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Decontamination Technologies Task 3 Urban Remediation and Response Project Prepared for New York City Department of Health and Mental Hygiene

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June 30, 2009

Environmental Sciences Department/Environmental Research & Technology Division

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DISCLAIMER

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EXECUTIVE SUMMARY

In the event of a large-scale radiological dispersion device event, long-term recovery will require decontamination of a substantial amount of material. This report provides an overview of radiological decontamination methods. The two major approaches are chemical or mechanical decon. Chemical decon approaches dissolve the contaminant in solution and can be tailored for specific radionuclides. Mechanical decon approaches release the radionuclides through mechanical agitation or physical removal.

Chemical techniques include washing with a liquid or foam. Liquids used for decon include water alone or with soap, surfactants, acids, bases, chelating agents, or redox changing agents. Foams, gels, or pastes are used to provide a longer contact time and thereby enhance removal. Chemical decon advantages and disadvantages are discussed in the report and individual chemical decon methods performance and costs are reviewed. Chemical decon methods on porous surfaces typically can remove up to 90% of the contamination. For non-porous surfaces (metals, glass, etc.) more than 99% can be removed in many situations.

Mechanical techniques include vacuuming, steam/pressure washing, blasting, scabbling and sorting. Mechanical decontamination advantages and disadvantages are discussed in the report including performance and costs. Mechanical removal technologies are effective on all surfaces but may require a treatment to repair the visual appearance to surfaces after treatment. Several techniques including strippable coatings, paint thinners, and washing are a combination of mechanical and chemical techniques. These offer a compromise between total removal in abrading technologies and pure chemical treatment.

Rapid deployment of large area decontamination techniques (fire hosing, washing with detergents, etc.) should be considered. The data shows that contaminants migrate into porous materials and become much more difficult to remove with time. This can happen over time scales of days to weeks.

A literature review focusing on U.S. companies with radiological decon experience culminated in a table with vendor information, their products and services, and contact information. The review focused on the larger companies and the list does not imply an endorsement of any one company nor does the list imply completeness. A large scale RDD incident will require one or possibly more major vendors to manage the complete process. In Goiania 550 people were involved in the decontamination process and the initial response to Chernobyl involved 90,000 soldiers. Vendors with large-scale capability are included in the table.

There has been very little work on pre-treatment options for protection against radionuclide contamination. Coatings (e.g. polyurethane) may be applicable for many surfaces and strippable coatings have been successfully used in nuclear facilities as a pre-treatment. Development and testing of protective coating technologies that are long lasting, esthetically pleasing and result in removing over 99% of the contamination when removed should be pursued. Protective coatings that are quickly and easily applied could be used strategically to coat surfaces that would be difficult, costly, or impossible to replace (e.g., pink Italian marble at Grand Central Terminal). Development of anti-contamination coatings for urban materials would likely require a federally funded research and test facility.

Response to large scale urban decontamination outside the U.S. (Goiania, and Chernobyl) indicated that decon techniques that were used were generally very simple (vacuuming, washing) for lightly contaminated areas with removal effectiveness ranging from 20 – 90%. For heavily contaminated areas decontamination involved removal of contaminated soils and roofs or demolition. This experience suggests that if the contamination is more than a factor of 10 higher than clean-up goals, removal or demolition will be needed. These events have for the most part shown decontamination efforts to have had limited effectiveness and to be economically burdensome.

Additionally, having low values for clean up goals can severely impact decon efforts by adding to the amount of work and time required to achieve these goals. The IAEA surmised, "After a radiological accident in which widespread contamination occurs, there is usually a temptation to impose extremely restrictive criteria for remedial actions, generally prompted by political and social considerations. These criteria impose a substantial additional economic and social burden to that caused by the accident itself" (IAEA, 1998).

The review indicated that the vast majority of decon work in the U.S. has focused on nuclear facilities and much less thought has been given to decontamination of urban environments. These technologies were designed more for dose reduction than to clean items to a pre-defined clearance level. Clearance levels will be based upon dose and may vary with location and means and time of exposure. Removal of 50 – 90% leads to a substantial reduction in worker dose, but may fall far short of being able to bring heavily contaminated items to a free release state. In addition, the materials in nuclear facilities are generally metals or concrete. Metals are relatively easy to decon and concrete is either decontaminated using surface removal techniques or disposed as waste. Decontamination research needs to move out of the nuclear facility mindset and focus on urban materials and clearance level release requirements. Removal of greater than 99% of the contamination may be needed for urban materials and would be extremely valuable in waste minimization and allowing clearance (free release). More technology development needs to be directed towards "personal items" that are ubiquitous in an urban environment.

Some focus should be placed on adapting clean up technologies from other industries that also have to deal with urban and residential environments and materials. Graffiti and soot removal are two examples of industries that are well developed and could offer methods easily adapted to radiation clean up after an RDD.

The challenges of multiple material surfaces, multiple property owners, quickly restoring the functionality of an area, and societal impacts make clean-up of an RDD event substantially different and much more difficult than decontamination of nuclear facilities.

Development of a strategy to handle these challenges would be extremely beneficial in responding to an RDD event.

Initial thoughts on developing a strategy for response included five major components:

- Preplanning the response (define initial triggers for decontamination and methods for setting priorities for decontamination, understand decon techniques and limitations, and understand resource availability (manpower and equipment). Consideration should be given to defining the criteria to allow early decontamination efforts using simple, rapid techniques that remove the contamination before it has time to enter into the porous structure of many materials.
- Develop a decision framework that specifies roles and responsibilities of different agencies during remediation.
- Establishing a process for defining cleanup standards. This may require a compromise between exposure of workers and the public to low-levels of radiation with a resulting low probability for potential health effects, a societal desire to remove as much radioactive material as possible, and the societal and economic cost of leaving critical facilities out of commission for extended periods of time.
- Performing regular drills to test response capabilities. The United Kingdom has begun this process and has an approach for testing decon contractors that could serve as a starting point for this work.
- Understand unique aspects of decon from an RDD in an urban environment (wide range of materials, private property issues, release criteria and documentation for release). Past events have demonstrated that technologies that have high productivity rates end up being used most and this is particularly true at the beginning of an event when contaminants are easiest to remove and haven't "stuck" or bound to surfaces as integrally as they will with time. These events have also shown that much of the initial decon will be performed by personnel unskilled in decon operations. The methods need to be simple so that training is minimal and the workforce can get up and running quickly.

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1.0 INTRODUCTION

In the aftermath of a Radiological Dispersal Device (RDD, also known as a dirty bomb) it will be necessary to remediate the site including building exteriors and interiors, equipment, pavement, vehicles, personal items etc. Remediation will remove or reduce radioactive contamination from the area using a combination of removing and disposing of many assets (including possible demolition of buildings), decontaminating and returning to service other assets, and fixing in place or leaving in place contamination that is deemed "acceptable". The later will require setting acceptable dose standards, which will require negotiation with all involved parties and a balance of risk and cost to benefit. To accomplish the first two, disposal or decontamination, a combination of technologies will be deployed that can be loosely classified as:

- Decontamination
- Equipment removal and size reduction
- Demolition

This report will deal only with the decontamination technologies that will be used to return assets to service or to reduce waste disposal. It will not discuss demolition, size reduction or removal technologies or equipment (e.g., backhoe mounted rams, rock splitter, paving breakers and chipping hammers, etc.).

As defined by the DOE (1994), decontamination is removal of radiological contamination from the surfaces of facilities and equipment. Expertise in this field comes primarily from the operation and decommissioning of DOE and commercial nuclear facilities as well as a small amount of ongoing research and development closely related to RDD decontamination. Information related to decontamination of fields, buildings, and public spaces resulting from the Goiania and Chernobyl incidents were also reviewed and provide some meaningful insight into decontamination at major urban areas.

In order to proceed with decontamination, the item being processed needs to have an intrinsic value that exceeds the cost of the cleaning and justifies the exposure of any workers during the decontamination process(es). In the case of an entire building, the value may be obvious; it's costly to replace the structure. For a smaller item such as a vehicle or painting, the cost versus benefit of decontamination needs to be evaluated. This will be determined on a case by case basis and again is beyond the scope of this report, although some thoughts on decontamination of unique, personal and high value items are given. But, this is clearly an area that starting discussions and negotiations early on will greatly benefit both the economics and timeliness of the clean up. In addition, high value assets might benefit from pre-event protection such as protective coatings or HEPA filtered rooms to prevent contaminated outside air from entering the room (e.g., an art museum).

Selection of the appropriate technology or technologies for a particular decontamination activity should consider the following:

- Radionuclide type and physical/chemical form
- Decontamination objective (is the purpose to reduce exposure to on-site personnel or release the item for unrestricted use)

- Material(s) requiring decontamination.
- Initial thickness and level of contamination (which may determine the surface layer thickness to be removed or the number of treatments required)
- Final decontamination goal ("acceptable" level of contamination).
- Final end state of the material surface (e.g., marble tiles may need to be polished after mechanical treatment such as scabbling)
- ALARA principles
- Complexity of the decontamination process (is it less effective if inexperienced users perform the cleaning)
- Amount of secondary waste generation and treatment required.
- Total Cost

1.1 Radionuclide type and physical/chemical form

There are a limited number of radioactive sources that are large enough to cause widespread contamination when used as part of an RDD. Table 1 (DOE, 2006) lists the major types of sources, the range in source strength, and the number licensed in the United States in 2006. While radioactive sources could be procured from other countries, the list provides an accurate representation of likely sources.

Table 1 Description of Applications and Numbers of Category 1 and 2 Units at Nuclear Regulatory Commission-Licensee Facilities (adapted from DOE, 2006).

Application	Radionuclides	Activity Range (Category 1 and 2)	No. of Units
Power Sources (RTGs)	Strontium-90 Plutonium-238	3,000 Ci – 244,000 Ci 85,000 Ci – 570,000 Ci	34
Industrial and Research	Cobalt-60 Cesium-137 Iridium-192	300 Ci – 40, 000 Ci 27 Ci – 213,000 Ci 22 Ci – 330 Ci	550 794 1903
Measuring Devices	Americium-241 Americium-beryllium Plutonium-238	20 Ci – 50 Ci 16 Ci – 44 Ci 38 Ci – 50 Ci	18 296 7

Based on Table 1, the isotopes of concern for this report are Co-60, Sr-90, Cs-137, Ir-192, Pu-238, and Am-241. Of these, Am-241, Co-60, Cs-137, and 1r-192 account for over 99 percent of the sealed sources that pose the highest security risks in the United States. The power sources are all under military control and have substantial safeguards. There are some large Sr-90 RTGs in Russia that may not have adequate control and this is the reason for keeping Pu and Sr on the list of isotopes. To the extent possible, decontamination factors for different techniques will be supplied for these six radionuclides.

In addition to their availability, dispersibility of the isotope and the surface material where deposition occurs impacts the decontamination requirements. Cesium sources are often provided as a CsCl salt that is easily dispersed and difficult to decontaminate. Other radionuclides are generally in a metallic (Co-60, Ir-192) or ceramic (Am-241) form. Porous surfaces, such as concrete, are typically more difficult to decontaminate than non-porous surface (metals, glass, etc.). For this reason much of the research has focused on decontamination of Cs from concrete.

1.2 Urban Materials

The items expected outdoors in an urban environment include; buildings with various materials (glass, metal, sandstone, brick, concrete, roofing materials (tar, shingles) etc.), siding materials (vinyl), vehicles (cars, trucks, trains, busses), roads (asphalt, concrete), and soil and vegetation (grass, trees, shrubs, flowers, etc.).

The items expected indoors in an urban environment include: electronic equipment (computers and servers, Television monitors, etc.), furniture (e.g., desks, chairs, rugs, drapes), electric equipment (e.g., air handling systems (HVAC), elevator motors, maintenance equipment), personal items (clothes, photos, knick-knacks, plants, etc.), paper items (books, magazines, and reports), plumbing and piping, duct work, art (paintings, sculptures, fountains, tapestries, etc), plastics such as vinyl, polyethylene, polypropylene, Plexiglas and Lexan, wall materials (wall board, plaster, molding, wall paper, paint) and floor materials (wood, ceramics, vinyls), and a myriad of other items.

For instance, in an EPA report dealing with construction and demolition debris, listed non-residential demolition debris from the northwest as consisting of 66% concrete, 16% wood, 9% landfill debris, 5% scrap iron, 2% asphalt, 1% brick and 1% roofing [EPA 1998]. The same report lists typical construction and demolition debris constituents (see Table 1). The list is extremely varied and only consists of materials from the actual buildings themselves and not the contents (e.g., personal items, inventory, furniture, etc).

Table 1 TYPICAL CONSTRUCTION AND DEMOLITION DEBRIS CONSTITUENTS [EPA 1998]

Asphalt
Brick
Carpet padding
Carpeting
Ceiling tiles
Cinder block
Concrete with rebar/wire mesh
Concrete without steel reinforcing
Corrugated shipping containers
Dimensional lumber & shapes (clean)
Dirt/earth
Electrical fixtures (metal, light tubes/bulbs, ballasts)
Electrical switches
Electrical wiring
Glass
Gypsum wallboard (mainly gypsum with paper backing)
Insulation-fiberglass
Insulation-sheathing

Insulation-treated cellulose
Masonite/slate
Metal-ferrous
Metal-nonferrous
Painted wood
Pallets/spools/reels
Plastic buckets/containers
Plastic pipe
Plastic sheet film
Plywood, particleboard, oriented strandboard, etc.
Porcelain, including bathroom fixtures
Pressboard/chipboard
Pressure treated wood
Roofing materials (e.g., roofing felt, asphalt shingles)
Rubber hosing/conduits
Tile-ceramic
Tires (some with wheels)
Wood composites

The optimum decontamination approach will depend upon the specific materials requiring decontamination. Based on the variety of materials present, it is clear that several decontamination technologies will be needed.

