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Off-Site Consequences of Radiological Accidents: Methods, Costs and Schedules for Decontamination

Prepared by J. J. Tawil, F. C. Bold, B. J. Harrer, J. W. Currie

Pacific Northwest Laboratory
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Off-Site Consequences of Radiological Accidents: Methods, Costs and Schedules for Decontamination

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Abstract

This report documents a data base and a computer program for conducting a decontamination analysis of a large, radiologically contaminated area. The data base, which was compiled largely through interviews with knowledgeable persons both in the public and private sectors, consists of the costs, physical inputs, rates and contaminant removal efficiencies of a large number of decontamination procedures. The computer program utilizes this data base along with information specific to the contaminated site to provide detailed information that includes the least costly method for effectively decontaminating each surface at the site, various types of property losses associated with the contamination, the time at which each subarea within the site should be decontaminated to minimize these property losses, the quantity of various types of labor and equipment necessary to complete the decontamination, dose to radiation workers, the costs for surveying and monitoring activities, and the disposal costs associated with radiological waste generated during cleanup. The program and data base are demonstrated with a decontamination analysis of a hypothetical site.

EXECUTIVE SUMMARY

The accident at Three-Mile Island resulted in increased attention by the public and by regulators to the off-site consequences of severe radiological accidents. The current study was commissioned by the Environmental Effects Branch of the Office of Nuclear Regulatory Research (NRR). It is a direct outgrowth of research conducted for NRR by the Pacific Northwest Laboratory (PNL) on the socio-economic impacts of serious reactor accidents.

One of the major findings of PNL's research on accident consequences is that decontamination costs and property losses resulting from a severe radiological accident could easily run into the billions of dollars, accounting for the majority of the off-site accident costs. At the time of these findings, however, only very limited means were available for assessing these costs. Also, it also seemed likely that the decontamination costs and property losses would be sensitive to site-specific factors, such as the land use of the affected property and its value. A final concern was that the evaluation of the decontamination costs was based on very rough estimates of the cost to decontaminate a few types of property with the same degree of contamination.

In view of the shortcomings of these evaluation techniques and the major contribution of decontamination costs and property losses to accident risk, the current research effort was undertaken. At the beginning of this effort, a search was conducted to determine the type of information that was available on decontamination procedures. It quickly became clear that information on well-documented procedures for decontaminating various materials was very limited. Some tests had been done with respect to nuclear weapons, but these results were not completely applicable, due to substantial differences in the nature of the contaminants. There were also documented procedures for using very powerful, but also very costly, techniques to decontaminate laboratory facilities and other small areas. However, because of the costs of these procedures and the specialized equipment used, they would be totally inappropriate for restoring an area of several hundred or several thousand square miles.

From these findings, a set of objectives was formulated to guide the present study. These were:

- to build upon the methods currently used by the NRC to estimate the decontamination and interdiction costs of a severe radiological accident. The method most commonly employed by the NRC staff and its contractors is the use of the CRAC2 computer model, which is based on the Reactor Safety Study (USNRC 1975).
- to collect information from both published and unpublished sources relating to decontamination procedures and to identify the circumstances favorable to the application of each.
- to develop sufficient information to describe the relationship between the physical inputs and the output of a production technique. This would enable us to identify the types of manpower and equipment required to carry out the decontamination efforts. Additionally,

acquiring the costs of these inputs would enable us to specify the costs of applying these procedures.

- to develop a methodology that would enable data commonly available by political subdivision to be imputed to the elements of a radial grid. CRAC2 utilizes a radial grid to characterize the accident site, and an analysis based on site-specific information requires the analyst to adapt population and property information to the radial grid. The difficulty of doing this can often become a major disincentive for conducting an analysis using site-specific information.

- to develop a computer program that is compatible with CRAC2 and that combines certain inputs from CRAC2 with other data to produce sufficient information to evaluate decontamination and interdiction costs. The program should also have the capability to assist in developing decontamination strategies.

In working toward these objectives, three major resources were developed at PNL for use in evaluating off-site accident consequences and in conducting site-restoration analyses. These are: 1) a reference data base; 2) a set of procedures and analytical tools for preparing a site database; and 3) a computer program, called DECON, to utilize the information in the two databases to produce analyses relating to the decontamination and interdiction of property.

The reference database contains information relating to the application of decontamination methods to surfaces. Currently, 347 methods have been defined for use on 22 different surfaces. For each method, the reference database includes the following information:

- the costs of applying the methods
- the efficiencies with which contaminants are removed
- the rate at which the methods are applied
- the quantity and type of labor required
- the quantity and type of equipment required
- the quantity and type of major materials required
- the costs for labor, equipment, fuel and materials
- the quantity of contaminated material requiring disposal
- the source(s) of the information

Except for the last item, the above data have been recorded in machine-readable format. The sources of the information have been provided to facilitate the updating of this database.

The second resource consists of procedures and analytical tools for preparing a site database. A major improvement of the current resources, as compared with CRAC2, is the ability to bring site-specific information into the analysis. Site-specific information is not often used with CRAC2 because it is not convenient to develop a site-specific database that can be used with it. The main reason for this is that a reactor accident under CRAC2 is located on a radial grid, and information must be supplied for each element of this grid. Unfortunately, site-specific information is commonly available by political subdivisions, but not by the elements of the grid.

The procedures developed for this second resource include methodologies and computer software to take demographic information available by political subdivision and use this to impute values to the elements of the radial grid. In addition, facilities have been developed for using, besides a radial grid, a rectangular grid and an irregular grid. The irregular grid is one in which each grid element has the same geographic boundary as a township or county. Thus, it makes direct use of the availability of information at the political subdivision level.

The third resource is a computer program for actually performing the decontamination analysis. The computer program, called DECON, has been designed to facilitate the planning of decontamination activities as well as to provide estimates of decontamination costs and property losses. The structure and features of DECON are described in this report. In addition, DECON's capabilities are demonstrated by applying it to a serious radiological accident at a hypothetical reactor site.

Among the information included in DECON is the following:

- the decontamination method used on each surface
- the rate at which the decontamination method is applied
- the type of labor used in the method
- the type of equipment used in the method
- the major materials required
- the efficiency of the method in reducing inhalation and external dose
- dose to radiation workers
- dose commitment from surface exposure
- year to decontaminate grid element to minimize property losses.

The capabilities of DECON include evaluating strategies to 1) vacuum exterior surfaces before they become rained on, 2) protect surfaces against precipitation, 3) prohibit specific operations on selected surfaces, 4) require pre-specified methods to be used on selected surfaces, 5) evaluate the tradeoff between cleanup standards and decontamination costs and property values, 6) affect decontamination costs by imposing different cleanup standards on different surfaces according to expected human exposure to the surface.

