volume (ft^3/Hr)       0.000   Mass Divisor (lbs)  5000.00
Volume Reduction Factor   0  Melting VRF   0  Mass Reduction Factor   0

EDIT              ║<C:>║TECHCOST                ║Rec: 4/10          ║      ║Num
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```
Structure for database: C:TECHCOST.dbf
Number of data records:       10
Date of last update   : 09/27/93
Field  Field Name  Type         Width    Dec
    1  OPCOSTFT2   Numeric          6      2
    2  OPCOSTLB    Numeric          6      2
    3  CAPCOST     Numeric         11      2
    4  NFCAPOPCST  Numeric          6      2
    5  FCAPOPCST   Numeric          6      2
    6  MSSREDFACT  Numeric          3
    7  MLTVRF      Numeric          3
    8  MSSDIVFER   Numeric          8      2
    9  MSSDIVNFER  Numeric          8      2
   10  PREPTIMEVL  Numeric          8      3
   11  SWSTVOLHR   Numeric          9      3
   12  EQUIPLIFE   Numeric          3
   13  PREPCOSTHR  Numeric          8      2
   14  RENTFACIL   Numeric          9
   15  PREPMSSDIV  Numeric          8      2
   16  SWSTVOLMTH  Numeric          8      2
   17  MTLCSTMNTH  Numeric          9      2
   18  EQPCSTMNTH  Numeric          9      2
   19  WKMNTHINHR  Numeric          4
   20  SWSTPROCCS  Numeric          8      2
   21  AREADIVISR  Numeric          8      2
   22  TECHNOLOGY  Character       35
   23  WORKYRINHR  Numeric          4
   24  TECHNO      Numeric          4      2
   25  SPVISERNO   Numeric          4      2
   26  RADMONNO    Numeric          4      2
   27  VOLDIVISOR  Numeric          8      2
   28  MSSDIVISOR  Numeric          8      2
   29  MOBILFACIL  Numeric          9
   30  MFACILLIFE  Numeric          3
   31  FIXEDFACIL  Numeric          9
   32  FFACILLIFE  Numeric          3
   33  EQUIPCSTYR  Numeric          9
   34  EQUIPCST    Numeric          9
   35  MATLCOSTHR  Numeric          8      2
   36  UTILCOSTHR  Numeric          8      2
   37  M_RPCOSTHR  Numeric          8      2
   38  PREPCOST    Numeric          8      2
   39  PROFITMRGN  Numeric          5      2
   40  VOLREDFACT  Numeric          3
** Total **                   298
```

```
Structure for database: C:COSTCOMP.dbf
Number of data records:       0
Date of last update   : 09/28/93
Field  Field Name  Type        Width    Dec
    1  WASTEVOL    Numeric        10      2
    2  IDCC        Numeric        12      1
    3  TECHCC      Character      30
    4  STRATEGY    Character      40
    5  STRATCOST   Numeric        10      2
    6  PREP        Numeric        10      2
    7  LABOR       Numeric        10      2
    8  MATERIAL    Numeric        10      2
    9  UTILITIES   Numeric        10      2
   10  MAINT_REP   Numeric        10      2
   11  EQUIPCOST   Numeric        10      2
   12  FACILITY    Numeric        10      2
   13  MOBILESTAT  Character      10
   14  WSTDISPOSE  Numeric        10      2
   15  CAPOPCOST   Numeric        10      2
   16  CONTING     Numeric        10      2
   17  SALVAGE     Numeric        10      2
   18  PROCESTIME  Numeric        10      2
** Total **                      233
```

```
Structure for database: C:TEMPSET.dbf
Number of data records:       0
Date of last update   : 09/28/93
Field  Field Name  Type       Width    Dec
    1  IDNUM       Numeric       12      1