1.3 Report Objectives

This summary report provides an overview of the two major decontamination techniques (chemical and mechanical). The details of proven technologies and methods that can be used for urban radiological decontamination (decon) are described along with information on their cost and performance. In addition, the document describes new technologies that are promising, but still unproven. The document also describes the technical feasibility of using pre-treatment and coating technologies for surfaces designated as high risk areas (i.e. government buildings, critical infrastructure, historic landmarks).

Decontamination of large urban areas has never been necessary in the United States and the U.S. experience base involves decontamination of commercial and Federal nuclear facilities. There are major differences in planning and conducting decontamination of a nuclear facilities and an urban environment with a much wider array of material surfaces and multiple property owners. These differences are reviewed and a detailed discussion of important considerations in decontaminating urban environments is provided. Guidance from decontamination of urban areas as a result of accidents in Goiania, Brazil and Chernobyl, Ukraine are presented.

2.0 CHEMICAL DECONTAMINATION TECHNIQUES

Decontamination (decon) techniques are primarily categorized as chemical or mechanical. Chemical decon technologies use solvents (e.g., detergent, acid, water) to wash or dissolve the contaminants from surface of an item or in some cases to dissolve the surface or coating (e.g., paint) that contains the contaminant. Some of the advantages of chemical decon are:

- Generally faster than mechanical decon, requiring less worker exposure time
- Far less re-suspension of airborne contaminants
- Allows decontamination of hard to reach or inaccessible areas (e.g., crack, crevices, tight corners, ventilation ducts, piping)
- Can decontaminate equipment in place
- Often can be performed remotely
- Uses chemical that are readily available (e.g., detergents)
- Waste processing/collection is fairly simple and straight forward

The disadvantages of chemical decontamination include:

- Performs poorly on porous surfaces such as brick or marble
- Can corrode the surfaces being cleaned
- Different isotopes and/or surfaces require different solvents
- Large volume of waste produced
- Care must be taken to avoid discharge to sanitary drainage
- Depending on the chemical(s), may result in mixed wastes

Chemical decontamination is an offshoot of industrial cleaning processes used to clean and maintain large pieces of equipment without having to remove and/or dissemble them. Wiping down or washing is the simplest decontamination method and is by far the most used method. This method is generally most effective on smooth non-porous surfaces. Many decon solutions are available and are widely used in the nuclear industry. Choosing which solution to use must take into account the contaminant and surface chemistry and to a lesser extent the disposal of the waste generated. The solution chemistry takes advantage of reactions such as dissolution, oxidation/reduction, complexation, and sequestration to remove contaminants from the surface. Often the cleaning process utilizes more than one of these either simultaneously or sequentially. In most cases, several possible solutions are available for each combination and other factors will be used to make the final choice. These considerations include; cost, safety, process ease and even final esthetics of the surface. A thorough discussion of chemical decontaminants is available in the DOE Decommissioning Handbook (DOE, 1994).

Chemical decontamination can be accomplished via soaking/spraying, spray on coatings and foams, electrochemical or bathing/dunking (ex-situ). In most every case, chemical decontamination uses mild mechanical scrubbing to aid removal of loosened contaminants and residue. Common reagents used for chemical decontamination include water or steam, acids, bases, acid salts, alkaline salts, detergents/surfactants, complexing agents, oxidizing/reducing agents and organic solvents. Some of the common chemical commercial decon systems include Radiac wash, Quick Decon, BY*PAS, Intek Decon Solution ND and Smart Strip.

3.0 MECHANICAL DECONTAMINATION TECHNIQUES

Mechanical decontamination techniques are physical methods that vacuum, sweep, scrub or abrade the surface or remove a sizeable layer from the surface by cutting or grinding. Mechanical decontamination is generally more effective than chemical decontamination, but requires the surface to be readily accessible. Corners, cracks, and crevices are difficult to decontaminate using mechanical techniques. Many mechanical techniques also tend to create dust and can create airborne contaminants. Some of the advantages of mechanical decontamination are:

- Effective on porous surfaces such as concrete or marble
- Effectiveness is not isotope specific
- Reduced waste volume
- Newer systems have remote operation capability

The disadvantages of mechanical decontamination include:

- Creates a dust and airborne contaminant hazard
  - Requires good HEPA filtration
- Removes the surface layer and may require post treatment such as polishing
- Time consuming and greater worker exposure
- Mechanical methods that remove or alter the surface of an item would destroy many assets (e.g., decorated furniture, inlays, etched metals)

Mechanical decontamination can be accomplished by vacuuming (with HEPA filtered vacuums), pressure washing, hydrolaser (very high pressure water), blasting (bead, CO_2, sponge, etc.), grinding, milling, scarifying, scabbling and ultrasonic cleaning. Some methods are a combination of chemical and mechanical or are a hybrid of the two. Paint strippers and strippable coatings are the two most obvious. Paint strippers chemically soften the paint then mechanical methods are used to remove the paint layer (paper peel, putty knife, etc.) with the contamination coming off with the paint layer. Strippable coatings use chemical and adhesive methods to loosen/remove the contamination from the surface and again require mechanical peeling of the coating.

It must be remembered that decontamination technologies have been developed mainly for nuclear grade facilities, not urban environments and materials. As such, many items and surfaces found in urban setting are not well suited for decontamination and they will need to have very high value to justify specialized decontamination techniques. Items such as rare art will need to be carefully decontaminated by hand using low impact techniques. These items may require initial stabilization (e.g., bagging) for storage and later decontamination when time, money and technology allow.

In general, hard porous materials such as concrete, mortar, brick, marble, granite, sandstone and limestone are difficult to decontaminate. Soft porous materials are also difficult to decontaminate such as wood and cloth (e.g., wool, cotton, silk). Hard non-porous metals such as steel, stainless steel, aluminum, brass, bronze, copper, chromium, nickel and zinc are easier to decontaminate, however these metals may corrode with certain decontamination solutions (e.g. strong acids or bases). Hard smooth surfaces that may be easier to clean also include glass and ceramics (glazed). However, grout materials used to hold the ceramics in place are porous and difficult to decontaminate.

No one technology is suitable for all of these materials. Conventional cleaning techniques (e.g., soak and wipe with decontamination solutions, power washing) are likely to have a high decontamination efficiency on a small subset of these materials, specifically, hard smooth surface where the contamination hasn't chemically reacted with the surface. Other techniques will have varying degrees of success requiring either repeated, costly applications (e.g., strippable coatings) or will result in some sort of damage to the item (e.g., scabbling and scarifying). The degree of contamination will also determine the success (either contaminant reduction or economic) of the decontamination process. Few of these processes will reduce the contamination more than one order of magnitude (even with multiple applications) so at some point many items will be "too contaminated" to economically return to service.

At the 2006 Workshop on Decontamination, Cleanup and Associated Issues for Sites Contaminated with Chemical, Biological, or Radiological Materials (Dun 2007), the presentation by Environment Canada, while discussing chemical contamination, listed two "Rules of Thumb". The first was "If the standard is lower than one or two orders of magnitude less than the average maximum contamination on the surface – it is infeasible and uneconomical to decon. The second rule was "There is a major difference between decon efficiencies of 85 and 95% - related to the time and number of times to decon." Even though this part of the presentation was dealing with chemical contamination, it still is a valuable lesson when considering radioactive contamination. Decontamination of chemical contaminants is generally easier than radionuclide decontamination and these rules are probably more valid for radionuclides.

4.0 DECONTAMINATION TECHNOLOGIES

This section provides an overview of chemical and mechanical decontamination technologies. Vendor contact information for each of these technologies is supplied in a table in Appendix A.

The performance of decontamination technologies is often measured using either a decontamination factor (DF) or the percent removal. The DF is defined as:

$$DF = A_i/A_f$$

and the percent removal is defined as:

$$\%R = (1- A_f/A_i)*100$$

where A_i = the initial activity on the contaminated surface and A_f = the final activity on the surface after treatment. Cost and performance data, representative DF values for different combinations of radionuclide and material surface, are provided in Appendix B.

4.1 Chemical Decon Solutions

In the simplest form, decon solutions can be sprayed or wiped onto the contaminated surface followed by wiping or collecting the resulting liquid/contaminant residue. Decon solutions can also be applied to large areas using pressure washing equipment (e.g., Kelly Decon Systems, Recyclean) and collected with wet vacuums. Other than washing with simple detergents to decontaminate loosely adhered contamination, chemical decontamination takes an expert knowledge of the chemistry of the solution/contaminant/surface interaction. This is particularly true in urban environments where there is a plethora of surface materials and many are complex composites or collections of different materials. In addition, a good characterization of the system to be decontaminated is required. For instance, concrete on subway walls have a heavy grim from decades of service. It has been shown that this grime can contain high concentrations of metals that may interfere with the chemical process and can influence the decontamination efficiency (Fischer 2008, EPA 2006).

Since decon solutions can be sprayed on, flushed or used in immersion baths they are effective on intricate surfaces and can penetrate otherwise inaccessible areas. The main decontamination method for high value personal items such as artwork and heirlooms (although the decon process will have to be carefully evaluated and tested before use) likely will be chemical decon.

Typical chemicals used in decontamination solutions include:

<u>Water</u> (with or without soap) is a good solvent for most ionic compounds and can be effective on salts. Applicable mainly to smearable contamination, water is most effective if applied as soon as possible following contamination so that the contaminant has little time to react with and stick to the surface. Water can be enhanced by temperature (e.g., steam) or the addition of wetting agents and detergents.

<u>Detergents and surfactants</u> are good general cleaners that can be used on most surfaces. Most commercial detergents have a detergent that also acts as a wetting agent or surfactant (e.g., sodium laurel sulfate). The detergent is good for cleaning grease, dirt and some organics. Surfactants decrease the surface tension and increase liquid contact with the surface to be

cleaned. They are safe, mild, inexpensive and present little handling problems. While detergents have limited effectiveness by themselves they are effective at enhancing other decon solutions. Detergents can be good choices to remove grease and dirt that may contain embedded contamination.

Acids such as hydrochloric, nitric, sulfuric and phosphoric are widely used in decontamination of metal surfaces and occasionally on other non-porous surfaces. Their main mode of action is to react with and dissolve metal oxide films that contain contamination or to etch the base metal and release the contaminant. Acids have the advantage of being inexpensive and readily available. Major disadvantages include compatibility issues with the metal being treated and side reaction concerns such with nitric acid which is a strong oxidizer and can cause fires with incompatible materials. Acid washing may require considerable personal protective equipment. In some cases, acid decontamination can be enhanced by the addition of acid salts.

Organic acids and weak acids are also used particularly when reuse and non-destructive cleaning is desired. They have the advantages over strong acid of safer handling and being able to sequester contaminants. Disadvantages include higher cost than inorganic acids and slower reactivity, which requires longer treatment times.

Cost for acid washing is on the order of $2.00 per square foot (DOE 1997).

Chelators such as oxalic acid, citric acid and ethylenediaminetetraacetic acid (EDTA) have been used to decontaminate metal, concrete, wood, and other surfaces. Chelation techniques are best used on non-porous surfaces and generally applied to fixed contamination that is not readily removed by simpler methods. Complexing agents are often used in combination with detergents, acids and oxidizing agents. They have the advantages of greatly increasing decontamination factors and are relatively safe and non-toxic. Disadvantages include cost and limited working range. Cost is on the order of $1.00 per square foot (DOE 1997). Large amounts of EDTA in the secondary waste stream may lead to limitations on disposal. Radioactive waste disposal sites limit the amount of EDTA acceptable for burial in their waste acceptance criteria.

Redox agents are used to change the oxidation state of a metal and make it more soluble or more conducive to other decon methods such as chelation. Reduction and oxidation agents are primarily restricted to metal surfaces where they react with the corrosion (oxide layer) products that act as getters for contaminants. Redox agents will likely have little use in urban areas other than as one step in a multi step decontamination wash. Additionally, the reaction is often complex and requires more skilled workers and good engineering/chemistry support. The simplest redox washes on a metal surface (e.g., bleach or sodium hypophosphate) have costs on the order of $2.00 per square foot (DOE 1997).

Foams and gels are used as carrier media for other chemical decontamination agents. By themselves foams and gels have little decontamination ability. Instead their benefit lies in enhancing other decon agent efficiency by allowing it to stick to a surface providing greatly improved contact times. Foams are good for decontaminating complex shapes, vertical and overhead surfaces as well as piping and vents, although foams and gels are not good for penetrating deep crevices. Foams are most often used with chelators and acids. Foam can be produced readily using available foaming detergents/agents in industrial foam generators. Foams also lower the potential for aerosol generation that can occur with water sprays. A disadvantage of foams is the thin contact layer with the surface which may require repeated applications. Costs are on the order of $2.00 per square foot (DOE 1997).

Hybrid and proprietary solutions have risen in popularity and can increase the decontamination factor somewhat over conventional chemical washes. These systems combine several solution types and use gels, foams pastes and combinations of each for delivery and enhanced efficiency. Systems such as TechXtract and Deconsolutions offer multiple set, multiple solution decontamination processes designed to increase decontamination factors.

Several hybrids have been developed specifically for urban decon after an RDD (focused on Cs on porous surfaces). Argonne National Laboratory (ANL) has developed a Supergel system that incorporates nanoparticle technology and Idaho National Laboratory (INL) has developed a long-lasting foam and clay paste system that remains in place for extended times to improve the overall decontamination factor.

4.1.1 New Chemical Decontamination Technologies

Two new technologies have been developed specifically for urban decon after an RDD (focused on Cs on porous surfaces). The first was developed at Argonne National Laboratory (ANL) and is a Supergel system that incorporates nanoparticle technology (ANL 2004). The second was developed at Idaho National Laboratory (INL) and consists a long-lasting foam and clay paste system that remains in place for extended times to improve the overall decontamination factor (INL Factsheet).