ACKNOWLEDGMENTS

Many individuals kindly volunteered their time and expertise in providing information and consultation concerning decontamination operations. Besides providing cost and productivity data, several people took the time to explain particular technologies and make constructive suggestions regarding how to accomplish a particular decontamination operation. Particular appreciation is extended to Bill Harding of the City of Los Angeles Department of Public Works; Jim Ajax and Jim Edwards of the City of Pasco, Washington, Department of Public Works; Don Steiner of Turco Products; Bob Weber of the U.S. Bureau of Land Management Interagency Fire Center in Boise, Idaho; Dick Pierce of the U.S. Forest Service in Portland, Oregon; and Dennis Jackson of the State of Washington Department of Transportation.

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Finally, we wish to thank Debra Young, Beverly Johnson and Dorothy Matthews for their tireless efforts in typing this report and its earlier drafts. To all of the many other individuals who assisted in the various aspects of producing this report, we extend our sincere thanks. And we, the authors, are alone responsible for any errors contained in this work.

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1.0 INTRODUCTION

This study was conducted by the Pacific Northwest Laboratory (PNL) for the U.S. Nuclear Regulatory Commission (NRC), Office of Nuclear Regulatory Research (RES). It was undertaken to provide the NRC with improved technical information and enhanced analytical capabilities regarding site restoration following a major radiological accident at a nuclear power plant.

1.1 ORGANIZATION

This report is organized as follows. In the next section we present an overview of three major resources developed at PNL for conducting a site restoration analysis for a radiologically contaminated area. The resources consist of:

- a body of technical information relating to the decontamination of property
- a set of procedures and software tools to facilitate constructing a database of information specific to the radiologically contaminated site
- computer software for analyzing the information.

We refer to the first resource as the reference database. The site-specific information on the contaminated site comprises the site database, and the program for analyzing the information is called DECON.

Chapter 2 describes the reference database. The chapter begins with a description of the database contents, which consist of numerical information relating to many aspects of decontamination procedures. The concepts embodying these data are discussed, and the underlying assumptions are made explicit.

The site database is addressed in Chapter 3. Unlike the reference database, which contains detailed but general information that can be applied to nearly any site, information in the site database will be site-specific. This means that the contents of the database for one site will generally be inappropriate for other sites. Rather than focusing on actual values in the site database, then, we concentrate our efforts on evaluating methods for characterizing the accident site and on developing procedures for producing the site-specific information.

In Chapter 4 a description of DECON and its supporting software programs is presented. In addition to discussing the logical flow of DECON, its various features and capabilities are also described. The supporting software programs have been developed for maintaining and updating the reference database, and for preparing the site database.

The final chapter demonstrates the use of these three analytical resources by applying them to a case study of a serious reactor accident. Although this study is not based on any particular reactor site, it provides a realistic

exercise in both assessing the consequences of the accident and planning a strategy for coping with the cleanup effort.

This report also contains several useful appendices. Appendix A provides a highly detailed description of how decontamination costs, rates and inputs were derived. A discussion of the assumptions and principles underlying the development of the decontamination efficiencies is presented in Appendix B. The preponderance of the data contained in these appendices was developed from information supplied by original sources. To facilitate updating of the reference database, these sources, along with their telephone numbers, are supplied in Appendix C.

The next three appendices provide detailed information about the software programs. Appendix D provides technical information on the software for maintaining and updating the reference database. Appendix E pertains to the site database. It describes the methods for characterizing an accident site, and it presents the technical relationships used in those methods where information must be imputed to geographical areas. Appendix F contains a detailed description of DECON.

1.2 BACKGROUND

This research was motivated by the NRC's need for more reliable information relating to the socioeconomic consequences of accidents at nuclear power plants. This information is applied in evaluating off-site accident risks posed by nuclear power plants. Major policy areas in which reactor accident risks need to be evaluated include the development and implementation of reactor safety goals and the assessment of alternative sites for yet-to-be constructed nuclear plants. To the extent that policy decisions in these areas are based on cost/risk criteria, the accident consequences to property must be evaluated since they comprise a significant component on the cost side. In addition, plant licensing requirements include the preparation of environmental impact statements (EISs), and these must also address the potential impacts of radiological accidents.

A severe radiological accident, although extremely unlikely, has the potential of causing early injuries and deaths, long-term cancers, genetic effects, and widespread damage to property. The off-site property costs of such an accident could run into the billions of dollars. To estimate these costs, the NRC often relies on a sophisticated computer model called CRAC2. This model simulates a radiological accident and provides estimates of evacuation, relocation, crop interdiction, milk interdiction, land interdiction, and decontamination costs, as well as various health effects.

The estimates from CRAC2 indicate that the land interdiction and decontamination costs tend to dominate the other estimated accident costs. It is therefore reasonable that these costs should be emphasized in any attempt to improve on the information provided by CRAC2. In addition to the cost aspects of such an accident, widespread social disruption could be expected. However, before the contaminated areas can be resettled, they will have to be decontaminated. The time schedule for decontaminating these areas should consequently be of considerable interest.

OBJECTIVES

This report has several major objectives. The first is to build upon the methods currently used by the NRC to estimate the decontamination and interdiction costs of a severe radiological accident. As already noted, the method most commonly employed by the NRC staff and its contractors is the use of the CRAC2 computer model, which is based on the Reactor Safety Study (USNRC 1975).

The second objective is to collect and present information from published and unpublished sources on acceptable decontamination procedures and the circumstances favorable to the application of each. This part of the study involves conducting a literature search and interviewing individuals having experience and/or expertise in these areas.

The third objective is to develop sufficient information to describe the production and cost functions for each decontamination procedure. A production function describes the relationship between the physical inputs and the output of a production technique; that is, it describes how the output changes as the quantity of one or more inputs is changed. The cost function, on the other hand, describes the minimum cost for producing each output quantity. Once input costs are known, cost functions can be derived directly from the production function.

The fourth objective is to develop a methodology that will enable data commonly available by political subdivision to be imputed to the elements of a radial grid. CRAC2 utilizes a radial grid to characterize the accident site, and an analysis based on site-specific information requires the analyst to adapt population and property information to the radial grid. The difficulty of doing this can often become a major disincentive for conducting an analysis using site-specific information. In addition to developing the methodology for making this imputation, the methodology is to be embodied in a computer program.

A final major objective is to develop a computer program that is compatible with CRAC2 and that combines certain inputs from CRAC2 with other data to produce a variety of information relating to decontamination activities at the accident site and the effects of the accident on property values. The computer program is to significantly exceed the capabilities of CRAC2 in providing an accurate and informative analysis of decontamination activities and property value effects.

1.4 METHODOLOGY AND OVERVIEW

Research that PNL has conducted over the past three years on off-site consequences of severe radiological accidents has shown that: 1) decontamination costs and property losses could be in the billions of dollars, accounting for the majority of all off-site costs, other than health effects; and 2) research tools for obtaining reliable estimates of these costs and for planning decontamination strategies in the event of such an accident have until now been unavailable. Because of this apparent importance of decontamination costs and losses associated with property, the NRC made a decision to support the

development of a set of comprehensive research tools for analyzing and assessing post-accident decontamination activities and property losses.