    2  DPROCESS    Character     30
    3  SWASTEVOL   Character     10
    4  REMOTEPOSS  Character      5
    5  EXPOSEHIGH  Character      5
    6  LABORINTEN  Character      5
    7  PENCREVICE  Character      6
    8  DISASSEMBL  Character     10
    9  PROCESCOST  Character      6
   10  PRETREATM   Character      5
   11  SURFDAMAGE  Character     10
   12  EASYTRAIN   Character      5
** Total **                     110
```

```
Structure for database: C:DECSET.dbf
Number of data records:       0
Date of last update   : 09/28/93
Field  Field Name  Type       Width    Dec
    1  RANK5       Numeric        3
    2  RANK4       Numeric        3
    3  RANK3       Numeric        3
    4  RANK2       Numeric        3
    5  RANK1       Numeric        3
    6  TOTALSTRAT  Numeric        3
    7  COST5       Numeric       10      2
    8  COST4       Numeric       10      2
    9  COST3       Numeric       10      2
   10  COST2       Numeric       10      2
   11  COST1       Numeric       10      2
   12  IDNUM       Numeric       12      1
   13  DPROCESS    Character     30
   14  TRU_LEVEL   Numeric        5
   15  STRATEGY1   Character     40
   16  STRATEGY2   Character     40
   17  STRATEGY3   Character     40
   18  STRATEGY4   Character     40
   19  STRATEGY5   Character     40
   20  SWASTEVOL   Character     10
   21  REMOTEPOSS  Character      5
   22  EXPOSEHIGH  Character      5
   23  LABORINTEN  Character      5
   24  PENCREVICE  Character      6
   25  DISASSEMBL  Character     10
   26  PROCESCOST  Character      6
   27  PRETREATM   Character      5
   28  SURFDAMAGE  Character     10
   29  EASYTRAIN   Character      5
** Total **                     383
```

```
Structure for database: C:REFER.dbf
Number of data records:       63
Date of last update    : 09/27/93
Field  Field Name  Type       Width    Dec
    1  JOURNAL2    Character     66
    2  TITLE2      Character     68
    3  SFIDLETTER  Character      1
    4  SFIDNUM     Numeric        6      3
    5  PROCESS     Character     30
    6  AUTHOR1     Character     50
    7  AUTHOR2     Character     50
    8  AUTHOR3     Character     50
    9  TITLE       Character     68
   10  JOURNAL     Character     66
   11  CONF_IDNO   Character     20
   12  VOLUME      Character      3
   13  PAGE        Character      9
   14  DATE        Character     20
   15  CITY        Character     20
   16  ST_COUNTRY  Character     20
** Total **                     548
```

```
Structure for database: C:DFPROCES.dbf
Number of data records:       10
Date of last update   : 08/07/93
Field  Field Name  Type       Width    Dec
    1  NOTES       Character     70
    2  MAXAFT      Numeric        9
    3  REMAFT      Numeric        9
    4  AVGAFT      Numeric        9
    5  TLMAH       Numeric        9
    6  TLAAH       Numeric        9
    7  DFPROCESS   Character     30
    8  EQUIPMENT   Character     30
    9  MATERIAL    Character     30
   10  DECON_RATE  Numeric        5
   11  MAX_DEPTH   Numeric        8      2
   12  MIN_DEPTH   Numeric        8      2
   13  AVG_DEPTH   Numeric        8      2
   14  REMAINDPTH  Numeric        8      2
   15  BULKAFT     Numeric        9
   16  MIN_DF      Numeric        9      2
   17  DF          Numeric        9      2