The ANL technology is a three step process. First a wetting agent is applied to a concrete surface to resuspend the bound contaminants within the pore structure. Then a super-absorbent, polymer gel is applied to the surface. The contaminants are drawn into the polymer gel and are fixated on engineered nanoparticles in the polymer matrix. The last step is to vacuum the gel off the surface for disposal. In a controlled test, greater than 70% removal of Cs from concrete after a single application was achieved and 97% after three repetitive applications. While the technology is listed as ready for market, no commercially licensed vendor could be found. In addition the process is slow, costly, and in a large urban environment would have limited general applicability. However, its high decontamination efficiency compared to other techniques may make it the best choice for very high value architecture with porous building materials (concrete, marble, granite, etc.).

The INL decontamination system consists of a long-lasting foam that is first applied to remove surface contamination. The foam remains intact for several hours allowing long contact time of the decontamination chemicals. After the allotted time, the foam is vacuumed off. The foam removes surface and near surface contamination but not the deep contamination in the pores. A deep surface process is then applied that consists of a clay paste. The paste is applied to the surface and left in place for days to weeks while the chemicals react with contaminants and draws them out of the porous material. INL laboratory tests showed up to 97% removal of Cs-137 for marble and 89% for concrete. For application to an RDD in an urban area the later result is likely not good enough except for lightly contaminated concrete which would probably be better served using simpler washing techniques. The results on marble may prove useful for high value items and architecture. Cost of the INL system is expected to be high and it is not yet commercially available.

4.1.2 Waste Management Issues

In addition to the volume of wastes generated during decontamination, waste management of chemical solutions needs to be considered and may require different techniques for waste minimization. Many chemical decon solutions can be treated by deionization using exchange resins. Others such as chelators may require chemical oxidation prior to disposal. Acidic and alkaline solutions will need to be neutralized before disposal. Co-precipitation and filtration can also be used to remove contaminants from the waste stream. Foams may require the addition of foam destabilizers.

4.2 Mechanical Decontamination Solutions

4.2.1 Vacuuming

Vacuuming of radioactive contaminants utilizes industrial grade vacuums equipped with high efficiency particulate air (HEPA) filters. The HEPA filter removes 99.97% of particulates larger than 0.3 microns. The particulates are collected in a chamber for disposal. HEPA vacuuming is effective on loose contamination and has been used effectively on many surfaces including floors, walls, vents, equipment and furniture. It will be a good initial decontamination tool for interior contamination after an RDD. Vacuuming also is compatible with intricate surface geometries and shapes and will be valuable in urban decontamination of lightly contaminated personal and high value items. Vacuuming works best on smooth surfaces and typically is followed by wet wiping. Porous surfaces tend to hold the loose particles better, which reduces efficiency. Still, vacuuming will reduce loose contamination even on porous and rough surfaces and may make the overall decon process more effective by reducing the source term.

Vacuuming can cause resuspension of contaminants and often is performed after tenting the area to prevent spread of contamination. HEPA Vacuuming is an important enhancement for many other mechanical decontamination processes, notably the high impact types such as scabbling, cutting, grinding, peening and blasting. Without vacuuming these technologies would have large amounts of dust and airborne particulates that could cause spread of contamination and increased worker dose.

Some things to look for in a HEPA vacuum include; a full alarm, low flow alarm, high flow capacity that allows long tubing (so moving the vacuum canister is minimized) and modular debris collection that allows rapid clean out (e.g., disposable canister, bag-in bag or direct collection in 55 gal. drum). Decontamination rates of 125 ft^2 /hr have been reported. Cost in on the order of $2.00 per square foot (DOE, 1997).

When using vacuums for larger debris consideration to the facts that large particles can damage the canister/filter and can also quickly fill the canister should be given. Chip collectors or rock stoppers protect the vacuum filtration system by providing a collection point for heavy material before it collects in the vacuum HEPA filter.

4.2.2 Strippable Coatings

Strippable coatings are paint-like polymer coatings that are applied to a surface, adhere to or encapsulate contaminants on the surface while curing and are then peeled off the surface taking the contaminant with it. The coating can be applied using typical paint finishing techniques such as brush, roller or sprayer. Removal is accomplished by manually pulling the coating away from the surface. On smooth flat surfaces the coating will come off in large pieces. As the surface roughness and complexity increases the removal ease decreases and the coating will come off in smaller pieces with greater effort required. To enhance strippability, fiber reinforcement can be added. To enhance contaminant removal, binding agents (chemical decontamination agents) can be added. The newer strippable coatings are non-toxic and non-hazardous, water-based products so organic solvent off gas and mixed waste disposal issues are not a problem.

Strippable coatings are applicable as a decontamination agent, as a protective coating put in place prior to a contamination event and as a fixation coating to hold loose contamination in place until a final decontamination plan is devised.

The drawbacks to using strippable coatings are cost ($50 to $200/m^2, $5 – $20/ft^2, James 2008a, James 2008b, DOE 2000, EPA 2006), for maximum decontamination multiple applications are required (typically the manufacturers recommend three), and work time to remove the coating. In addition, decontamination factors may not provide adequate removal in highly contaminated areas, particularly on concrete. Best case testing indicates 80-85% removal for Cs after three applications on concrete coupons. This will not allow free-release for any but the lightest contaminated surfaces and then the cost and time factor will likely preclude the use of strippable coating over less intensive technologies (simple detergent wash).

4.2.3 Paint Strippers

Paint stripper decontaminates by removing the paint coating on the surface of an item. The presumption is the contamination will be on the paint and not have migrated through and into the substrate. Many paint strippers exist, both non-hazardous and hazardous, that can treat most types of paint. The stripper should be tested on the paint and substrate before general use to insure it effectively removes the paint and doesn’t harm/corrode the substrate. Water-based, non-toxic, non-hazardous gel strippers seem best suited for radioactive decontamination following an RDD. Paint strippers are moderate to expensive and the quantity needed could become prohibitive. Waste generated by this process includes the removed paint and the stripper and in many cases a neutralization or cleansing rinsate. Removal of the treated paint is completed manually and is time consuming.

4.2.4 Steam and pressure washing

The simplest of decontaminations methods is a soap and water wash to remove dirt and surface grime. For radiological decontamination, water (or solution) wash is still the most widely used decon technique. Water washing can be enhanced by adding heat and/or pressure. Adding heat increases the solubility of many contaminants and hence increases the removal efficiency of the wash. By adding mechanical agitation of some sort the efficiency of removing loose contamination increases. By adding low pressure water the mechanical action of the wash is greatly increased and strongly adhered particles and those trapped in the grime begin to come off. Increase the pressure further and the wash can remove paint and coating layers taking contaminants along with it. Using high pressure allows the water stream to remove surface material and thick layers of concrete can be removed. At this point the chemical action of the wash solution is not very important and the mechanical action is solely responsible for contaminant removal. Pressure washing, because it is delivered via a wand, can be used for cleaning of inaccessible surfaces such as the interiors of pipes and vents. It is expected pressure washing will have good value in an urban area following an RDD due to the ability to treat large areas quickly, many surfaces and the relatively quick mobilization and set up times.

Hot water pressure washing uses heated water at pressures up to 1000 psi. The water is delivers via a hand-held wand and residual water must be captured using dikes or wet vacuums. Cleaning rates (once dikes or recovery systems are set up) is 300 to 350 square feet per hour. The water wash can be enhanced with detergents.

Steam vacuuming uses super heated water (250°C to 300°C) that flashes to steam when it contacts the surface being cleaned. Stream delivery pressure is up to 250 psi and can accommodate detergents. The water stream is delivered via a hand-held wand that can incorporate different spray nozzles. The spray head is enclosed in a vacuum recovery system that collects the water, contaminants and steam. Rates are 100 to 150 square feet per hour, but no dike or recovery system set up is required.

High Pressure washing uses much higher water delivery pressure to remove not only the contaminants but some of the surface as well. Pressures up to ~15,000 psi are commonly known as hydroblasting, hydrolasing and hydraulic blasting. Pressures up to 50,000 psi are used in water jetting and can remove large amount of the surface being treated. Pressure washing requires a more skilled labor and careful matching of pressure to surface material and depth of contamination. Lower pressure can remove paint from concrete while leaving the concrete intact. Higher pressure can be used to remove 3/16” to 3/8” or more of the concrete from the surface. With the right configuration and a skilled worker water jetting can remove galvanized layers from sheet metal.

Hydrowashing can be used in a lance configuration to create a “pipe mole” to remotely decon the inside of pipes and ducts.

4.2.5 Blasting

Blasting uses air pressure to propel a fine abrasive media out a nozzle and onto the surface to be treated. The kinetic energy of the media abrades and cleans the surface. Air pressure typically ranges from 50 to 250 psig. Treatment rate is on the order of 60 to 100 square feet per hour. Most surface types can be treated with proper choice of grit and complex surface geometries and intricate surface can be blasted. Blasting removes the surface layer and therefore is generally not specific to a particular contaminant(s). HEPA vacuums are used to collect and recycle the grit. Grit can be recycled a number of time but then wears out and must be replaced. Blasting can generate static electricity so grounding can be an issue. The waste stream consists of the removed surface material and spent grit.

Grit Blasting is the most common form of blasting. Formerly known as sand blasting, many grit types are available. Care should be taken to avoid sand/silica containing grit due to concerns about silicosis. Blasting uses a large amount of grit so cost depends on the grit chosen. Synthetic grits are available (e.g., PlasTek, and Plasti-Grit) that are claimed to be safe for primers, gel coats, and circuit boards and can be purchased in different sizes and hardness types. Grit blasting can remove thick or thin layers from the surface depending on the grit choice. This type blasting is often done in a containment housing and requires a HEPA vacuum to control dust.

Sponge Blasting uses soft urethane sponges in place of a hard grit. The sponges have several advantages. The sponges are absorptive and can be wetted with cleaning agents to enhance decontamination. As the media hits the surface it collapses and expands which creates a scrubbing action. Bounce back of the grit is greatly reduced over hard media as the kinetic energy of the sponge is mostly transferred the surface. The sponge can also be impregnated with abrasives (e.g., aluminum oxide) and then tailored to a specific surface. Using soft sponge media with a cleaning agent may allow intricate surface features to be cleaned. This is a technology that should be tested for cleaning complex high value and personal items.

CO_2 Blasting uses dry ice pellets as the blasting media. The pellets vaporize when they contact the surface, creating an added lifting action. Since the grit vaporizes there is no secondary waste, just the removed surface material. The vaporized CO2 can be problematic particularly in confined spaces and poorly ventilated areas. Monitoring must be done in these situations. Dry ice blasting has proven effective on plastics, ceramics and stainless steel. Wood, some soft plastics and brittle materials may be damaged. Dry ice blasting also requires specialized equipment to produce the ice pellets.

Centrifugal Shot Blasting has the advantage of being airless. An enclosed spinning centrifugal head throws an abrasive against the surface to be treated. The abrasive cleans the surface and the grit and removed debris bounce back to a separation system that recycles the shot. Shot blasting can remove up to ¼” of concrete per pass and is an aggressive blasting method.

4.2.6 Scabbling/scarifying

Scabbling is an aggressive surface removal process for concrete. Typically, one to seven multi-point, tungsten-carbide chipping bits attached to high-speed, pneumatically-driven pistons strike the concrete surface. The chipping action removes concrete in 1/16” to 3/16” increments. Scabbling produces no secondary waste but must incorporate shrouding with HEPA vacuums to collect the fine dust produced during the scarifying process. With such protection scabbling can be done without increasing airborne exposure. Reported removal rates are up to 250-450 ft^2/hr at 1/16” removal thickness.

Scabblers are available in floor models as well as wall and hand-held versions. In general, scabbling is limited to open areas and is most economical on large open areas. Floor models cannot reach close to walls and corners and specialized units are need for these areas (e.g., Corner Cutter and Rotopeen). Scabbling leaves a flat but roughly finished surface after treatment. The roughness depends on the cutter type used. Scabblers often have problems with bolts or metal objects imbedded in the concrete. Such items may need to be worked around using a hand-held unit.

In an urban environment, intricate shapes and vertical surfaces are the biggest hindrance to scabbling. Exterior building surfaces will be hard to treat using scabbling due to the height of buildings. Scabblers may be useful for sidewalks and large roadway scarifiers may be useful to remove contaminated roadway surfaces. Scabbling may be more useful for interior spaces and those that are more industrial in nature (large open areas). Hand-held scabblers may prove very useful in hot spot removal or localized hard to decontaminate areas.

<u>Cutters</u> are related to scabblers in that they remove the surface of concrete/cement. Instead of hammering the surface with a chipping bit, cutters use a rotating, diamond-tipped blade to remove the concrete surface. Cutting generally removes concrete in smaller thickness increments than scabblers. Concrete shavers leave a smoother finish than scabbling and it can be a ready to paint surface. Both floor and wall shavers exist with the wall unit requiring considerable set up time and open access. Cutting has the same limitations as scabbling; corners and floor-wall interfaces are inaccessible, intricate shapes cannot be treated and exterior vertical surfaces are extremely difficult to treat.

Data from Chernobyl generally indicated that the contamination deposited on roadways remained either in the thin dust layer on the surface or was adsorbed directly on the asphalt surface (Roed, 1998). If scabbling or cutting is performed reasonably soon after the deposition, very high DFs should be attainable. One test, completed approximately 11 years after the Chernobyl event, removed two 1 cm layers from an asphalt roadway to reduce contamination and dose in the area. Even after this long wait time, where the contaminants could leach deeper into the asphalt, 80 percent of the activity was removed (the decontamination factor, DF, was five).

4.2.7 Soil Sorting

Soil sorting using a series of conveyors and detectors to monitor excavated soil and separate out the contaminated soil from clean soil. This has only been used for gamma emitters as the detectors for such are sensitive and fast enough for large through puts. Typically, the system consists of several survey instruments and software that integrates the detector together and with the conveyor system. Depending on the clean up goals (how clean is clean) soil sorting can survey 10 to 20 acres per day (30 to 300 tons per hour) at a cost of $20 to $80 per ton.