In considering the problem of restoring a radiologically contaminated site, it was decided to implement a decision framework based on sound economic principles. The foremost principle that was applied was that all decisions should promote minimizing the net present value of the social costs of the accident. A decision process based upon this principle would encompass effects of an accident other than those concerned directly with site restoration; health effects costs are the most important among these.[1]

The principle actually applied in this study is to minimize direct site restoration costs and other property losses caused by a reactor accident. This approach allows the cleanup criteria to be set prior to and independently of the costs of cleanup and the property losses. However, because stricter criteria will generally result in higher cleanup costs, the policymaker may wish to scrutinize this tradeoff before finalizing the cleanup criteria.

The next step in constructing the decision framework was to consider the types of decisions that would need to be made. A severe radiological accident could contaminate thousands of square miles of property. As already noted, potential losses to society could be in the billions of dollars. In view of this situation, two central concerns would likely emerge: 1) recovery costs would need to be kept manageable, and 2) personnel and equipment in relatively abundant supply should be utilized so that the recovery process would not be delayed. In view of these likely concerns, a search was made for effective decontamination procedures that were relatively inexpensive and that made use of widely available equipment and personnel.

Our search for decontamination procedures meeting these two requirements was generally successful. Published sources provided information on the decontamination efficiencies of several techniques applied to a variety of surfaces. Unfortunately, this information was deficient in several respects, but it did provide a nucleus around which to build a more comprehensive and useful database. Furthermore, one of the insights obtained from these published data was the idea of applying the decontamination procedures to surfaces rather than to objects.

1.4.1 The Reference Database

The next logical step was to prepare an inventory of decontamination procedures and to identify the surfaces on which they could be applied. Well-defined procedures for decontaminating surfaces are henceforth called decontamination operations. Table 1.1 presents a list of the operations currently

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[1] For a detailed discussion of the socioeconomic consequences and social costs of reactor accidents, see (Tawil et al., 1983); a detailed discussion of the health effects costs of reactor accidents is presented in (Nieves et al., 1983).

implemented and the symbol for each. Where more than one operation is described for a symbol, the actual operation referenced will be clear from the context in which it is used. The operations for automobiles are separately identified for clarity.

TABLE 1.1. Decontamination Operations

A	Plow	P	Thin Asphalt/Concrete Layer
B	Vacuum Blast	Q	Very High Pressure Water
C	Strippable Coating	R	Remove and Replace
D	Defoliate	S	Sandblasting
E	Leaching, EDTA	T	Surface Sealer/Fixative
F	Foam	U	Hydroblasting
G	Three-Inch Asphalt and	V	Vacuum
G	Cover with 6" Soil (No Trees)	W	Low Pressure Water
H	High Pressure Water	X	Scrape 4"-6"
I	Steam Clean	Y	Deep Plow
J	Wash and Scrub; Shampoo Carpet	Z	Remove Structure
K	Resurface	g	Cover with 6" Soil (Trees in Place)
L	Leaching, $FeCl_3$	h	Hand Scrape
M	Close Mowing	t	Fixative, Aerial Application
N	Clear; Harvest	v	Double Vacuum
O	Plane, Scarify; Radical Prune	x	Double Scrape

Operations to Automobiles

D	Detailed Auto Cleaning	T	Tow
E	Clean Engine with Solvent	V	Vacuum
I	Steam Clean	W	Water
J	Wash and Scrub	c	Drive Auto Out
K	Repaint	m	Auto Transport Truck
R	Replace/Reupholster	v	Double Vacuum
S	Sandblasting	z	Remove Interior/Clean/Replace

As noted, decontamination operations are applied to surfaces. The surfaces that are currently implemented are presented in Table 1.2. While some of the surfaces listed in this table are actually composed of several surfaces--e.g., orchards and auto interiors--it is reasonable to assume that the composition of surfaces within each surface type does not vary significantly. Thus, for example, it is assumed that the leaves, branches and ground in one orchard will require essentially the same treatment as the leaves, branches and ground in another equally contaminated orchard with the same land area.

Each of the operations identified in Table 1.1 will apply only to a subset of the surfaces listed in Table 1.2. In addition, an operation with the same name but applied to a different surface is treated as a different operation. Thus, for example, vacuuming a roof is a distinct operation from vacuuming a concrete street.

TABLE 1.2. Surface Types Currently Implemented

1. Agricultural Fields	12. Interior Walls, Concrete
2. Orchards	13. Streets and Roads, Asphalt
3. Vacant Land	14. Streets and Roads, Concrete
4. Wooded Land	15. Roofs
5. Exterior Walls, Wood	16. Lawns
6. Exterior Walls, Brick	17. Auto Exteriors
7. Floors, Linoleum	18. Auto Interiors
8. Floors, Wood	19. Auto Tires
9. Floors, Carpeted	20. Auto Engine and Drive Train
10. Floors, Concrete	21. Other Paved Surfaces, Asphalt
11. Interior Walls, Painted	22. Other Paved Surfaces, Concrete

In decontaminating a surface, it seems reasonable in many cases to use a sequence of operations rather than just a single operation. For example, before treating a concrete street with high pressure water, it may make sense to vacuum it first. Similarly, it may be cost-effective first to apply a fixative and then to clear vacant land before scraping dirt from it. An effective decontamination strategy will likely include such sequences of operations rather than only single operations. We therefore define a sequence of one or more operations as a decontamination method.

The reference database consists of information on decontamination methods. The information it contains can generally be applied to any radiologically contaminated site without making alterations to the data. The contents of the reference database are described in the next chapter, along with the assumptions that underly the reference data.

1.4.2 The Site Database

The site database contains information that pertains specifically to the contaminated site. To facilitate analysis of the site, the contaminated area is first partitioned into a number of subareas. Since we assume that the level of contamination is constant throughout each subarea, the reasonableness of this assumption will depend on the size selected for these subareas. We consider three alternative ways of partitioning the contaminated area. They are: a grid with area elements of equal size and shape; a radial grid; and a grid with irregularly sized grid elements whose boundaries conform with those of political subdivisions. The advantages and disadvantages of each of these is discussed in Chapter 3.

To conduct the decontamination analysis, three major types of information must be provided. They are:

- the type of property that is contaminated
- the degree to which the property is contaminated
- the value of the contaminated property.

This information must be supplied for each of the grid elements, and the size, shape and number of the grid elements will depend upon the analyst's choice of grid.

It is recalled that the reference database provides information on the decontamination of surfaces. However, a look at the list of surfaces in Table 1.2 makes it clear that such information would be available for few if any reactor sites. On the other hand land use information is often compiled by state and local agencies. This land use information commonly gives the allocation of various land uses among political subdivisions, such as townships and counties. We have opted for an approach that can take advantage of the general availability of land use information. To implement this appraoch, two major obstacles need to be overcome: 1) a mechanism must be created for transforming land use information into information on surface types; and 2) a procedure must be developed that enables information obtained at the county or township level to be imputed to the geographical areas represented by the grid elements. Given this approach, an important component of the site database is land use information.