   18  MAX_DF      Numeric        9      2
   19  AVGBEFLO    Numeric        9
   20  AVGAFTLO    Numeric        9
   21  AVGBEFHI    Numeric        9
   22  AVGAFTHI    Numeric        9
   23  AVGAFTOVHI  Numeric        9
   24  REMBEFLO    Numeric        9
   25  REMAFTLO    Numeric        9
   26  REMBEFHI    Numeric        9
   27  REMAFTHI    Numeric        9
   28  REMAFTOVHI  Numeric        9
   29  SSRBL       Numeric        9
   30  SSRBH       Numeric        9
   31  SSPAL       Numeric        9
   32  SSRAH       Numeric        9
   33  SSRAO       Numeric        9
   34  ALRBL       Numeric        9
   35  ALRBH       Numeric        9
   36  ALRAL       Numeric        9
   37  ALRAH       Numeric        9
   38  ALRAO       Numeric        9
   39  TLRBH       Numeric        9
   40  TLRAH       Numeric        9
   41  TLRAO       Numeric        9
   42  EERBH       Numeric        9
   43  EERAH       Numeric        9
   44  EERAO       Numeric        9
   45  MAXBEFLO    Numeric        9
   46  MAXAFTLO    Numeric        9
   47  MAXBEFHI    Numeric        9
   48  MAXAFTHI    Numeric        9
   49  MAXAFTOVHI  Numeric        9
   50  TRUAFT      Numeric        8      2
** Total **                     566
```

```
Structure for database: C:PBULKNUC.dbf
Number of data records:       0
Date of last update   : 09/28/93
Field  Field Name  Type       Width    Dec
    1  IDNUMBER    Numeric       12      1
    2  DFPROCESS   Character     30
    3  RADNUC      Character     35
    4  PBCONTAM    Numeric        9
    5  TRU_LEVEL   Numeric       10      2
** Total **                      97
```

```
Structure for database: C:PSURFNUC.dbf
Number of data records:       0
Date of last update   : 09/28/93
Field  Field Name  Type       Width    Dec
    1  IDNUMBER    Numeric       12      1
    2  DFPROCESS   Character     30
    3  RADNUC      Character     35
    4  PAVG        Numeric        9
    5  PMAX        Numeric        9
    6  PREM        Numeric        9
    7  TRU_LEVEL   Numeric       10      2
** Total **                     115
```

APPENDIX B. COST DATA AND ASSUMPTIONS

MELTING: COST DATA AND ASSUMPTIONS

Item	Cost-Related Information	Cost	Dollar Year	Range	References
Capital & Operating Costs					
ferrous metal		$1/lb	1992	$0.65-2/lb	1, 2, 3
non-ferrous metal		$2/lb	1992	$0.65-2/lb	1, 2, 3
Fixed Facility	25 year life	$11 million	1992		2
throughput for above facility	25000 tons/yr				2
equipment*					
materials*					
utilities*					
maintenance & repair*					
labor*					
preparation*					
Process Time					
ferrous metal**	5000 lbs/hr			4-6 tons/hr	4
non-ferrous metal**	1600 lbs/hr			1.6 tons/hr	4
Secondary Waste					
mass	5 wt. %				5, 6
volume	5 ft^3/24000 lbs				3
processing cost***					
Volume Reduction Factor	20			8.5-30	7, 8

1. Oak Ridge K-25 Site, 1993
2. Scientific Ecology Group, 1992
3. Staggs, 1992
4. Kellog et al., 1983
5. Sappok, 1989
6. Heshmatpour et al., 1983
7. Sappok and Rettig, 1992
8. Copeland and Heestand, 1980

* Assumed included in capital and operating costs
** Assumed based on 8 ton furnace
*** Assumed none required

FREON CLEANING: COST DATA AND ASSUMPTIONS

Item	Cost-Related Information	Cost	Dollar Year	Range	References
Mobile Facility*		$400000	1992		1
equipment**		$8000	1992		1