Soil sorting can result in large savings by discriminating between contaminated and clean soil; instead of treating all the soil from a site as contaminated. It also allows reuse of the excavated clean soil.

4.2.8 Soil Washing

Soil washing uses mechanical size reduction methods (e.g., agitation, hydrolasers) and chemical washing (e.g., water, acids, bases, surfactants, solvents, chelating or sequestering agents) to separate contaminants from soil and sediments. The process water is typically recycled. The chemical wash is used to remove soluble contaminants from the soil and capture them in the rinsate. The rinsate can then be treated with conventional methods such as exchange resins.

Typically, most of the insoluble contamination is associated with the fine particle fraction of the soil (clays and silt), so that separation of the fines can be used to effectively decontaminate and reduce the volume of contaminated soil for disposal. The fine particles can be separated from the heavier particles (sand and gravel) by suspending them in water followed by hydrocycloning or other techniques. Once separated, flocculating agents that agglomerate the particles can be used to enhance the removal of the fines from the bulk soil washing effluents. Settling tanks or filter presses can be used to collect the agglomerated fines.

Advantages to soil washing;

- Soil washing is one of the few permanent treatment alternatives for soils contaminated with radionuclides.
- A broad range of influent contaminant concentrations can be accommodated.
- The clean coarse soil fraction can be returned as fill to the site.

Disadvantages to soil washing;

- The rinsate requires further treatment before disposal
- High humic or organic content can complicate the process
- Requires a large set up area
- Not cost effective for small volumes of soil or soils containing a large fraction of fines.

Mobile soil washing units are available that can treat tons per hour. Typically, a small soil washing (20 ton/hr) process requires about ½ acre for equipment and staging areas. Noise and air pollution produced by the process are minimal. And the units can be set up and be operational quickly. Takedown time is also fast. The chemicals used in the washing process are dependent on the radionuclide(s) involved. The components offer reasonable flexibility and can be tailored to most soil/contaminant combinations.

Soil washing requires considerable knowledge of the system and needs to be matched to the contaminant type and concentration, soil type, job size and cleanup goals. Soil washing can remove 85% to 95+% of the contamination. One soil washing company, Biogensis, states "the average treatment system requires: a system supervisor, a quality technician, two operators, and a materials handler." Cost (excluding waste disposal cost) is on the order of $200 - $500 per cubic meter (http://www.biogenesis.com/ssebbs.html, Suer, 1995). Soil washing is generally not cost effective if the fines/clay/silt (fraction less than 200 mesh) content exceeds 30%-50% or the site contains less than 5000 tons of contaminated soil (ITRC 1997).

Two facts limit the potential for soil washing after a dirty bomb in an urban environment. First, the amount of soil is expected to be minimal. Few high value targets are near large parks or areas with large amounts of soil. Second, a dirty bomb will contaminate the topsoil and will not penetrate deeper into the lower soil layers. Unless large amounts of rain occur before site decontamination can be accomplished the contaminant will remain near the surface. This means only the upper 6 inches of soil need to be removed to remove the contamination. This reduces the amount of soil requiring washing, but more importantly the topsoil has considerable fines and organic content which lowers the efficiency of soil washing. It is doubtful contaminated soil would be left untreated for long, thus preventing deep penetration into the soil. In addition, to prevent resuspension of the contaminants a fixative coating should be applied to contaminated soil. This will also help prevent mobilization of the contaminants and redistribution to the lower soil layers.

4.3 Fix in Place

Fixing of loose contamination can reduce resuspension and spread of contaminants and allows more time (and thought) before final decontamination takes place. Loose contamination can be locked in place either temporarily or long-term by coating the contamination with a fixative agent. Water can be used as a basic short term fixative to remove airborne particulates and to keep dust down (e.g., to reduce dust from traffic on dirt roads). Of course, the fixative ability lasts only until the water evaporates. Longer lasting fixatives that encapsulate the contaminants may be as simple as latex paint or glycerin coatings. They may also be very durable, long lasting coatings such as epoxies or polymers. Typically, the coating is applied by brushing, rolling, spraying or fogging. Fixatives for radioactive contamination include polyurea, Polymeric Barrier System and CC Fix. Fixatives should be considered for higher contamination areas rather than low level contamination areas. The fixative will make later decontamination harder and should be used in areas that must be accessed immediately or to get to other areas. Fixatives can allow vehicle traffic into and out of contaminated zones without spread of contaminants.

Fixatives are also good for fixing loose contamination on the surface of equipment or a building to be demolished. Demolition can then be accomplished with substantially reduced airborne spread of contamination.

4.4 Summary

Table 2 summarizes the vendor capabilities into 9 broad categories. More details on the vendors are provided in Appendix A. The first two categories address general needs that will be part of any response to a large scale RDD event. The Decon Engineer category includes large firms who have experience in decontamination of nuclear facilities or emergency response. A few mid-size companies have been included in the list due to their proximity to New York City. The second category highlights support needs for decon including PPE, HEPA filtration systems for tented areas, waste containers, decon showers, and other equipment needs. The focus of this report was radiation decontamination technologies and for this reason the list of support service companies in Appendix A may not be complete. The remaining categories address the mechanical and chemical decontamination technologies discussed in Section 4 of this report.

Table 2 **Summary of Vendor Capabilities**

Decon Technique	Number of companies	Function
Decon Engineer	10	Provide full service decon support. Only large companies considered.
Support Services	12	Includes providing PPE and respirators, HEPA filtration, waste containers, decon showers, washing of clothes, decon vehicles, trailers and skid mount units, and fogging equipment for dust suppression.
Mechanical Removal	13	Blasting, scabbling techniques that lead to removal of the surface of a material.
Removable Coatings	16	Strippable coating or paint strippers. Includes coatings that can be used as fixatives and later removed.
Soil Treatment	3	Soil sorting, soil washing
Chemical Solutions	5	Chemical decon
Decon Foam/Gels	3	Chemical decon
HEPA Vacuum	7	Mechanical decon
Fixatives	4	Prevent spread of contamination.

Table 3 summarizes the cost and performance data in Appendix B. Further details are presented in Appendix B. The table contains the type of decon technology, applicable material surfaces, cost, manpower requirements, and effectiveness (Decontamination Factor, DF). Costs were collected from a series of reports and have all been normalized to 2008 dollars. Examination of the table indicates that the identified surfaces and decontamination factors are generic. This is consistent with the available data. Radionuclide specific DF values are provided in Appendix B, but they are for a limited number of surfaces and conditions. In general, there are very few DF values for urban materials.

Table 3 Summary of Cost and Performance Data

Decon Technology	**Material**	**Production cost ***	**Manpower**	**DF**	**Comment**
Chemical Washing	Best on metals and smooth surfaces without cracks and crevices	$2.50 per sq. ft. for non-proprietary products; order of magnitude higher for proprietary solutions	Typically one person, but crews can be used to increase productivity (10's of sq. ft per hour per worker).	Typically 1 to 10 for metals; 1 to 4 on non-metals. For metals corrosive removal increases DF	Liquid waste often requires treatment for characteristic hazard, but waste is fairly easily treated.
HEPA Vacuuming	All	$2.50 per sq. ft.	Typically one person, but crews can be used to increase productivity (100's of sq. ft per hour per worker). Productivity depends on surface complexity	2 to 3	Best on loose contamination and best if performed soon after event
Strippable Coatings	Best on smooth surfaces, can be applied to all	$6 to $16 per sq. ft.	Two	2 to 20+ on metals (3 to 8 typical); 1 to 5 on concrete and porous surfaces (1 to 2 typical).	Best on flat surfaces; complex or textured surfaces very difficult to strip coating off
Steam Vacuum Cleaning	All	$4 to $5 per sq. ft.	Two to three (~100 sq. ft. per hour)	Highly variable	Best on flat surfaces otherwise diking and/or water recovery systems may be needed
Pressure Washing	All	$5 per sq. ft.	Two to three (very high production rates)	2 to 50 with water; 40 to 50 with detergents	Good for irregular surfaces and geometries; large amount of waste water; removes surface material
Blasting	All but blasting media must be specificall y chosen for the material	$2 to $5 per sq. ft.	Two	2 to 10 for no to low surface removal; to free release with aggressive surface removal	Good for irregular surfaces and geometries; water; removes surface material

Scabblers, Cutters, and Grinders	Primarily concrete, some coating removal	$2.50 to $20 per sq. ft. on floors; $12.50 per sq. ft. on walls	Two to four	To free release with aggressive surface removal	Limited to flat surface
Soil Sorting	Soil	$20 to $80 per ton	Large crew to move soil	Sorts contaminated soil from clean; 10 to 20 acres per day; 30 to 300 tons per hour	Limited to gamma radiation where detectors are fast enough; large staging area
Soil Washing	Soil with less than 30% fines	$200 to $500 per cubic meter	Five or more	Separates contaminated fines from soil	Not cost effective for less than 5000 tons; large staging area
Fixatives	All		One or two	Not decon - fixes loose contamination	Temporary to reduce spread of contamination
Laundering of Clothing	Clothing that would not be damaged by water laundering		one	100 to 250 for cotton with soluble nuclides; 3 to 14 for insoluble nuclides	May be useful for some personal items

* costs are normalized to 2008 dollars using conversion tables from http://oregonstate.edu/cla/polisci/faculty-research/sahr/sahr.htm

5.0 URBAN DECONTAMINATION EXPERIENCE

The Chernobyl and Goiania accidents are the two major environmental radioactive contamination incidents that resulted in extensive decontamination of urban areas. Although both occurred more than twenty years ago, the response protocol and the lessons learned provide valuable information for future large-scale urban radioactive contamination response actions. This discussion focuses on the decontamination aspects pertinent to this project.

5.1 Chernobyl, Ukraine

The Chernobyl incident occurred in April, 1986 and released radioactivity that covered thousands of square miles with substantial contamination. In the near field, within 15 Km of the plant, most contamination was deposited in particulate form under dry conditions. Many of these particles were fuel fragments (UO_2) with the associated fission products. Traditional chemical approaches which attempt to dissolve the radionuclide were largely unsuccessful due to the stability of the UO_2 particles. Mechanical techniques (collection and removal) were needed for this contamination. At larger distances, much of the contamination was in aerosol or gaseous form and deposited due to both wet and dry deposition processes. Cesium was the primary radionuclide of concern at the larger distances for decontamination.

The contamination was widespread covering several countries with levels detected well above background for hundreds of kilometers. Houses, farms, roads, soil and vegetation received fallout from the event. An exclusion zone for 30 km was established around the plant and people were required to vacate this area. Outside the exclusion zone, many regions of Russia, Ukraine, and Belarus have contamination that led to personal exposures above 100 mrem/yr for more than ten years. Two hundred and seventy thousand people lived in regions that had depositions greater than 15 Ci/km^2. The average dose received by these people over the first three years following the accident was 3.6 rem (NEA, 2002)

Substantial efforts were undertaken to reduce personal exposure through decontamination. More than fifty decontamination techniques (countermeasures) were applied. This motivated a major effort by European Countries to collect and review data from the event and develop decision support tools to assist in the response to similar large scale events. A new generic European decision support handbook has been produced on the basis of lessons learned on the management of contaminated inhabited areas (Euranos, 2007). The handbook contains detailed descriptions of 59 countermeasures in a standardized form that allows intercomparisons between technologies. The review discusses each countermeasure in terms of objective of the countermeasure, constraints on implementation (legal and technical), effectiveness, requirements (equipment, manpower, safety, etc.) cost, wastes, side effects (social and environmental implications) and practical experience in implementing the technique. As an example from the Euranos project, decontamination factors for outdoor surfaces are provided in Table 4. It is important to note that DF values are less than 10 for anything other than complete removal of the contaminated material. The guidance also contains information on selection of an appropriate technology and methods for managing the recovery of inhabited areas using decision flowsheets, tables and check lists. Guidance is consistent with the recommendations of the International Council on Radiation Protection (ICRP).

Table 4 Estimated external dose rate reductions following remediation after a dry deposition of ^{137}Cs (from Euranos, 2007).

Description of countermeasure	Assumed DF[a]	Reduction of external dose rate (μSv/d per MBq/m^2)[b]	% reduction in external dose rate
Buildings			
External surfaces (walls, roofs, windows)			
Fire hosing walls	1.3	Negligible	
Roof brushing	4	0.4	7
Sandblasting (walls)	4-10	0.1	~1
High pressure hosing (walls)	3	0.1	~1
High pressure hosing (roofs)	3	0.4	6
Roof cleaning by pressurised hot water	4	0.4	7
Roof replacement	Full	0.6	9
Treatment of walls with ammonium nitrate	1.7	Negligible	
Mechanical abrasion on wooden painted walls	2	Negligible	
Indoor surfaces (all buildings)			
Vacuum cleaning	10	Negligible	
Washing	2	Negligible	
Paved/roads (and other hard outdoor land surfaces)			
Firehosing	3	0.6	10
Vacuum sweeping	3	0.6	10
High pressure hosing	4	0.7	11
Surface removal (road planing)	8	0.8	13
Soil, grass and plants			
Grass cutting	4[c]	0.1	1
Turf removal / harvesting	8	4.1	65
Top soil and turf removal (mechanically)	10	4.2	67
Top soil and turf removal (manual)	10	4.2	67
All outside areas			
Snow removal	10	5.0	80
Trees / shrubs			
Tree & shrub pruning/removal and replacement	50	0.1	1

a) Taken from the appropriate data sheet
b) Deposition onto reference outdoor grassed surface and underlying soil
c) Decontamination factor for the grass surface only. Not applied to the contamination on the underlying soil surface.