The mechanism that has been developed to transform land use information into surface type is based on observed relationships between land uses and their constituent surfaces. For example, property designated residential is comprised of exterior walls (wood, brick and concrete), floors (wood, carpeted and concrete), interior walls (painted and concrete), roofs, lawns, and "other paved surfaces" (asphalt and concrete). The relationships between types of property and their surface components is discussed in Chapter 3.

The site data base must also provide information on how severely the property is contaminated. This information may consist either of radiological survey data taken directly from the field, or of predicted values produced by computer models that simulate reactor accidents and their effects.

Finally, the site database should include information on the value of the property that is contaminated. Because the basic principle underlying our appproach is to minimize the net present value of site restoration and other property costs caused by the reactor accident, property value information is needed to determining <u>when</u> a property should be decontaminated. Several factors affect this decision. First, the natural radioactive decay process causes the effective dose to decline over time. This suggests that delaying decontamination may make it possible to utilize less costly procedures. This opportunity will be greater, the larger the proportion of the total dose that derives from radionuclides with short half-lives. A second factor relates to the weathering process. Weathering has the effect of reducing the effective dose in any particular area by carrying contaminants deeper into the soil via precipitation and by spreading wind-borne contaminants over an increasingly wider area. Like the decay process, weathering also offers advantages to deferring decontamination. On the other hand, such delay causes potentially useful property to remain in disuse. The longer is the delay and the more valuable is the property, the greater is the social cost that results from loss of use of the property. These three effects must be weighed together in determining when a property should be decontaminated.

1.4.3 DECON

DECON is a computer program that takes the information in the reference data base on decontamination procedures and systematically applies **it** to the information in the site database. DECON reports the site restoration costs, the decontamination procedures used, the manpower and equipment required, property losses, a decontamination schedule and a variety of other information that is potentially useful in developing a site restoration strategy. A detailed discussion of DECON is presented in Chapter 4.

2.0 THE REFERENCE DATA BASE

In this chapter we describe the development of the reference database. We earlier stated that the main principle underlying our approach in developing a site restoration strategy is to minimize the net present value of the site restoration and other property costs caused by a radiological accident. These costs can be minimized via several choice mechanisms. First, it is necessary to select a procedure for decontaminating each surface. The choice will depend in large part on how little residual contamination will be permitted, the effectiveness of the procedure in removing contamination, and the cost of applying the procedure. Generally, the least costly method that reduces contamination anywhere below the permissible level will be the top choice. However, other factors may also need to be addressed. For example, the procedure may require specialized equipment that is not available in sufficient quantities. Or decontamination procedures that rely on the use of water may contaminate underground water supplies or water treatment facilities. Such external effects need to be considered to ensure that the selected method will not be more costly overall than other available alternatives.

Another choice that must be made relates to when decontamination should take place. As noted in the previous chapter, at least three factors affect this choice. Radioactive decay and weathering offer opportunities to reduce the cleanup costs by deferring the decontamination into the future. Both of these natural processes generally work to reduce exposure over time; and the less the exposure, the less drastic measures will be required to return the site to some given level of residual contamination. On the other hand, while the property is awaiting decontamination it cannot be used. This loss of use of the property will be costly; the more valuable the property and the longer that it lies in disuse, the greater will be the cost. By carefully choosing when to decontaminate a property, losses can be minimized. In addition to the factors mentioned, however, there are other relevant considerations. For example, except in unusual circumstances, it will not generally be desirable to decontaminate a property while all of the surrounding property remains contaminated. Another example relates to the political pressure that will be brought to bear by those suffering property losses. To the extent that the decontamination costs will not be borne directly by those owning contaminated property, there will be pressure to decontaminate the property as quickly as possible.

A decision also must be made regarding how thoroughly the contaminated area is to be restored. The less the allowable residual contamination, the more costly will be the cleanup. While the current approach does not provide a mechanism for selecting the cleanup standard, it does produce sufficient information to elucidate the relationship between decontamination costs and health risks from residual contamination. Thus, the selection of the cleanup standard can be made using the best available information.

2.1 CONTENTS OF THE REFERENCE DATABASE

To implement the choice mechanisms described above, and thus to facilitate a cost-minimizing site restoration strategy, it is necessary to have available

a comprehensive database relating to decontamination activities. At minimum, the database must contain information for determining the cost of using a decontamination procedure and the efficiency of the procedure at removing contaminants. The database that has in fact been developed contains the following information:

- cost of the inputs used in each decontamination operation (measured in dollars per unit area decontaminated)
- the efficiency of each decontamination method (measured as a percent)
- output rate of each decontamination operation (measured as area decontaminated per shift-hour)
- physical inputs to each decontamination operation (measured in manpower, capital and material requirements).

Throughout this report we use the term "operation" to refer to a basic single decontamination procedure. Examples are vacuuming pavement and hosing roofs. Some operations involve more than one step. For example, the operation of removing and replacing a roof involves the three separate steps of applying a fixative, removing the roof, and replacing the roof. One or more operations executed on a single surface, constitute a "method". For example, the operation of vacuuming pavement followed by the operation of resurfacing the pavement constitutes a unique method. This designation is important because the particular sequence of operations comprising a method determines the net decontamination efficiency.

2.2 DECONTAMINATION OPERATIONS, COSTS, AND EFFICIENCIES

Decontamination operations and methods have been developed for all of the surfaces listed in Table 1.2. This section describes the principal operations for decontaminating these surfaces. The average cost per square meter, the average number of square meters decontaminated per hour, and the composition of cost in terms of physical inputs are presented for each operation. In addition, the efficiencies for each operation are briefly discussed.

2.2.1 Decontamination Costs

It is important to be clear about what the cost estimates developed in this report do and do not represent and to explain some of the general methods used in compiling these estimates. The cost estimates presented here refer only to the direct costs of actual decontamination activities. Not only are the decontamination activities just one source of costs resulting from a major reactor accident, but the direct costs of decontamination activities are only a subset of total cleanup costs. For example, in estimating the costs of applying a low-pressure water wash to pavement, we have omitted the costs of protective clothing, radiation monitoring, and health costs.

The direct costs of the decontamination operations have also been somewhat narrowly defined. Many of the operations give rise to contaminated materials

that require transport to a disposal site and subsequent disposal. Examples are scraping of vacant land and replacement of pavement and roofs. Because transport costs will depend in large measure on how far the contaminated materials must be transported, and because this distance would likely vary from situation to situation, transport costs are not included in the cost estimates of the operations. However, the reference database does contain sufficient information to enable the transportation costs to be estimated. Specifically, for each relevant operation an estimate is developed of the volume of contaminated material that must be disposed of for each unit area of the surface decontaminated. Also, cost estimates based on distance have been developed for hauling. With regard to disposal, because these materials may be disposed of in different ways, the disposal problem is also treated separately.