(2 pumps, reservoir, filter, vacuum, return system)					
materials					
(Freon, dry cleaning fluid)	127 gallons/hr $5/gallon	$6.34/hr	1992		2, 3
utilities***		$3960/yr	1992		4
maintenance & repair****		$3600/yr	1992		5
labor					
technicians	7 people				1
supervisor	1 person				1
preparation*	for 5000 lbs	$11,286	1992		6
Process Time					
tools	3 min.			2-5 min.	1
not tools	32 ft^3/hr				1
Secondary Waste					
volume reduction factor	40				1
processing cost*****					

1. McVey et al., 1981
2. Mayfair Cleaners, 1993
3. Allen and Hazelton, 1984
4. Hazelton and McCoy, 1982
5. Pang, 1992
6. Knight and Blackman, 1992
7. Voit, 1984
8. Oak Ridge K-25 Site, 1993
9. Gillis, 1992

* Assumed equal to costs for carbon dioxide pellet decontamination

** Assumed mid-range between abrasive jetting and high pressure water equipment costs

*** Assumed equal to utilities for vibratory finishin

**** Assumed equal to maintenance and repair cost for laser decontamination

***** Assume Freon is recycled and there is no secondary waste processing

ACID CHEMICAL DECONTAMINATION: COST DATA AND ASSUMPTIONS

Item	Cost-Related Information	Cost	Dollar Year	Range	References
Capital Costs					
(facility and equipment)*		$7 million	1992	$4-10 million	3
Operating Costs		$0.14/lb	1992		3
equipment**					
materials**					
utilities**					
maintenance & repair**					
labor**					
technicians	7 people				1
supervisor	1 person				1
preparation**					
including size reduction	0.32 hr/ft^3				2
excluding size reduction	0.03 hr/ft^3				2
Process Time	9.5 ft^3/hr			8-11 ft^3/hr	1
Secondary Waste					
volume reduction factor	7			1.5-12.5	2, 4
processing cost		$0.22/gallon	1980		4, 5
		$1.63/ft^3	1980		
		2.13/ft^3	1992		

1. McVey et al., 1981
2. Wobser, 1984
3. Oak Ridge K-25 Site, 1993
4. Hebrant, 1989
5. Manion and LaGuardia, 1980

* Assumed a 25 year life for facility and a 7 year life for equipment

** Assumed included in capital and operating costs

SURFACE LASER DECONTAMINATION: COST DATA AND ASSUMPTIONS

Item	Cost-Related Information	Cost	Dollar Year	Range	References
Capital Costs					
(facility and equipment)		$750,000	1992	$0.5-1 million	2
facility		$550,000	1992		2
Operating Costs		$1/ft^2	1992		2
equipment		$97,140	1992		1
materials (gases, HEPA filter)		$2300/yr	1992		1
utilities		$1830/yr	1992		1
maintenance & repair		$3600/yr	1992		1
labor					
technicians	1 person				1
preparation*	for 5000 lbs	$11,286	1992		3
Process Time	2 m^2/hr 21.53 ft^2/hr			1-2 m^2/hr	1
Secondary Waste					
volume	0.0126 ft^3/hr				1
processing cost**					

1. Pang, 1992
2. Oak Ridge K-25 Site, 1993
3. Knight and Blackman, 1992

* Assumed as for carbon dioxide pellet decontamination
** No secondary waste processing required

HIGH AND ULTRA-HIGH PRESSURE WATER: COST DATA AND ASSUMPTIONS

Item	Cost-Related Information	Cost	Dollar Year	Range	References
Facility (high and ultra-high pressure water) (glove box & work room)		\$300,000	1992		1
equipment					
ultra-high pressure water (w/vacuum system)		\$600,000	1992	>\$500,000	1
high pressure water (non-remote operation)		\$62,500	1992	\$50-75,000	1
high pressure water (remote operation)		\$250,000	1992		1
materials*					
utilities**		\$3.34/hr	1992		1, 2
maintenance & repair***		\$3600/yr	1992		3
labor					
technicians	2 people				1