5.2 Goiania, Brazil

A teletherapy unit with 1375 Curies of Cs-137 was abandoned in 1985. In 1987 two people found the unit and thought that the metal was valuable for scrap. They opened the unit and removed the source and sold the remainder to a junkyard. The people noticed that the source material glowed blue in the dark and were fascinated by this. They invited friends and family over to see this and gave pieces (the size of a grain of rice) away as gifts. Within a week many of these people became ill with gastrointestinal problems. Initially the cause of the sickness (radiation poisoning) was not recognized. Eventually someone brought a piece of the source to the local health agency where its radioactive characteristics were discovered.

Contamination spread throughout the town and characterization work determined that 85 houses had significant contamination. Evacuation of the residences was required if the dose exceeded 2.5 uSv/hr at 1 m above the floor in the house. Working under intense political and social pressures, a total dose limit was set at 5 mSv/yr to the maximally exposed individual in the first year. This was apportioned as follows:

- inside houses (external exposure); 1 mSv;
- outside houses (pathways from contaminated soil): 4 mSv, broken down into 3 mSv due to external irradiation and 1 mSv due to internal exposure, such as via contaminated fruit and produce.

Forty-one of these houses were evacuated until decontamination was completed and eight houses were eventually destroyed because of contamination. Decontamination consisted of sealing the house with plastic and removing the easily movable objects outside the house (clothes, small furniture, dishes, etc.) where they were surveyed. Items that were not contaminated were sealed in plastic and placed in a clean area. For contaminated items, a decision was made to either dispose of the item or attempt to decontaminate it. The decision was based on the level of contamination and their economic and sentimental value to the owner. After the house was cleared, HEPA vacuums were used on all surfaces (walls, windows, floors). Painted surfaces were stripped. Most floors were ceramic tiles that were cleaned with acid mixed with Prussian Blue. Roofs were HEPA vacuum cleaned from the inside and power washed on the outside. This reduced the dose rate at the surface by about 20% indicating a poor decontamination factor. The roofs on two houses had to be removed and replaced. The fact that the roofs were contaminated even though there was no explosive release of Cs indicates that re-suspension was significant. Vegetation was treated by pruning and removing and disposing of all fruits. Decontamination of 45 different public areas including roads, public squares, and bars was conducted. The public places were generally less contaminated than the homes and the contamination was localized occurring in discrete spots suggesting transfer from contaminated clothing or skin. Over fifty vehicles had contamination levels requiring decontamination. Decontamination was continued until government required free release limits were met.

A total of 3500 m^3 of radioactive waste was produced in the Goiania accident. In comparison, the World Trade Center waste volume was 500,000 m^3 (Martin, 2003). A volume of 500,000 m^3 far exceeds commercial capacity for radioactive waste disposal in the U.S. The volume of waste from an RDD event most likely would fall between these two. The Goiania release was not explosive and contamination was spread by wind and transfer by humans. In New York City due to the density of buildings, and roads the volume could be large if effective decontamination methods are not found.

5.3 Discussion

In both major urban contamination events the decontamination technologies used were primarily washing, vacuuming or removal. Decontamination factors for these approaches ranged form 1.3 – 10 suggesting a limited ability to treat highly contaminated surfaces which necessitated demolition or removal actions. Voronik, on the Belorussian efforts after Chernobyl, stated "However, the methods of total decontamination turned out to be little effective and economically unacceptable" (Voronik 1999). He points out that later decon efforts were directed at "social items of vital importance" (e.g., hospitals, schools). In Russia, the Chernobyl accident eventually resulted in the relocations of some 260,000 people (Hubert 1996). Roed, discussing the 1989 decon efforts in Russia wrote, “Decreases in dose rate by generally a factor of 1.1 to 1.5 were recorded. A similarly low efficiency was found to be the result when the same procedures were carried out in the Belorussian settlement Kirov.” (Roed 1998). He also stated, “the operation was clearly not cost-effective”.

Advanced technical solutions such as strippable coatings, chemical decontamination, scabbling, etc. were not widely used. This may be due to their limited availability at the time and locations of these incidents. However, these techniques do not show much greater decontamination factors for porous surfaces common in urban environments.

6.0 DECONTAMINATION LOGISTICS AND STRATEGIES

A search of the literature for decontamination methods results in one overwhelming observation; 99% of the research and technology developed for decontamination is geared towards commercial and government nuclear facilities. Little research has been performed that examines urban environments and materials. This is for good reason, RDDs are a recent concern and with a few exceptions, radioactive contamination has been relegated to commercial and governmental facilities. Even events like Goiania, Chernobyl and TMI did little to drive research into decontamination of urban/residential environments in the U.S. Only post 9-11 has decontamination of these areas and materials become a real concern.

There is some belief that the commercial decontamination technologies could transfer to urban environments. This is true only on a very limited basis. Both commercial nuclear and governmental facilities tend to use limited surface materials in radiation areas. The radiation areas are fairly sterile structures in terms of building materials and furnishings. Concrete and steel predominate and generally, you will not find things like drapes, curtains, rugs, personal items, etc in the radiation areas. Personal items, lunchrooms, lounges and the like are found in the support buildings/areas. Even computers and electronics are kept as separate as possible from contamination zones as is reasonable. Some experimental laboratories will have scientific instrumentation and associated computers, but these (if contaminated) are normally disposed of as radwaste after reaching end-of-life status. Decontamination is rarely effective enough to allow free-release, as would be desirable for urban items.

The material found in urban environments offers much greater variety than one expects to find in nuclear facilities. Of interest is part of a study guide for radiation protection personnel (DOE 1997a). It discusses the ideal surface for decontamination and suggests the ideal surface have the following features;

- Be non-absorbent, since porous materials are very difficult to decontaminate
- Contain as few acidic groups as possible, since these groups are chemically reactive
- Have a low moisture content
- Be protected from exposure to solvents or chemicals, which attack the material
- Possess sufficient chemical resistance to withstand decontaminating agents
- Be capable of withstanding abrasive action
- Be smooth with no cracks and ledges

It further states no one material has all these characteristics and compromises are made such as surfaces being covered with strippable coatings or disposable plastic sheet.

What should be noted from this is that urban materials are as far from the "ideal" surface as can be. The decon technologies that address nuclear facilities were developed knowing that the nuclear industry used the best materials, in terms of decontamination ease, as possible. Obviously, concrete was used for every nuclear facility, but decommissioning of the concrete consists of demolition either total or surface (via scabbling, scaling, etc.). Some urban surfaces will be serviceable using decon geared towards dose reduction (e.g., air ducts where fix in place might be used). Most urban surfaces will need to be cleaned to meet clearance levels or disposed /demolished and replaced.

A few recent Federal research programs have focused on urban environments (e.g., DHS, DTRA, EPA) but even these focus on concrete with occasional studies on brick, marble and granite. Obviously, concrete is a major building component in urban areas and research must include this material. In addition, concrete decontamination methods do not have decontamination factors that would allow free-release of concrete in the higher contaminated zones (closest to RDD epicenter). Besides limited material focus these studies all examine flat surfaces (e.g. flat mosaics of concrete coupons, marble tiles). Most of the research has concentrated on return to service of vital facilities (e.g., Grand Central Terminal). But still seem to ignore the surface variety and intricacies associated with an urban environment. The U.S. Environmental Protection Agency's National Homeland Security Research Center (NHSRC) reported at the 2006 NHSRC Decontamination Workshop that decontamination is based on historical technologies, which are inadequate for an urban area event (Dun 2007).

Urban environments have many intricate surfaces that greatly complicate decontamination. In fact, the most historically/socially important buildings in an urban environment are often the most intricate surfaces (e.g., City Hall, Castle Clinton, St. Patrick's Cathedral). Many have intricate adornments such as gargoyles, finials, pediments, gilding and ornate railings. Unlike surfaces in nuclear facilities, urban surfaces are often are ornamented for added social value (e.g., subway art). High value items (e.g. jewelry, computers, paintings, paper business records, historic artifacts) are numerous and most will have intricate composite surfaces and require specialized decontamination.

6.1 Preplanning a Recovery Action

All of this mandates not only increased research in decontamination technologies geared directly at urban materials, but also much greater preplanning. Current planning documents point to who will be in charge, what agency will perform which function, etc. This is absolutely required as the logistics and administrative challenges of orchestrating so many agencies, owners, and concerned parties are daunting. However, on top of this high level planning, there is a need for specific decision making tools including a decontamination strategy focused on urban decontamination issues that includes:

- Outdoor decontamination methods and triggers
  - Roadway and building surfaces may need temporary fixative treatment – before or after emergency decon for dose reduction
- Indoor decontamination methods and triggers
- Prioritization of facilities
  - Economic (e.g., financial district, transportation hubs)
  - Social (e.g., hospitals, schools, parks)
  - Historic
- Prioritization of indoor spaces
  - HVAC
  - Office space
  - Living Spaces

    - Elevators and support services
- Handling of high value personal items
    - Designate a facility to store items for later decontamination
    - Temporary stabilization of the item
    - Determine return to service requirements
        - Regulatory
        - What will public/stakeholder allow/accept
            - May be regionally specific
- Handling of low value personal items
    - Dispose
    - Sort and dispose
    - Attempt simple decon
    - Allow owners to decide (at their cost)
- Data and record protection and recovery
    - Decon of computers (PCs, PDAs, IPODs) and other electronics
    - Data retrieval versus decon cost
    - Digital copying of paper records
- Vehicles and Subway decontamination methods and triggers[1]
    - Carwash
    - Fixatives until decontamination at a remote facility can occur
        - Bring subway cars to rail yard for decon?
    - Dispose

Preplanning needs a national level strategy, but must have a regional flavor as well, since many urban areas, such as NYC, have unique characteristics (e.g., NYC subway, average building height in the uptown area of Manhattan). Many of the decisions can and should be made well ahead of an event. Knowing the current state of decontamination technologies, current economics of these technologies and assuming certain contamination levels should allow basic decision making trees to be developed along with trigger levels for certain actions. These decision making tools will aid determinations on what items are best disposed (e.g., rugs, drapes, pens, paper), which do not need immediate treatment to return the area to service but need to be stored for later treatment (e.g., jewelry and paintings), which areas are essential to return a building to service and what preliminary treatments are required to allow decontamination crews to even reach an area, etc.

6.1.1 Maintaining Capabilities

To maintain preparedness there should be a constant update of lessons learned not only from radiological events such as Chernobyl and Goiania, but from biological and chemical events (e.g., sarin in the Tokyo subways, anthrax at the Washington D.C. and NJ mail centers). Thus far the lessons learned from radioactive cleanups at Chernobyl, Goiania and the DOE facilities such as Rocky Flats seem to indicate that many items will be disposed and demolition versus decontamination is often the faster, cheaper method. These clean ups have also proven that many simple decontaminations methods, such as vacuuming, washing, and paint/surface removal are

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[1] LLNL program on response to an RDD event in Grand Central Terminal will develop a decontamination plan for subway and train cars.

the most effective. Decontamination after Chernobyl also showed that certain simple methods applied quickly can be effective. Firehosing of roadways soon after deposition was reported as 95% effective in removing Cesium for dry depositions, however, wet deposition (e.g., delays followed by a rainfall) resulted in only 45% removal (Brown 1991, Demmer 2007, Andersson 2003).

From the Goiania event two lessons learned are very important to the overall remediation process (IAEA, 1988). The first is the clean up goals were set low due to public perception rather than being based on risk optimization. Stringent clean up goals affected the cost and extent of the remediation. Public perception will be a great influence on final return to service levels and need to be set early to avoid having to later change the decontamination plan or having to re-clean already treated areas because clean up goals were assumed and not fully negotiated. The second lesson learned in Goiania was that a waste storage site was needed quickly. In the 1988 IAEA report, it was stated that along with logistical and political problems the lack of a repository caused a loss of momentum in the remediation process.

6.1.2 Developing a Decision Framework

If an RDD event occurs, decisions will be required quickly. To facilitate this process a well developed decision framework that has been agreed upon with the major stakeholders would be of major benefit. As a result of the Chernobyl incident, twenty-three European Countries have been working together since 2002 to form such a decision framework. There work has developed dose assessment models for urban contamination based on the information from Chernobyl, reviewed and evaluated all decon techniques applied over the 20 years since the event, developed a database of these technologies, and developed computerized decision support tools to aid in quickly addressing major issues using the best available information and technologies. All of this work is used to formulate guidance documents for all aspects of response (early phase through decontamination). (www.euranos.fzk.de).

Focusing on the recovery aspects of the response to an RDD event, the decision framework should include (Bettley-Smith 2008):

- Agreed Policy framework with defined responsibilities
- Agreed process to define clean-up standards
- Agreed remediation arrangements
- Identified decon capability and capacity for response.

One approach to defining the decision points and actions needed for recovery would be to prepare a decision tree. Some of the factors that should be included in the decision making tree are:

- Type, form, spatial distribution, and level of contamination
- Weather conditions during and immediately following the RDD
- First response decisions impacts on long-term recovery
- Type, location and geometry of substrate/item
- Value of the item or building
    - Social
    - Economic
    - Abandon or reoccupy

                - Demolition
                    - Rebuild
                    - Reassign use of land
- Prioritization for Resource and Infrastructure Recovery
- Desired endpoint levels
    - Can fix in place be used?
        - Ventilation ducts
        - Waste/storm drains
        - Exterior surfaces above ground level
    - Stakeholder acceptance
- Ease of application of decontamination technology
- Storage facilities to store valuable items
- Cost of decontamination
    - Worker safety
- Technical feasibility of decon technology
- Stakeholder acceptance of decon technology
- Cost of storage
- Cost of replacement
    - Can it be replaced

Careful and detailed pre-event planning can greatly reduce the total time to decontaminate an area. Prioritizing decontamination tasks will allow best use of available assets, funds. and man power and bring some structure to a chaotic event. It will also serve to educate the public and involved parties as to what to expect and what the steps to return to normalcy will be. A comprehensive decontamination strategy will help reduce the economic and psychological damage of an RDD.