Another characteristic of the cost estimates is that they pertain only to the decontamination of the surface under consideration. In practice, the contaminants originally on a surface may be transported to surrounding surfaces due to factors other than weathering. This phenomenon may occur either prior to decontamination or during the decontamination process itself. For example, if roofs are decontaminated with a method that relies on water, no costs are included for treating the contaminated water. One reason for excluding these costs is that when several alternatives for dealing with the water are available, one technique may not be preferred in all circumstances. In the case of using water on roofs, allowing the runoff to penetrate into the ground will be perfectly adequate in some situations; in other situations, the runoff might need to be collected in drums via a gutter system; in still other situations, disposal in the sewage system may be the best choice. Because of uncertainty about the preferred method, excluding the cost of disposing of the contaminated water was felt to be the most reasonable approach. This way, the costs for decontaminating roofs--as this operation has been defined--retain their accuracy; the costs for dealing with the contaminated water can be added later once the disposal method has been selected.

A second reason for excluding these ancillary costs is that when the contaminants are transported to other surfaces, the cost of dealing with them will depe'nd on the type of surface to which they have moved. Removing contaminated runoff from soil represents a very different problem from removing the same runoff from a paved surface.

Still another reason relates to the contamination level on the surface that receives the transported contamination. If the surface is at the outer fringe of the contaminated area, the added contaminants may be sufficiently dispersed so that they are of no concern. On the other hand, if the contaminants are added to a surface that is already heavily contaminated, the decontamination costs for this surface could rise dramatically.

Potential problems due to transmigration of contaminants can be minimized through mitigating actions. For example, the application of a fixative to heavily contaminated surfaces soon after the accident will significantly diminish movement of contaminants prior to and during decontamination. Decontaminating surrounding lawns and pavements after roofs have been decontaminated, and decontaminating downwind areas after upwind areas will also reduce potential problems.

The costs that have been developed for all of the operations are based on the assumption that large areas require decontamination. This means that the cost estimates fully incorporate all economies from large-scale operations. If only small areas need to be decontaminated, a premium should be added to the costs to reflect the scale of operations.

Working in a contaminated environment will usually be more costly than working in an uncontaminated environment for at least three reasons. First, personnel and equipment will be subject to radiation control measures. Personnel may be required to wear anti-c's or other protective gear; putting on and removing this gear will take time out of every work shift. Equipment will also need to be decontaminated periodically, and probably often. We have allotted one hour per eight-hour shift for these radiation control measures. A second reason is that protective clothing will reduce worker productivity, which in turn will increase decontamination costs. This will be particularly true in warm and hot weather. Currently, we make no allowance for this effect. A third reason is that workers will likely demand a premium to work in a contaminated environment. Because we have not investigated what an appropriate premium might be, we have excluded this effect from our cost estimates. (However, in the software that utilizes this database, we have made it very easy to make adjustments to labor and equipment costs to reflect these and other factors.)

The dollar amounts of these costs are expressed in terms of 1982 price levels. To the extent that price levels change, the figures given in this report should be adjusted by using a price index or by reestimation. The information contained in Appendix A shows how these costs have been developed. In many cases, the information underlying these costs shows significant variation, and in a few cases the information is inconsistent. We recommend that in cases such as these the cost estimates be viewed as relative measures. Thus, for any particular operation, while the cost estimate could prove to be somewhat over or under actual costs, the ratio of the estimated costs of any two operations should be a good indicator of the actual cost ratio.

2.3 PROCEDURES FOR INTERDICTED AREAS

In interdicted areas it would usually be good practice to apply a fixative to all exterior surfaces to prevent decontaminated areas from being recontaminated. Aerial application of road oil appears to be the most practical method to accomplish this.

The application of road oil by aircraft requires an airfield with facilities to perform routine airplane maintenance and to rapidly load road oil on the planes in large volume. Both large planes such as DC-7s with a 3,000-gallon capacity and small planes with a 350-gallon capacity can be used. Flight crews for the larger planes consist of two people, while one person is sufficient for the smaller planes.

Application of several thin coats of road oil to build up an average coverage of 0.4 gallons per square meter should assure fairly uniform coating. The cost of aerial application at this coverage rate ranges from $0.11 to $0.24 per square meter in 1982 dollars, depending primarily on the type of aircraft used. Adding the cost of the road oil at $0.31 brings the total cost per

square meter to $0.42-$0.55. The expected cost is therefore about $0.45 per square meter. The rate of application will be from 1,808 to 16,461 square meters per hour, again depending on the type of aircraft used. Since the larger aircraft is more likely to be used, we take a rate of 14,000 square meters per hour as representative.

2.4 DECONTAMINATION COSTS FOR VARIOUS SURFACES

In this section we consider appropriate decontamination operations for the surfaces listed in Table 1.2. For each operation, a discussion is provided on the costs, inputs and coverage rates. Also addressed are the advantages, disadvantages and special conditions that may attend the use of these operations. Costs and rates for the various operations are summarized in tables in Section 2.4.1.11.

2.4.1 Paved Surfaces

Four types of pavement surfaces are considered in this report. Asphalt roads and concrete roads refer to large paved areas constructed of those materials. In addition to highways, streets, and roads, these surfaces include large commercial parking lots and other large paved areas. The other types of pavement surfaces are designated here as other asphalt and other concrete. These surface are smaller in area than roads. In addition, access to them may be limited. As a result, the options with respect to particular equipment and techniques may be limited. Therefore, while the basic nature of the operations for other asphalt and other concrete are the same as for asphalt and concrete roads, the production rates in terms of square meters per hour are lower, and the costs in terms of dollars per square meter are higher, on other paved surfaces.

2.4.1.1 Mobile Vacuuming

Mobile vacuum street sweeping as done by municipal public works departments, airports, and highway departments is a practical technique for reducing radioactive contamination of pavement. While the decontamination efficiency of vacuuming streets is lower than most other operations, the relative cost per square meter of vacuuming is so low that it would be used alone or in conjunction with other procedures in essentially all pavement decontamination methods.

The reported cost figures for vacuuming ranged from $0.0020 to $0.0057 per square meter, with $0.0043 being a representative estimate. Subsequent vacuumings over the same surface are likely to cost somewhat less per unit area than the first pass, though they will also be less effective.

The rate of surface treatment is highly variable, with sources reporting rates from 7,177 to 29,462 square meters per hour. A rate of 8,632 square meters per hour is a reasonable expectation. For smaller paved areas or areas with restricted access, it may be necessary to use other equipment such as an industrial parking lot vacuum.