preparation**	for 5000 lbs	\$11286	1992		2
Process Time					
ultra-high pressure water	1 ft^2/min				1
high pressure water	1 ft^2/min (60 ft^2/hr)				1
Secondary Waste					
volume					
non-recycled					
HPW (@2000 psi)	32 ft^3/hr			3-5 gpm	1, 4, 5
UHPW (@ 40000 psi)	60 ft^3/hr			5-10 gpm	1, 4, 5
recycled					
HPW (@2000 psi)	24 ft^3/hr			3-5 gpm	1, 4, 5
UHPW (@40000 psi)	40 ft^3/hr			5-10 gpm	1, 4, 5
processing cost****		\$2.31/ft^3			6

1. Oak Ridge K-25 Site, 1993
2. Knight and Blackman, 1992
3. Pang, 1992
4. LaGuardia, 1989
5. Allen, 1985
6. Manion and LaGuardia, 1980

* Assumed negligible
** Assumed equal to carbon dioxide pellet decontamination costs
*** Assumed equal to laser decontamination maintenance and repair costs
**** Assumed equal to acid chemical decontamination waste processing costs

CO_2 PELLET DECONTAMINATION: COST DATA AND ASSUMPTIONS

Item	Cost-Related Information	Cost	Dollar Year	Range	References
Capital Costs					
CO2 system		$200,000	1992		3
glove box		$50,000	1992		3
work room		$250,000	1992		3
Operating Costs					
manual operation		$10/ft2	1992	$2-20/ft2	3
remote manipulator system			1992	$0.4-$4.10/ft2	3
Facility*					
40'x16'		$400,000	1992		1
20'x16'		$350,000	1992		1
rental (includes 2 technicians, 1 supervisor)*		$16,000/mnth	1992	$13-19,000/mnth	1
materials		$40.71/hr	1992		2
utilities		$3.34/hr	1992	$0.68-6/hr	2, 3
maintenance & repair**		$3600/yr	1992		4
labor					
technicians	2 people				2
supervisor	1 person				2
preparation (size reduction)	for 5000 lbs	$11286	1992		2
Process Time					
tools	2 min/tool			1-3 min/tool	1
not tools	130 lbs/hr				2
Secondary Waste					
volume	1 ft^3/month				2
processing cost***					

1. Gillis, 1992
2. Knight and Blackman, 1992
3. Oak Ridge K-25 Site, 1993
4. Pang, 1992

* Equipment included
** Assumed cost is as for laser decontamination
*** Assumed no processing required

3 of 3

VIBRATORY FINISHING: COST DATA AND ASSUMPTIONS

Item	Cost-Related Information	Cost	Dollar Year	Range	References
Facility	11 yr life	$500,000	1982		2
		$588,000	1992		
equipment $239.20/hr		$421,000/yr	1981		2, 4
		$505,000/yr	1992		
materials		$36,300/yr	1981		2
		$43,560/yr	1992		
utilities		$3300/yr	1981		2
		$3960/yr	1992		
maintenance & repair		$35,000/yr	1981		2
		$42,000/yr	1992		
labor					
technicians	2 people				2
supervisor	0.5 person				2
radiation monitor	0.5 person				2
preparation (size reduction)*	for 5000 lbs	$11286	1992		2
Process Time (for 8.83 ft^3)					
re-classify TRU->LLW	15 min			10-15 min	1
release	1 hr				1, 2
90% decrease in contam	6 min				5, 7
Secondary Waste					
volume reduction factor	67				5
processing cost**	(0.6*original volume)	$1.63/ft^3	1980		5, 6
(evaporation)		$2.13/ft^3	1992		

1. Allen, 1993
2. Hazelton and McCoy, 1982
3. Knight and Blackman, 1992
4. McCoy et al., 1983
5. Allen et al., 1981
6. Manion and LaGuardia, 1980
7. McCoy et al., 1980

* Assumed as for carbon dioxide pellet decontamination

** Assumed equal to acid chemical decontamination waste processing costs

ELECTROPOLISHING: COST DATA AND ASSUMPTIONS

Item	Cost-Related Information	Cost	Dollar Year	Range	References
Facility (mobile)*		$400,000	1992		8
equipment (rental)		$9750/month	1984		4
		$11,057/month	1992		
materials		$1250/month	1984		4
		$1418/month	1992		
utilities**		$3960/yr	1992		6