6.1.3 Contractor Evaluation and Pre-qualification

Along with a comprehensive decontamination strategy and decision support toolbox, pre-qualification and evaluation of contractors will greatly enhance the overall recovery action. Since the US EPA will be the lead Federal Agency in the cleanup after an RDD, it makes sense that this agency should be the one developing a database of contractors and technologies for radioactive decontamination and to test, evaluate and qualify contractors. Technologies can be qualified through existing avenues (e.g., National Homeland Security Research Center, DOE National Laboratories).

The contractors, their ability to bring forth equipment and man-power and their technical expertise must be evaluated and pre-mobilized. An example of this is the UK Governmental Decontamination Service (GDS) which utilizes the EU Specialist Supplier Framework (Bettley-Smith 2008, http://www.defra.gov.uk/gds/). This is a system put in place to speed up decontamination by prequalifying vendors so they can join the framework, set up model contracts, evaluate and exercise framework contractors, and set up facilities for testing and evaluation of decontamination technologies and materials. This system is designed to bring commercial decontamination companies rapidly from HAZMAT and nuclear facilities to the CBRN scene.

GDS develops viable scenarios associated with an actual location (e.g., NYC financial center), plot likely consequences through modeling and experience and set up a case study based on this scenario for the contractors. The contractors then visit the site, are briefed by GDS on the scenario and the contractor develops a decontamination strategy. The strategies remain proprietary and are evaluated by GDS for strengths and weakness. The plan is iterated back and forth and improvement plans are developed and are further tested with exercises. GDS also identifies critical unresolved issues and then looks to resolve these issues through other avenues (e.g., feeding this into a needs document for future research and development).

This approach offers many advantages in providing for a timely response to an RDD event. In this approach, the decontamination technologies should also be tested in urban decontamination test facilities. Right now there is no real knowledge of what it would take to decontaminate a typical urban office or lobby with all the attendant paraphernalia. Setting up a facility that simulates an urban office and then going through actual decontamination procedures would improve planning for future events. The time required to characterize, stabilize the room for decon, perform the actual decon and scan for release cleaned items all are critical to recovery planning. Once a good baseline for general decon technologies (e.g., vacuum and wipe, wash and wipe) has been developed for the test room(s) then new technologies or technology improvements could be tested at the facility.

The ultimate goal of this task is to have a database of technologies and contractors (national, regional and local) that are prequalified or at least evaluated for a variety of specific sites such as the NYC subway, NYC financial district or Washington DC mall. Much of the success of a recovery action will depend on getting equipment and manpower to the site when and where needed and doing so an orderly, prioritized and equitable fashion. Without a detailed, agreed upon recovery plan, much time will be lost as agencies and owners fight for available resources. Management of decontamination activities for an RDD event will require a major environmental/engineering firm with experience in large projects to provide central planning and coordination of the work. At a higher level, EPA is likely to provide management of the entire decontamination process. Pre-assessing scenarios and involving contractors in the assessment and planning process will help develop a sound strategy for future recovery actions following an RDD.

6.1.4 Resource Availability

One last item for pre-planning is the availability of decontamination materials and manpower. Many of the products listed in the appendix for decontamination and evaluated by EPA, DOE or others are from smaller firms and/or are available on a limited basis. Many have shelf lives measured in months, not years, so stockpiling may not be an option. If an RDD event occurs there may not be sufficient supply of many of the decontamination agents, products and equipment. A company’s ability to supply certain quantities of material needs to be evaluated before an event. Evaluation of contractors alone is not sufficient; the database needs to include manufacturer evaluations as well. Not only should the product be listed, but the quantity that could be delivered in a month’s time to a few months’ time.

Manpower requirements for a major RDD event will be enormous. The highest manpower requirements will be associated with decontamination. The radiation fields and operating characteristics of the machinery (e.g. noise from some mechanical removal technologies) may limit the working time of an individual. The sheer number of samples required for post-decon clearance surveys may overwhelm existing capabilities leading to long times for data turnaround. EPA has estimated that a large scale RDD could require approximately 360,000 samples over a one-year period (EPA, 2007).

6.2 Decontamination in Urban Settings

Decontamination of a large urban area will require prioritization and juggling of many tasks. The first order of business will be allowing first responders to evacuate or secure highly contaminated areas, treat medical injuries, put out fires, secure the area and determine the worst hot spots that will need source term reduction prior to the majority of remediation taking place. For an RDD, the area will also be considered a crime scene and recovery efforts can not begin until area is released by NYPD/FBI. Once the area is stabilized and decontamination technicians can enter, prioritization of tasks will be needed. Most scenarios for an RDD have the roads, sidewalks and building entries areas as being major contamination areas. However, complete remediation of these could take a long time, preventing building and facility decontamination from beginning. It would likely be wise to apply a fixative coating, either temporary or "permanent" (removable or non-removable by simple methods), to the roadways, sidewalks and entryways to allow traffic and equipment access to essential facilities. Additionally, it is unlikely that roadways would be remediated first since they are low lying and decontamination of walls and roofs would have a high probability of recontaminating the road (cleaning is generally done top to bottom).

Fixatives will likely play a big part in the initial recovery action. Using them to stabilize loose contamination in highly contaminated areas and/or where resuspension is likely to occur will prevent spread of contaminants to clean areas, lower worker exposure to airborne contaminants, and allow access to areas without requiring extremes in Personal Protective Equipment (PPE).

In the less contaminated areas, conventional decon methods that are simple, fast and reasonably effective on loose contamination are expected be the norm. There will be a need for large numbers of decon technicians, HEPA vacuums (wet and dry), decon solutions, wipes and low pressure power washers. This is an area that commercial decontaminations and nuclear power plant outage firms will need to be recruited. The gathering and assignment of these assets may best be coordinated by one of the larger remediation engineering and construction companies that specialize in serving the nuclear industry and DOE complex. As discussed earlier, having one or more such large companies prepared for this task will certainly help the over all recovery process.

With all of the individual objects in an urban environment the decontamination process will consist of a huge sorting process. Every office, lobby, living space, etc. that is contaminated will have to have all the objects in the room evaluated for contamination. Based on contamination levels, material type, value, and costs to decon, a decision to dispose or treat the item will be needed. Many items will be disposed without treatment, but for many items it may be worthwhile to try simple, fast decon methods. A valuable lesson-learned from Goiania was stated by the IAEA, "The decontamination techniques used depended on the objects in question. The decision whether to decontaminate or dispose of items depended on the ease of decontamination, except for items of special value such as jewelry or personal items of sentimental value. To see toys, photographs and other items of obvious sentimental value heaped in a yard for possible disposal had a disturbing effect on residents and technicians This is a psychological aspect of an accident that should not be overlooked." (IAEA 1988).

With this in mind, it may be beneficial to have mobile decontamination tents set up with shower/spray heads that could be used to give a "first chance" treatment to items that decon may save from disposal. Even for items that will be disposed, rinsing should be considered if it can reduce the amount of waste that requires a radioactive disposal facility. Many items will be very lightly contaminated and a simple rinse and scrub may be enough to meet clearance levels and release the item. Performing a very rudimentary decontamination on items that when characterized were deemed clean may also give the public/owner greater confidence to reuse the item. Using decon tents at an entry way could allow a simple in one end out the other assembly line approach for decontaminating small items that can be handled by one technician.

Individual items and offices/rooms that are lightly contaminated would be expected to have loose contamination and would benefit from vacuuming followed by wiping. Vacuuming and light wiping could be done during the sorting process.

While decontamination of complex surfaces and composites is time consuming and very expensive there are workable solutions and these can be improved. Research into treatment methods and pretreatment (to prevent contamination from sticking or allow easier removal of contamination) needs to be directed towards complex urban materials. This must include low impact technologies that can be used on high value items with the intent of treatment to keep the intrinsic value not just the functionality.

6.2.1 Decontamination of Miscellaneous items

In urban NYC contamination will affect numerous vehicles (cars, buses, trucks, etc.) as well as portions of the subway transportation system. Vehicles are very difficult to decontaminate with many surfaces and materials. Many will end up as waste and some method of treating them needs to be planned/developed. Having a prearranged area to bring contaminated vehicles, a method of transporting them (without spreading contamination) and a washing/decontamination process should be in place well before an event. Washing/decontamination may remove some vehicles for release (thus reducing radwaste), but owner perception may preclude reuse. For agency owned vehicles such as buses and trucks, efforts to return to service may greater due to the value of the vehicles and the need to keep systems operational. Long waits for replacement vehicles may be unacceptable. In these cases, decontamination efforts may take on a greater impetus. Many private owners may refuse return of a decontaminated vehicle due to unfounded fears and a recycling method should be in place. Perhaps simple scrap metal recycling or offering the vehicles to non-profits for use will remove the vehicle from being land-filled.

Subway cars, if contaminated, also present a problem. While a few cars or even an entire train are not difficult to treat or remove as waste, the cars present a threat of spreading contamination. During an RDD, the protocol for subway operations may be to stop all trains where they are. [According to NYCT the entire subway system will be shut down during an RDD at least long enough to inspect for secondary devices.] If moved, those trains that are contaminated could provide a pathway to spread contamination. Leaving contaminated trains in place could block portions of the transportation system that are vital to the area. A protocol should be developed for applying a fixative coating to contaminated subway cars and engines that allows them to be safely brought to a rail yard (or other locale). Once at the yard an area needs to set up for decontamination or preparation for waste disposal. Protocols should be developed for this as well. Lawrence Livermore National Laboratory is working on developing a decontamination plan for Grand Central Terminal which will include plans for subway and rail cars.

Current fixatives are either permanent or strippable coatings. Permanent coatings would require extensive removal processes (e.g., paint removers, grit blasting) to restore the car for reuse. Strippable coating would require less extensive methods but still would require considerable man power to remove the coating due to the irregular surface geometries that would be encountered on the car/engine. This is one area that research into new coating might be beneficial. There are polymer stabilizers being developed in Russia that can be applied using standard spraying techniques and removed with simple solution wash down. Whether these would be applicable to urban materials and bind contaminants/dust strongly enough and long enough would need confirmation (current use is for soils) but they seem well suited.

6.2.2 Decon of Protective Clothing and Laundering

During any radiologic event there will be a huge need for protective clothing. Either reusable or disposable clothing can be used. Reusable clothing can be decontaminated using existing hot laundry techniques. For soluble contamination very high DFs are possible (Klochkov 1990) but for insoluble contaminants laundering either with detergents or chemical (organic solvents) has poorer results with DFs of 3 to 10. Many nuclear facilities use reusable coveralls/PPE and have them laundered by an outside service provider. The reject rate is often high (20%), but one vendor claims that with good care and proper processing reject rates can be less than 1% (see www.unitech.ws - company claim).

There are also dry cleaning methods to decontaminate cloth and a few new promising technologies available such as water with supercritical CO_2 and electrolytic cleaning (Wang 2004) (Yim 2003). These newer technologies are not fully proven but may be useful for high value cloths that might be damaged by high mechanical action laundering.

Disposable PPE creates a large amount of very low level waste. There are some newer PPE that address the waste management problem. These PPE are made from polyvinyl alcohol (PVA) and utilize a patented (Orex) process to decompose the waste PPE and separate the PVA from the contaminants and recycled. Waste reduction is reported to be large. (Kay 2004). Orex dissolution technologies are reported to equal or exceed the volume reduction capabilities and efficiencies for incineration, which currently exceeds the efficiencies of all other applicable volume reduction technologies (EPRI 2002).

6.3 Pre-Treatment - Making contamination easier to remove

Radionuclides show an affinity for many materials, particularly porous surfaces like concrete or granite. Whether through adsorption, static or chemical bonding many radionuclides can be hard to clean off surfaces. Some protective coatings exist that can be applied to a surface that seal the surface and prevent contamination from sticking to the surface. These can be strippable coatings applied prior to contamination (same as the strippable decon coating already described), durable, protective coatings that contaminants don't stick to or sacrificial coatings that can be removed with a solvent taking the contaminants with it.

It may be possible to use anti-graffiti coatings on concrete, marble, brick etc. Such coatings may allow much greater DFs than would be possible for the bare surface. While it is unlikely that coating every surface in an urban area would be feasible or prudent, there are many high value areas (e.g., Grand Central Terminal) that would benefit greatly from protective coatings that would allow effective decontamination in the event of an RDD. There are also urethane and epoxy coatings that might be useful as sacrificial coatings. They are clear, non-yellowing and can be had in gloss, flat, satin or most anything in between. Applied over porous surfaces they would seal the pores and prevent or slow contamination from migrating into the interior pore network. If contaminated removal could be accomplished with one of many available paint/coating removers.

As mentioned earlier, there are also Russian polymer compounds developed for dust suppression that seal a surface and have high affinity for radionuclides. These coating wash off with mild ionic solutions and would take most of the contamination with them.

Unfortunately, none of these other than a few strippable coatings have been tested in the laboratory with radionuclides, let alone field tested with urban materials. The few available strippable coatings are esthetically displeasing and not available in a clear coat. These might be useful for industrial areas as a replacement for paint (or on top of paint), but are not useful for historic and decorative surfaces. It would be useful to devise a program similar to that for graffiti. With graffiti, the problem drove a commercial market and product development. Anti-graffiti coatings have been the focus of research by private organizations (e.g., the Paint Research Association of the UK) as well as government funded research. Anti-graffiti coating have developed to a point that an ASTM test method exists to test/rate coatings (ASTM 2000).

Development of anti-contamination coatings for urban materials would require a federally funded research and test facility. The facility should be independent and test real world scenarios. Pilot-scale first phase testing might be completed on flat walls of marble, granite, brick, etc. As expertise was obtained, testing could evolve to more complicated surfaces and conditions (e.g. on weathered coatings on intricate surfaces of marble, granite, brick, concrete, etc). Test methods would include accelerated weathering of the coatings after application and standard contamination and decontamination methods.