2.4.1.2 Low-Pressure Water Wash

Washing paved surfaces with water will remove about 95 percent of the radioactive contamination. Water achieves its effectiveness primarily as a consequence of the fact that many radioactive particles solubilize readily in water. Water also has the ability to reach into crevices which might shield the contaminants from the air blasts of a vacuumized street sweeper or from other mechanical decontamination methods.

The least costly way to effect a water wash of this sort is to employ standard mobile street flushers. The unit cost for this treatment is about $0.0013 per square meter. One reason the cost in terms of surface area is so low is that not only do these machines move along at an average speed of over three miles per hour, but they can flush half a street width, 20 feet, at a time.

While this method is quite cost effective in terms of reducing pavement contamination, there is a possible drawback to this procedure which could greatly limit or even prevent the use of street flushing. This problem concerns the resulting contaminated water. If there are curbs and storm drains, it may be desirable or acceptable to allow the contaminated water to drain into the storm sewer system. The hazard of radiation in underground mains to people on the surface would be significantly mitigated by the shielding of the intervening pipe, soil, pavement, and so forth. The storm drain system could also serve as a mechanism to gather the contaminated water from various locations to a central site where the water could be treated or stored. In the absence of storm drains, it may be acceptable or desirable to let the water run off the pavement and percolate into the soil. However, because of the threat to subterranean water supplies or for other reasons, it may be necessary to prevent as much as possible any seepage of contaminated water.

The issue of the appropriate handling of contaminated water bears on all the water-using decontamination techniques including those on roofs and lawns. Indeed, even rain could create large volumes of contaminated water. A thorough treatment of this question, however, is beyond the scope of this study.

2.4.1.3 High-Pressure Water

Hosing paved surfaces with water at pressures in the range of from 80 to 120 pounds per square inch adds significant scouring action to the solubilizing attribute of water. However, the pressure can also act to drive the contamination further into pavement.

The way in which a high-pressure wash of pavement would be done would depend primarily on the facilities available. If fire hydrants on high-pressure water mains are available, a relatively inexpensive way to accomplish. this procedure is to simply equip teams of two or three individuals with a few hundred feet of firehose. They can hose all pavement surrounding the hydrant within the reach of the hose. After hosing one area, they would move on to the next hydrant. The estimated cost of this method is $0.021 per square meter.

Where there are no hydrants or accessible high-pressure water mains, fire department equipment could be used to boost the water pressure and, if necessary, to transport water to the hosing site. However, the accumulated cost data indicate that this is a costly operation. Even if an on-site water supply is available, using a pumper truck to provide the required water pressure would raise the cost per area about sevenfold over the manual hosing method just described. If tanker trucks to supply water to the pumper trucks are also required, the cost will rise to about $0.32 per square meter.

A third method is to equip tanker trucks with a pump and a spray bar. This would allow a single piece of equipment to hose a swath ten feet wide while moving forward. Even with nearly half the time spent refilling the tanker, the cost of this method is comparable to that of manual hosing. This method is the basis for deriving representative cost and rate figures. With an application of 0.18 inches of water to the road, the cost per square meter would be around $0.020, and the rate of surface coverage would be about 2,578 square meters per hour.

2.4.1.4 Very High-pressure Water

Greater scouring and, therefore, greater removal of embedded radioactive particles can be achieved with a very high-pressure blast of water. Very high pressure refers to a pressure of about 400 pounds per square inch. Higher pressures would tend to erode the pavement.

Fire equipment pumps are customarily set to pump at around 100 pounds per square inch, but can be configured to pump at four times that pressure. However, in doing so the volume of water drops sharply. In order to maintain an adequate flow of water at very high pressure, it is necessary to use a large pump powered by a six- or eight-cylinder engine. Such a pump would be mounted on or towed behind a tanker truck equipped with a spray bar. This would permit the truck to spray a path one lane wide while driving forward. To apply enough water per unit area, the truck's speed would be about one mile per hour. The cost per square meter would be about $0.022.

2.4.1.5 Foam

An acidic lather-like foam can be an effective method to lift contaminants out of pavement. The foam works by inducing reverse osmosis. An acid concentration gradient is maintained through the foam's thickness. As long as the acidity above is greater than that below, less acidic compounds originating on the pavement surface will move up into the foam, tending to erase the acidity gradient.

The foam can be sprayed from a properly equipped tanker truck. After allowing the foam to remain on the pavement for at least an hour, it can be vacuumed with a vacuumized street sweeper. A foam suppressant will allow the sweeper to pick up a large volume of foam by reducing it to a liquid form.

This operation will cost in the neighborhood of $0.09 per square meter. Over 90 percent of the costs are for the necessary chemicals. Because the

operations of foam application and removal can be done from vehicles, the rate of treatment, over 12,000 square meters per hour, is relatively high.

Following an initial vacuuming, a foam treatment is estimated to remove about 30 percent of the remaining contamination if these operations are accomplished before any rain or snow.

2.4.1.6 Strippable Coating

An interesting decontamination method involves spraying or rolling a special chemical solution onto the surface to be decontaminated. After the liquid dries, it can be peeled off like cellophane tape. This strippable coating will take with it much of any loose surface contamination.

Besides their use as a decontaminant, these coatings are also useful as a fixative that can be easily removed and as a protective coating to minimize contamination. For example, before entry into a contaminated area, vehicles could be coated with a peelable coating. This would protect the actual surface of the vehicle from radioactive particles. By peeling off the coating, nearly all the contamination would be removed.

The liquid coating solution could also be sprayed on roads in much the same way as high-pressure water is sprayed on roads from a tanker truck with pump and spray bar. Mechanical removal of the coating using a specially equipped moving vehicle may be within the realm of possibility. If such a fairly efficient removal using a motorized vehicle can be perfected, the cost per square meter would be about $1.90. Because the chemicals are so expensive, they would account for nearly all the cost. Removal of the coating by hand would be slow and would raise the cost somewhat, but the percentage increase in the cost would be small.

Besides the cost, there are some additional considerations about this approach to decontamination that need to be mentioned. While there are a number of manufacturers of this type of material, it is not clear that there exist sufficient inventories and manufacturing capacity to supply quantities on the scale that would be meaningful in the cleanup of a major reactor accident. Further, practical experience with this material on large areas of pavement is limited enough so that there is considerable uncertainty as to its removal efficiency in such applications.

2.4.1.7 Planing

An obvious way to remove the radiation hazard of contaminated pavement is to remove the pavement itself, or at least to remove the contaminated surface. An assortment of road construction operations are discussed in this report. Some can be used alone or in combination with other operations.

Planing is an operation in which the top surface of the pavement is removed. Planers are machines, varying in width, which remove pavement by abrasion. Planers are used to remove from one to six inches of pavement surface. In the present case we are only interested in removing one inch.