maintenance & repair***		$3600/yr	1992		7
labor					
technicians	2 people				
preparation (size reduction)*	for 5000 lbs	$11286	1992		5
Process Time					
tools (30 ft^3/0.5 h)					
LLW	0.5 h				1, 2
TRU	0.33 h				1, 2
not tools	function of depth and area (assume 247.57 ft^2/h)				3, 4
Secondary Waste					
volume reduction factor	73.5 ft^3/month				4
processing cost****		\$1.63/ft^3	1980		9
(evaporation)		\$2.13/ft^3	1992		

1. Allen et al., 1984
2. McVey et al., 1981
3. Allen et al., 1981
4. Voit, 1984
5. Knight and Blackman, 1992
6. Hazelton et al., 1982
7. Pang, 1992
8. Gillis, 1992
9. Manion and LaGuardia, 1980

* Assumed costs are as for carbon dioxide pellet decontamination
** Assumed costs are as for vibratory finishing
*** Assumed costs are as for laser decontamination
**** Assumed equal to acid chemical decontamination waste processing costs

ABRASIVE JETTING: COST DATA AND ASSUMPTIONS

Item	Cost-Related Information	Cost	Dollar Year	Range	References
Facility (mobile)*	11 year life	$400,000	1992		1, 2
equipment (rental)		$8700/month	1984		1
		$9866/month	1992		
materials		$200/month	1984		1
		$227/month	1992		
utilities**		$3960/yr	1992		5
maintenance & repair***		$3600/yr	1992		6
labor					
technicians	1 person				1
preparation (size reduction)*	for 5000 lbs	$11,286			4
Process Time					
function of depth and area [assume 3* electropolishing= (3*247.57 ft^2= 1238 ft^2]					1
Secondary Waste					
volume reduction factor	7.4 ft^3/month				1
processing cost****		$1.63/ft^3	1980		3
(evaporation)		$2.13/ft^3	1992		

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1. Voit, 1984
2. Gillis, 1992
3. Manion and LaGuardia, 1980
4. Knight and Blackman, 1992
5. Hazelton and McCoy, 1982
6. Pang, 1992

* Assumed costs are as for carbon dioxide pellet decontamination
** Assumed costs are as for vibratory finishing
*** Assumed costs are as for laser decontamination
**** Assumed equal to acid chemical decontamination waste processing costs

PRODUCER PRICE INDEX VALUES USED TO ADJUST COSTS TO 1992 DOLLARS:

Year	Producer Price Index
1975	58.4
1976	61.1
1977	64.9
1978	69.9
1979	78.7
1980	89.8
1981	98.0
1982	100.0
1983	101.3
1984	103.7
1895	103.2
1986	100.2
1987	102.8
1988	106.9
1989	113.0
1990	118.6

APPENDIX C. ACCOMPANYING DISKETTE AND RELEVANT TECHNICAL INFORMATION

System requirements for computer disk: IBM PC or compatibles; 384K or higher; MS-DOS (2.0 or higher); hard disk; VP-Expert Version 3.0; dBASE III+.

Disk contains dBASE III+ datafiles, ASCII text files, and VP-Expert knowledge base files which constitute the radioactive metal waste management expert system. This system will analyze radioactive metal waste characteristic data to determine appropriate metal waste management strategies.

To run program:

- Load files from floppy disk to hard drive as follows:
    - ➢ Load files from <VPX3> directory on floppy disk onto hard drive directory housing VP-Expert software.
    - ➢ Load files from <DBA> directory on floppy disk onto hard drive directory housing dBASE III+ software. This hard drive directory must also be named <DBA> for the program to run as it should.

- Enter VP-Expert software by typing <VPX> and select file <OPTSELEC.kbs>.
- Select <GO> to begin consultation.

DATE
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2/25/94

END