7.0 CONCLUSIONS

This report provides an overview of radiological decontamination methods. The two major approaches are chemical or mechanical decon. Chemical decon approaches dissolve the contaminant in solution and can be tailored for specific radionuclides. Mechanical decon approaches release the radionuclides through mechanical agitation or physical removal.

Chemical techniques include washing with a liquid or foam. Liquids used for decon include water alone or with soap, surfactants, acids, bases, chelating agents, or redox changing agents. Foams, gels, or pastes are used to provide a longer contact time and thereby enhance removal. Chemical decon advantages and disadvantages are discussed in Section 2. Individual chemical decon methods are discussed in Section 4. Chemical decon methods on porous surfaces typically have decon factors between 1 – 10.
Decon factors greater than 100 can be achieved for non-porous surfaces (metals, glass, etc.).

Mechanical techniques include vacuuming, steam/pressure washing, blasting, scabbling and sorting. Mechanical decontamination advantages and disadvantages are discussed in Section 3. Several mechanical techniques are discussed in more detail in Section 4. Mechanical removal technologies are effective on all surfaces but may require a treatment to repair the visual appearance to surfaces after treatment. Several techniques including strippable coatings, paint thinners, and washing are a combination of mechanical and chemical techniques. These offer a compromise between total removal in abrading technologies and pure chemical treatment.

A literature review focusing on U.S. companies with radiological decon experience culminated in a table (Appendix A) with vendor information, their products and services, and contact information. The review focused on the larger companies and the list does not imply an endorsement of any one company nor does the list imply completeness. A large scale RDD incident will require one or possibly more major vendors to manage the complete process. In Goiania 550 people were involved in the decontamination process and the initial response to Chernobyl involved 90,000 soldiers. Vendors with large-scale capability are included in the table.

As part of the review, data on performance (decontamination factors), cost, operating requirements, and waste generation were collected and incorporated into Appendix B.

There has been very little work on pre-treatment options for protection against radionuclide contamination. Coatings (e.g. polyurethane) may be applicable for many surfaces and strippable coatings have been successfully used in nuclear facilities as a pre-treatment. Development and testing of protective coating technologies that are long lasting, esthetically pleasing and result in DFs well over 100 when removed should be pursued. Protective coatings that are quickly and easily applied could be used strategically to coat surfaces that would be difficult, costly, or impossible to replace (e.g., pink Italian marble at Grand Central Terminal). Development of anti-contamination coatings for urban materials would likely require a federally funded research and test facility.

Response to large scale urban decontamination outside the U.S. (Goiania, and Chernobyl) indicated that decon techniques were generally very simple (vacuuming, washing) for lightly contaminated areas with DF values ranging from 1.3 – 10. For heavily contaminated areas decontamination involved removal of contaminated soils and roofs or demolition. This experience suggests that if the contamination is more than a factor of 10 higher than clean-up goals, removal or demolition will be needed. These events have for the most part shown decontamination efforts to have had limited effectiveness and to be economically burdensome (Voronik, 1999).

Additionally, having low values for clean up goals can severely impact decon efforts by adding to the amount of work and time required to achieve these goals. The IAEA surmised, "After a radiological accident in which widespread contamination occurs, there is usually a temptation to impose extremely restrictive criteria for remedial actions, generally prompted by political and social considerations. These criteria impose a substantial additional economic and social burden to that caused by the accident itself (IAEA 1988).

The review indicated that the vast majority of decon work in the U.S. has focused on nuclear facilities and much less thought has been given to decontamination of urban environments. These technologies were designed more for dose reduction than to clean items to a free release level. Decon factors of 2 to 10 do a lot to reduce overall dose, but may fall far short of being able to bring heavily contaminated items to a free release state. In addition, the materials in nuclear facilities are generally metals or concrete. Metals are relatively easy to decon and concrete is either decontaminated using surface removal techniques or disposed as waste. Decontamination research needs to move out of the nuclear facility mindset and focus on urban materials and clearance levels for release. DF values of 100 or more for urban materials would be extremely valuable in waste minimization and attaining free release. More technology development needs to be directed towards "personal items".

Some focus should be placed on adapting clean up technologies from other industries that also have to deal with urban and residential environments and materials. Graffiti and soot removal are two examples of industries that are well developed and could offer methods easily adapted to radiation clean up after an RDD.

The challenges of multiple material surfaces, multiple property owners, quickly restoring the functionality of an area, and societal impacts make clean-up of an RDD event substantially different and much more difficult than decontamination of nuclear facilities. Development of a strategy to handle these challenges would be extremely beneficial in responding to an RDD event.

Initial thoughts on developing a strategy for response included five major components:

- Preplanning the response (define initial triggers for decontamination and methods for setting priorities for decontamination, understand decon techniques and limitations, and understand resource availability (manpower and equipment).
- Develop a decision framework that specifies roles and responsibilities of different agencies during remediation.

- Establishing a process for defining cleanup standards. This may require a compromise between exposure of workers and the public to low-levels of radiation with a resulting low probability for potential health effects, a societal desire to remove as much radioactive material as possible, and the societal and economic cost of leaving critical facilities out of commission for extended periods of time.
- Performing regular drills to test response capabilities. The UK model for testing decon contractors could serve as a starting point for this work.
- Understand unique aspects of decon from an RDD in an urban environment (wide range of materials, private property issues, release criteria and documentation for release).   Past events have demonstrated that technologies that have high productivity rates end up being used most and this is particularly true at the beginning of an event when contaminants are easiest to remove and haven't "stuck" or bound to surfaces as integrally as they will with time. These events have also shown that much of the initial decon will be performed by personnel unskilled in decon operations. The methods need to be simple so that training is minimal and the workforce can get up and running quickly.

This review found three documents that are extremely useful for understanding radiological decontamination. The DOE Decommissioning Handbook (DOE, 1994, http://www.efcog.org/wg/dd_fe/docs/Decommissioning%20Handbook.pdf) provides a thorough discussion of decontamination options and techniques for nuclear facilities. A state-of-the-art review of decon techniques is found in The Technology Reference Guide for Radiologically Contaminated Surfaces (EPA, 2006, http://www.epa.gov/radiation/docs/cleanup/402-r-06-003.pdf). Attempts to address many of the issues related to large scale radiological contamination in urban environments have been conducted in Europe under the EURANOS (European approach to nuclear and radiological emergency management and rehabilitation strategies) project (Euranos, 2007; www.euranos.fzk.de).

8.0 REFERENCES

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Acronym Glossary

ALARA	As Low As Reasonably Achievable
ANL	Argonne National Laboratory
ASTM	American Society for Testing and Materials
BNL	Brookhaven National Laboratory
DF	Decontamination Factor
DHS	Department of Homeland Security
DOE	Department Of Energy
DTRA	Defense Threat Reduction Agency
EDTA	EthyleneDiamineTetraacetic Acid
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
EU	European Union
FBI	Federal Bureau of Investigation
GDS	Governmental Decontamination Service
HEPA	High Efficiency Particulate Air-filter
HVAC	Heating, Ventilation and Air Conditioning
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
INL	Idaho National Laboratory
NEA	Nuclear Energy Agency
NHSRC	National Homeland Security Research Center
NYC	New York City
NYCT	New York City Transit
NYPD	New York Police Department
PC	Personal Computer
PPE	Personal Protective Equipment
RDD	Radiological Dispersion Device
RTG	Radioisotope Thermoelectric Generator
TMI	Three Mile Island
UK	United Kingdom
US	United States

APPENDIX A: VENDOR INFORMATION

ID	DECON Process	TRADE NAME	Comments	VENDOR	CITY	STATE	PHONE E-MAIL	HOME PAGE
11	Blasting	PlasBlast	Bead blasting using plastic beads. Claim of 97% of loose contaminants and 85% of fixed contaminants from common tooling and components	Bartlett	Plymouth	MA	800-225-0385	www.bartlettinc.com
67	Blasting	Sponge-Jet	Soft media blasting	Sponge-Jet Inc.	Portsmouth	NH	603-610-7950	http://www.spongejet.com
68	Blasting	Advanced Recyclable Media System (ARMS™)	recyclable fiber reinforced polymer matrix media (sponge)	Solutient Technologies, LLC.	North Canton	OH	330-497-5905	http://www.solutientech.com/services_decontamination.php
17	Blasting - dry ice	Cold Jet	CO2 blasting	Cold Jet, LLC	Loveland	OH	800-337-9423	http://www.coldjet.com
12	Decon engineering		Claims to be the largest supplier of decontamination technicians to the commercial nuclear industry	Bartlett	Plymouth	MA	800-225-0385	www.bartlettinc.com
14	Decon engineering			Burns and Roe	Oradell	NJ	201-265-2000	http://www.roe.com/federal_index.htm
16	Decon engineering		D&D of highly contaminated former nuclear weapons facilities, nuclear	CH2M HILL	Englewood	CO	888-242-6445	http://www.ch2m.com

			reactors, and military and industrial buildings and facilities					
27	Decon engineering	Includes former Duratek, Envirocare and BNG America	full range of services for the decommissioning and remediation of nuclear sites and facilities	Energy Solutions	Salt Lake City	UT	(801) 649-2000	http://www.energysolutions.com
47	Decon Engineering			Parsons	New York	NY	212-266-8300	http://www.parsons.com/govt/nuclear/default.asp
57	Decon Engineering		industry leader in the engineering and application of specialty surface decontamination	Qal-Tek Associates	Idaho Falls	ID	888-523-5557	http://www.qaltek.com
61	Decon Engineering		Global and large	URS Corp.	San Francisco	CA	415-774-2700	http://www.urscorp.com
62	Decon Engineering			Cabrera Services	East Hartford	CT	860-569-0095	http://www.cabreraservices.com/
63	Decon Engineering		Some Homeland Security experience	Weston Solutions	West Chester	PA	610-701-3000	http://www.westonsolutions.com
73	Decon Engineering		Large engineering firm with disaster relief background	The Shaw Group Inc.	Baton Rouge	LA	225-932-2500	http://www.shawgrp.com
44	Decon equipment	various	Decon vehicles, trailers and skid mount units	Modec, Inc	Denver	CO	800-967-7887	http://www.deconsolutions.com/index.html
29	Decon foam - INL licensed	Rad Release	Company also supplies full decon services	Environmental Alternatives, Inc.	Keene	NH	603-352-3888	http://www.eai-inc.com

31	Decon foam followed by clay paste	NA	On concrete, the foam removed about 30 percent of the radioactive contaminant and within six weeks after paste application, approximately 89 percent removal was obtained	Idaho National Laboratory		ID	208-526-3876	http://www.techcommjournal.com/index.php?articleID=289
2	Decon Gel	SuperGel	Polymer gel with nanoparticles	Argonne National Laboratory		IL	630-252-5580	http://www.anl.gov/Media_Center/News/2004/news040702.htm
30	Decon shower	FSI® DAT Hazmat Decon Shower Systems	Portable showers may be useful for parts washings	FSI	Sheffield Lake	OH	440- 949-2400	http://www.fsinorth.com
10	Decon solution	BY*PAS	Manufacturers claim safe for concrete and tile floors, painted surfaces, fabrics, plastics, rubber, neoprene, nylon, glass and most metals	Bartlett	Plymouth	MA	800-225-0385	www.bartlettinc.com
13	Decon solution	Radiacwash	Contains chelators	Biodex Medical Systems, Inc.	Shirley	NY	800-224-6339	http://www.biodex.com/radio/radiopharmacy/decontam_100.htm
36	Decon solution	Intek Decon Solution ND	Decon solutions Paper in WM'06 R.W. Durante	Intek Technology	Fairfax	VA	703-691-4110	http://intekmarine.com
58	Decon solution	Quick Decon™ Mass Effect™ Radiation Decon Solutions™ RadDecon	Three different and specific solutions along with resins. Paper in WM'04 – J.H.	Radiation Decontamination Solutions, LLC	Oldsmar	FL	813-854-5100	http://www.raddecon.com

			Kuperus					
28	Decon solution - three part	TechXtract Previously RadPro	Non-hazardous, multistep decon washing, complex formulation of inorganic acids, organic acids and organic compounds, requires expert user	Environmental Alternatives, Inc.	Keene	NH	603-352-3888	http://www.eai-inc.com http://techxtract.com/about_frame.html
1	Electrochemical and strippable coating	ElectroDecon™	uses an electrochemical strippable coating	ADA Technologies, Inc.	Littleton	CO	303-792-5615	http://ada.communityisoft.com/
8	Fix in place or strippable coating	Fogging Technology	Uses aerosol generator so can capture airborne contaminants	Bartlett	Plymouth	MA	800-225-0385	www.bartlettinc.com
4	Fix-in-place	PBS- Polymeric Barrier System	Not really decontamination, anti-dispersion	Bartlett	Plymouth	MA	800-225-0385	www.bartlettinc.com
32	Fix-in-place	CC Fix	permanently fix contamination on surfaces	Instacote	Erie	MI	734-847 - 5260	http://instacote.com
35	Fix-in-place	CC Epoxy SP	Durable to truck traffic	Instacote	Erie	MI	734-847 - 5260	http://instacote.com
37	Fix-in-place and strippable	IsoFIX-RC	Evaluated by PNNL, holds in pace for at least a few months. Is designed for application using conventional firefighting foam systems	Isotron	Seattle	WA	877-632-1110	http://www.isotron.net/