While some planers are equipped with a water spray for dust suppression and cooling, a problem with other planers is that they tend to generate much dust which, in a decontamination operation, would contain radioactive particles. This dust, then, could lead to significant recontamination of the surfaces just planed unless special measures are taken. Affixing rubber containment skirts around the base of the planing machine and attaching a high-power mobile vacuum intake hose would greatly alleviate the problem. The mobile vacuum would continuously draw in the dust from the grinding. These vacuums normally operate with adequate filtration (down to one micron) so that most of the contaminants would be collected.

Planing with dust control would cost around $2.43 per square meter for an asphalt surface and about $2.91 per square meter for a concrete surface. The surface after planing is rough, but it is driveable. In most cases planing would be followed by laying a thin (one inch thick) coat of asphalt pavement over the planed road surface.

2.4.1.8 Thin Surface Coatings

Thin surface coatings such as tack coating, sealer, or road oil can act as fixatives durable enough to permit road traffic. The costs of these coatings range from about $0.30 to $0.54 per square meter. Of these coatings, road oil has been used successfully as a durable fixative on desert soil at the Nevada Test Site.

2.4.1.9 Asphalt Pavement Overlay

Applying a layer of asphalt has three major functions. First, the asphalt layer will prevent resuspension of radioactive particles. Paving therefore has a high efficiency with respect to the inhalation-ingestion pathway. Second, the asphalt provides a certain amount of shielding and thereby is effective in terms of the exposure pathway. The effectiveness naturally increases with the thickness of the asphalt layer. Three inches of asphalt will reduce exposure by about half. Third, paving can be advantageously combined with other operations. For example, paving, following planing, not only removes, fixes, and shields the radiation, it also restores the pavement surface.

Two asphalt paving operations are considered here. The first is a minimal-thickness asphalt overlay. For an existing asphalt base, the minimum-thickness asphalt overlay is one inch. On a concrete base the minimum thickness is two inches. The second paving operation is a medium-thickness pavement overlay. The asphalt layer applied is three inches thick.

The costs and rates of these operations are usually estimated in terms of the volume of asphalt applied. Thus, covering 100 square meters with asphalt one inch thick would normally take the same time as paving 50 square meters two inches thick. The cost of a thin overlay on asphalt roads comes to $2.02 per square meter, and because of the greater thickness, the cost is twice that on concrete roads. About 90% of the cost is for the asphalt material. Labor and equipment comprise only about 5% each.

2.4.1.10 Remove and Replace

For severely contaminated paved surfaces, the most costly operation - pavement removal and replacement - may be indicated. The operation consists of two distinct steps, both with fairly similar production rates. The material cost, however, makes replacement about five times more costly than removal. Replacement includes applying a six-inch thick layer of pavement.

2.4.1.11 Summary of Pavement Decontamination Operations

Tables 2.4.1.11.1 through 2.4.1.11.4 present the basic cost data for the various decontamination operations for the pavement surfaces.

2.4.2 Roofs

The cost estimates for the decontamination of roofs, as opposed to the estimates for paved surfaces, are subject to three important considerations. First, in most cases, treating roofs to remove radioactive particulates will cost much more per unit area than will a procedure of equal effectiveness for pavement. This is due largely to the poor accessibility and the discontinuity of roof surfaces.

Second, there is a greater variety in the factors affecting roof cleanup costs than there is affecting pavement cleanup costs. Important variables include the material with which the roof is constructed, the slope of the roof, the height of the roof, and the size of the roof. In general, the costs of roof decontamination were figured with the assumption that roofs were for single-family homes, one to two stories in height.

The third consideration is that there is very little accumulated experience in most of the roof cleanup operations. This means that the cost and rate estimates will be more vulnerable to error.

Costs of the various operations for decontaminating roofs are presented in Table 2.4.2.1. Vacuuming does not remove as much of the contamination as other methods, only about 60 percent, but it is a relatively low-cost procedure and it does not create any major problems as might be the case with methods using water.

A step up from vacuuming, in terms of effectiveness, is a low-pressure water wash. This could be accomplished for about $0.23 per square meter and would reduce the contamination by about 95 percent. Both vacuuming and low-pressure hosing require very little in the way of equipment. Almost all of the cost of these two operations is for labor.

Using a high-pressure water source would raise the effectiveness somewhat. If high-pressure water mains are located in the area being treated, then the necessary equipment will be no more extensive than several lengths of fire hose, a nozzle, and a ladder. Hosing would be done with two- or three-man

TABLE 2.4.1.11.1. Summary of Representative Cost and Productivity Data for Asphalt Road Decontamination Operations

Operation	Rate (m^2/hr)	Cost (1982 $/$m^2$)			
		Total	Labor	Equipment	Material
Vacuum	8,632	0.0043	0.0021	0.0022	
Low-pressure water	25,958	0.0013	0.0007	0.0006	
High-pressure water	2,685	0.0175	0.0074	0.0102	
Very high-pressure water	2,685	0.0206	0.0074	0.0132	
Foam	17,186	0.0911	0.0044	0.0040	0.0827
Strippable coating	4,297	1.7829	0.0094	0.0035	1.77
Planing	750	0.91	0.35	0.56	
Tack coat	12,890	0.3055	0.0035	0.0024	0.2996
Sealer	1,933	0.54	0.07	0.05	0.42
Road oil	12,890	0.3258	0.0077	0.0081	0.31
Pave with 1-inch asphalt	2,837	2.02	0.11	0.10	1.81
Resurface	2,837	2.93	0.46	0.66	1.81
Pave with 3-inch asphalt	946	6.06	0.33	0.30	5.43
Remove and replace	71	15.40	2.68	3.32	9.40

TABLE 2.4.1.11.2 Summary of Representative Cost and Productivity Data for Concrete Road Decontamination Operations

Operation	Rqte (m /hr)	Cost (1982 $/$m^2$) Total	Labor	Equipment	Material
Vacuum	8,632	0.0043	0.0021	0.0022	
Low-pressure water	25,958	0.0013	0.0007	0.0006	
High-pressure water	2,685	0.0175	0.0074	0.0102	
Very high-pressure water	2,685	0.0206	0.0074	0.0132	
Foam	17,186	0.0911	0.0044	0.0040	0.0827
Strippable coating	4,297	1.7829	0.0094	0.0035	1.77
Planing	625	1.09	0.42	0.67	
Tack coat	12,890	0.3055	0.0035	0.0024	0.2996
Sealer	1,933	0.54	0.07	0.05	0.42
Road oil	12,890	0.3258	0.0077	0.0081	0.31
Pave with 2-inch asphalt	1,419	4.04	0.22	0.20	3.62
Resurface	1,419	5.13	0.64	0.87	3.62
Pave with 3-inch asphalt	946	6.06	0.33	0.30	5.43
Remove and replace	171	19.62	2.48	3.77	13.37

TABLE 2.4.1.11.3. Summary of Representative Cost and Productivity Data for Other Asphalt Decontamination Operations

Operation	Rqte (m /hr)	Cost (1982 $/m^2)			
		Total	Labor	uipment	Material
Vacuum	4,316	0.0086	0.0042	0.0044	
Low-pressure water	12,979	0.0026	0.0014	0.0012	
High-pressure water	1,342	0.0350	0.0148	0.0204	
Very high-pressure water	1,342	0.0412	0.0148	0.0264	
Foam	8,593	0.0995	0.0088	0.0080	0.0827
Strippable coating	2,148	1.7978	0.0188	0.0070	1.772
Planing	375	1.82	0.70	1.12	
Tack coat	384	0.46	0.16		0.30
Sealer	91	1.04	0.41	0.12	0.51
Road oil	6,445	0.3416	0.0154	0.0162	0.31
Pave with 1-inch asphalt	1,418	2.23	0.22	0.20	1.81
Resurface	1,418	4.05	0.92	1.32	1.81
Pave with 3-inch asphalt	473	6.69	0.66	0.60	5.43
Remove and replace	35	21.40	5.36	6.64	9.40

TABLE 2.4.1.11.4. Summary of Representative Cost and Productivity Data for Other Concrete Decontamination Operations

Operation	Rate (m^2/hr)	Cost (1982 $/$m^2$) Total	Labor	Equipment	Material
Vacuum	4,316	0.0086	0.0042	0.0044	
Low-pressure water	12,979	0.0026	0.0014	0.0012	
High-pressure water	1,342	0.0350	0.0148	0.0204	
Very high-pressure water	1,342	0.0412	0.0148	0.0264	
Foam	8,593	0.0995	0.0088	0.0080	0.0827
Strippable coating	2,148	1.7978	0.0188	0.0070	1.772
Planing	312	2.18	0.84	1.34	
Tack coat	384	0.46	0.16		0.30
Sealer	91	1.04	0.41	0.12	0.51
Road oil	6,445	0.3416	0.0154	0.0162	0.31
Pave with 2-inch asphalt	709	4.46	0.44	0.40	3.62
Resurface	873	11.99	2.10	6.28	3.61
Pave with 3-inch asphalt	75	8.54	2.10	1.18	5.26
Remove and replace	85	25.87	4.96	7.54	13.37

TABLE 2.4.2.1. Summary of Representative Cost and Productivity Data for Roof Decontamination Operations

Operation	Rate (m^2/hr)	Cost (1982 $/$m^2$) Total	Labor	Equipment	Materials
Vacuum	81	0.23	0.21	0.02	---
Low-Pressure Water	81	0.23	0.22	0.01	---
High-Pressure Water	81	0.74	0.72	0.02	---
Wet Sandblast	21	4.84	2.11	2.73	---
Fixative	81	1.22	0.43	0.56	0.23
Foam	81	1.73	0.86	0.79	0.08
Strippable Coating	81	3.26	0.90	0.59	1.77
Remove and Replace	24	19.08	12.95	0.43	5.70

crews and most of the cost would still be for labor. However, in the event that a pumper truck is necessary to generate the required water pressure, the cost of the procedure would rise from about $0.74 to $2.34 per square meter, and labor's share of the input cost would fall sharply.

Sandblasting can be done either wet or dry. Both methods, however, pose serious potential for recontamination of adjacent surfaces, as well as those just treated. Dry blasting generates much airborne dust, while wet blasting can spread the contamination via the water waste. There is a technique called vacuum blasting in which the dry blast is combined with a vacuum intake which surrounds the blast nozzle. The result is that dust and sand do not escape from the area being blasted to recontaminate other areas. However, the coverage with this apparatus is so slow that this method becomes prohibitively expensive.

At $4.30 per square meter for dry blasting without dust control, and $4.84 per square meter for wet blasting without water treatment, these operations are sufficiently costly that they are likely to be used only in special situations. Wet blasting would be appropriate where water could be allowed to either absorb into the soil or run into the storm drains. Working from the top down on a roof with a good slope, it is estimated that this method can achieve a removal efficiency of 99 percent if the surface has not been rained on and about 97 percent if it has been rained on.

Application of a fixative to prevent resuspension could be done in much the same manner that other materials such as foam or strippable coating are applied. An appropriate choice of fixative in this use might be Compound SP-301. This will form a thin latex coating over the surface. Once cured, this material can be removed, but to do so requires use of a solvent. This operation would be particularly advantageous when used in conjunction with other operations such as removal and replacement.

Acidic foam can be used on roofs to draw contaminants out of surface cracks and irregularities. This material could be applied using the type of spray truck used for commercial lawn and tree spraying. To remove the foam, a

long extension to the standard hose intake of a mobile vacuum sweeper would be used. The cost of this operation comes to around $1.54 per square meter.

Strippable coating could be applied to roofs in much the same way as the foam, except that a non-aerosal spray would be used. Again, a mobile spray truck would be the basic piece of equipment. Removal, however, would be largely a manual operation, with a worker pulling off pieces of the coating for later pickup. Despite the considerable labor time involved for this operation, about 56 percent of the $3.37 per square meter cost would be for the coating material itself. In addition to achieving an estimated 75 percent removal efficiency if accomplished before rain, a strippable coating would act as an effective fixative.

The most effective and the most costly operation for decontaminating roofs is simply to remove and replace them. To assure that the radioactive particles on the roof surface are in fact removed and not scattered over surrounding surfaces, actual removal should be preceded by coating the roof with road oil to fix the particulates to the roof. Roof removal and relacement are steps for which there is some established experience-based cost data available. Of course, the cost of removal, and especially replacement, depend in large part on the type of material used. For five-ply, built-up tar and gravel construction, the total cost is estimated at $18.51 per square meter. For asphalt strip shingles, the cost would be less, and for cedar shingles the cost would be more. If done before rain, removal and replacement is estimated to have near total effectiveness--99.9 percent. The effect of the rain, however, would be to move some of the radiation off of the roof and on to other surfaces which would not be directly affected by replacement of the roof. Thus, following rain, the estimated effectiveness of roof replacement would fall to 98%.

2.4.3 Lawns

Table 2.4.3.1 summarizes the data for lawn decontamination operations. Vacuuming is one of the simplest methods for decontaminating lawns. Using an extension hose to a standard vacuumized street sweeper, this method is estimated to achieve about 30 percent removal efficiency for lawns not rained on, and the cost would be around $0.19 per square meter. Rain is likely to render this method much less effective.

TABLE 2.4.3.1. Summary of Representative Cost and Productivity Data for Lawn Decontamination Operations

Operation	Rate (m^2/hr)	Cost (1982 \$/m^2)			
		Total	Labor	Equipment	Materials
Vacuum	326	0.19	0.13	0.06	---
Water	1,302	0.014	0.013	0.001	---
Leaching	6,400	0.07	0.022	0.022	0.026
Close Mowing	150	0.147	0.129	0.017	---
Fixative	3,545	0.365	0.017	0.038	0.31
Remove and Replace	90	4.50	1.67	1.11	1.72