33	Fogging	CC Wet	1st step for CC Fix	Instacote	Erie	MI	734-847 - 5260	http://instacote.com
70	Fogging	Passive Aerosol Generator	Fogging to coat airborne and loose contamination	Encapsulation Technologies	Los Angeles	CA	323-266-6531	http://www.fogging.com
72	Fogging	DustBoss	Fogging cannons to reduce airborne particulates	Dust Control Technology	Peoria	IL	800-707-2204	http://www.dustboss.com
5	HEPA filtration	AP-500, AP-1000, etc	Portable HEPA filtration up to 10,000 cfm	Bartlett	Plymouth	MA	800-225-0385	www.bartlettinc.com
52	HEPA filtration	Vac-Pac	Portable HEPA and drumming system	Pentek	Coraopolis	PA	412-262-0725	www.pentekusa.com
6	HEPA vacuum	Minuteman	Wet/dry vacuums in many sizes and configurations	Bartlett	Plymouth	MA	800-225-0385	www.bartlettinc.com
21	HEPA vacuum	Many types including custom		DeMarco Vacuum Corporation	McHenry	IL	800-262-9822	http://www.maxvac.com
22	HEPA vacuum	Many types including custom	Includes battery operated units	Depureco	Shropshire	England	01952 290590	http://www.depureco.co.uk
43	HEPA vacuum	X250, X829, X839, BPV H.E.P.A. (Hako minuteman)	Part of the Hako Group	Minuteman International Inc.	Addison	IL	630-627-6900	http://www.minutemanintl.com/Critical_Filter/CriticalVacs.html
46	HEPA vacuum	Safe-Pak many others		Nilfisk CFM	Malvern	PA	610-647-6420	http://www.nilfiskcfm.com/FindVacuum.aspx
53	HEPA vacuum	RADVAC	Air and electric powered HEPA vacuums and air handling	Power Products and Services Co., Inc.	Georgetown	SC	843-545-0766	http://www.powerproductsonline.com
56	HEPA vacuum	102, 86 and 30 series		Pullman/Holt	Tampa	FL	800-237-7582	http://www.pullman-holt.com/

3	Paint remover	Ready Strip	Non-hazardous	Back To Nature Products Co.	Englishtown	NJ	800-211-5175	http://www.ibacktonature.com
23	Paint remover	404 Rip Strip	Hazardous corrosive alkaline	Diedrich Technologies Inc.	Oak Creek	WI	800-323-3565	http://www.diedrichtechnologies.com
24	Paint remover	Smart Strip™	Non-hazardous	Dumond Chemicals, Inc.	New York	NY	212-869-6350	http://www.dumondchemicals.com/
25	Paint remover	Peel Away® I	Hazardous corrosive alkaline UN1823	Dumond Chemicals, Inc.	New York	NY	212-869-6350	http://www.dumondchemicals.com/
45	Paint remover	EFS-2500	Non-hazardous	Molecular-Tech Coatings Inc.	Maple Ridge	BC, Canada	604-465-8028	http://www.m-tc.com
54	Paint remover	Enviro Klean® Safety Peel 2	Hazardous corrosive alkaline	Prososo, Inc	Lawrence	KS	800-255-4255	http://www.prosoco.com/
55	Paint remover	Enviro Klean® Safety Peel 3	Hazardous ignitability	Prososo, Inc	Lawrence	KS	800-255-4255	http://www.prosoco.com/
9	Pressure washer	Hydrolasers, pressure washers	10000 to 40000 psi units, modular and trailer mounted	Bartlett	Plymouth	MA	800-225-0385	www.bartlettinc.com
19	Pressure washer	Kelly Decon Systems, Kelly cavity decon system		Container Products Corp	Wilmington	NC	910-392-6100	http://www.c-p-c.com/products/kelly_decon_systems.html
26	Pressure washer	Recyclean		Dumond Chemicals, Inc.	New York	NY	212-869-6350	http://www.dumondchemicals.com/html/otherframe.html
40	Pressure washer	Kärcher		Kärcher Commercial	Camas	WA	888-805-9852	http://www.karchercommercial.com/
59	Pressure washer	Many types	Pressure, steam, combos and solution heaters	Sioux Corp.	Beresfords	SD	605-763-3333	http://www.sioux.com
69	Pressure washer	Many models	Heated water pressure washer	Hotsy			800-525-1976	http://www.hotsy.com

74	Protective clothing	Orex	Laundry services, Orex processing, rentals, disposables	EASTERN TECHNOLOGIES, INC.	Ashford	AL	800-467-0547	http://www.easterntechnologies.com also see: http://www.orex.com/products.htm
75	Protective clothing	ProTech UniWear	Laundry services, rentals, disposables	Unitech Services Group	Springfield	MA	413-543-6911	http://www.unitech.ws
60	Respirator service		Provide mobile respirator facility	Unitech Services Group	Springfield	MA	413-543-6911	http://www.unitech.ws/
41	Soil sorting	SS-Series		MACTEC	Alpharetta	GA	770-360-0600	http://www.mactec.com/Services/Construction/SS-Series.aspx
64	Soil washing	Terra Wash		Terra Resources, Ltd.	Palmer	AK	907-746-4983	http://www.terrawash.com
65	Soil washing			BioGenesis Enterprises, Inc.	Springfield	VA	703-913-9700	http://www.biogenesis.com
7	Strippable coating	Stripcoat TLC Free	Non-toxic, non-hazardous, water-based	Bartlett	Plymouth	MA	800-225-0385	www.bartlettinc.com
15	Strippable coating	Alara 1146	Single package, water-borne vinyl, strippable coating	Carboline	St, Louis	MO	314-644-1000	http://www.carboline.com
20	Strippable coating	DeconGel	A one component, water-based, broad application, strippable decontamination hydrogel	Cellular Bioengineering, Inc	Honolulu	HI	808-949-2208	http://www.decongel.com
34	Strippable coating	CC Strip		Instacote	Erie	MI	734-847 - 5260	http://instacote.com
38	Strippable coating	Radblock	RADBlock can be applied before or after a contamination	Isotron	Seattle	WA	877-632-1110	http://www.isotron.net/

			event					
39	Strippable coating	Orion SC		Isotron	Seattle	WA	877-632-1110	http://www.isotron.net/
48	Surface removal - scabbler	Moose	Robotic scabbler with HEPA and drumming built in	Pentek	Coraopolis	PA	412-262-0725	www.pentekusa.com
51	Surface removal - scabbler	Roto-Peen	Hand held scabblers	Pentek	Coraopolis	PA	412-262-0725	www.pentekusa.com
66	Surface removal - scabbler	En-vac Robotic Wall Scabbler	Need unobstructed wall access	MAR-COM, Inc.	Portland	OR	503-285-5871	
71	Surface removal - scabbler	Wall Walker	Robotic wall scabbler	Pentek	Coraopolis	PA	412-262-0725	www.pentekusa.com
49	Surface removal - scabbler	Squirrel I, Squirrel II, Squirrel III	Pneumatic scabblers with one to three high-speed, reciprocating tungsten carbide tipped pistons	Pentek	Coraopolis	PA	412-262-0725	www.pentekusa.com
50	Surface removal - scabbler	Corner-Cutter	Hand-held scabbler for odd shape surfaces	Pentek	Coraopolis	PA	412-262-0725	www.pentekusa.com
42	Surface removal - shaver	model DTF25	self-propelled, electric-powered, concrete diamond-shaving machine	Marcrist Industries Limited	Doncaster	England	44 (0) 1302 890 888	http://www.marcrist.co.uk/
18	Waste containers		Containers, compactors, Decon systems	Container Products Corp	Wilmington	NC	910-392-6100	http://www.c-p-c.com/home.html

APPENDIX B: TECHNOLOGY PERFORMANCE

This appendix presents the performance data found for each of the decontamination technologies. Information was collected on the following categories:

Production rate -	area (volume) treated per unit time
Crew size -	number of people required to operate the equipment. (may or may not include Health Physics support).
Unit cost -	cost to purchase the unit
Production cost -	cost per unit area
Waste production -	volume of waste generated per unit area (volume) treated.
Radionuclides treated -	mechanical treatment techniques treat all radionuclides, chemical techniques may be radionuclide specific.
DF -	decontamination factor
Special note -	

Much of this data is obtained from the manufacturers and must be viewed cautiously. This is particularly true with respect to the decontamination factor values which can be highly variable due to different chemical forms of the nuclides or different materials. If a category is blank or not listed, the information is not available. In viewing the table, the absence of data becomes quite apparent.

Decon Technologies Cost and Performance Data

Treatment Technology	Production Rate	Crew Size	Unit Cost	Production Cost	Waste Production	Nuclide	Decon Factor	Comments
Chemical (all work best on metals and non-porous surfaces)								
TechXtract (formerly RadPro)	20 ft^2/hr	2 + 1 HPT	Chemicals- mobile lab- 1tech $25,000/60 hour week.	$27.50/$ft^2$	0.1 gal/ft^2	Can be tailored to specific nuclides.	DF = 10 – 30 loose cont on concrete. DF = 3 fixed cont on concrete.	3 step multi-component process. Requires hand scrubbing for best results.

Radiacwash			\$16/gal				Linoleum – DF = 4 I-131 DF =2,Tl-201 DF = 2, Tc-99 Stainless Steel DF = 2 I-131, Tl-201, and Tc-99 Concrete; DF = 1 for I-131, Tl-201, and Tc-99.	
Deconsolutions							Linoleum – DF = 14 I-131 DF =8,Tl-201 DF = 18 Tc-99 Stainless Steel DF = 74 I-131 DF =21,Tl-201 DF = 17 Tc-99 Concrete; DF = 1 for I-131, Tl-201, and Tc-99.	
Acid Washing				\$2/ft^2 (1997)			HCL on SS & CrMo DF = 10; HNO_3 on SS & CrMo DF = 10; H_3PO_4 on CS & Brass DF = 5- 37. Oxalic Acid DF = 3 – 20; Oxalate Peroxide (200C) DF = 100 - 1000	
Chelators & Organic Acids				\$1/ft^2 (1997)				Wastes are liquids with chelators that must be destroyed by oxidation prior to disposal.
Foams & Gels				\$2/ft^2				Reduced liquid waste due to

				(1997)				longer contact time.
INL Decon Foam							DF = 9 for Cs on Concrete; DF = 33 for Cs on Marble	Not yet licensed.
HEPA Vacuuming								
Dry	125 ft^2/hr		€90,000 Eur (2003) (roadway vacuum)	\$2/ft^2 (1997)		All	2 – 3 if early.	Depends strongly on the physical/chemical form. Very effective for collecting particles > 0.3 micron in diameter.
Steam Vacuum Cleaning								
Steam Vacuuming	136 ft^2/hr			\$2.74 – 13.64/ft^2 (1997)	0.34 gal/ft^2			
Kelly Decontami-nation SVC System	145 ft^2/hr	3			0.39 gal/ft^2			
Hotsy Model 550B HPWC	360 ft^2/hr	2	\$5530 (1999).	\$3.63/ ft^2	0.36 gal/ft^2			
Strippable Coatings								
ALARA 1146	130 ft^2/hr	2 – 3	\$96/gal (1999)	4.83/ft^{2*}		Loose cont.	For α contamination, DF = 8 on steel, DF = 5 on painted steel, DF=20 on painted equipment, DF=6 on epoxy. For β,γ cont. DF = 6 on steel, DF=9 on painted steel, DF = 9 on painted equipment, DF=3 on epoxy,	Coverage 2 – 2.5 m^2/gal. * Cost includes PPE and waste disposal

							DF= 6 on loose CS on SS, DF = 2 on fixed Cs on SS	
Isotron Orion SC	4.6 m^2/hr/coat apply; 1.6 m^2/hr/coat removal (on small coupons)	1 -2	$175/gal	$58.84/ m^2/coat. (2008)**	0.5 kg/m^2 treated.	All loose contamin ation.	DF = 4 – 5 for Cs on concrete.	** Manufacturer suggests 3 coats.
Stripcoat TLC	12 m^2/hr/coat apply; 4.9 m^2/hr/coat removal (on small coupons)	1 - 2	$84/gal	$17.67 m^2/coat (2008)**	0.26 kg/m^2 treated.	All loose contamin ation.	DF=8 loose Cs on SS; DF = 2 fixed Cs on SS; DF = 1.5 Cs on concrete; DF = 10 loose TRU on aluminum DF = 2 loose TRU on Plexiglass, DF=9, loose TRU on SS.	** Manufacturer suggests 3 coats.
RADblock DB			$150 – 200/gal (2008)	$4.5 - $6 /$ft^2$				Coverage 3.1 m^2/gal. Contains ammonia and requires ammonia respirator for application. Shelf life 10 months.
InstaCote							Loose TRU: DF = 20 on SS DF = 2 on Plexiglass; DF = 10 on Aluminum.	
Electrodecon							Stainless Steel DF = 12 - 50 for fixed Cs, DF = 9 – 20 for fixed Zr.	
Decon Gel			$122/gal				Pu on cast steel,	Requires 3 applications.

			($6500/ 200 l drum) (2008)				DF = 2 after one app; DF = 130 after 3 app; Pu on lexan DF = 210 after 2 app; Pu on aluminum, DF = 165 after 3 app.	
Pressure Washing								
Hydroblasting	40 yd^2/hr @ 3/16” to 3/8”			$3.63/$ft^2$ (1999)		All		Removal action. Some soluble radionuclides can be driven deeper into porous materials.
Blasting Technologies								
ARMS	40 – 125 ft^2/hr	3- 4 plus 1 HPT	$35,000 (1998)	$1.52 ft^2 (1998)	1 ft^3 per 265ft^2 treated.	All		Surface removal. Noise 130 dB is a worker safety issue.
Sponge Jet	50 – 100 ft^2/hr			$4.6/$ft^2$ (1999)	0.01 ft^3 per ft^2 treated.	All		Can coat sponge with radionuclide specific solution. Noise 106 - 113 dB is a worker safety issue.
CO_2 Ice Blasting						All	DF = 6 to 14 for loose contamination; 1.5 to 10 for fixed.	
Grit Blasting			€3,000 EUR (2003)			All	DF = 1 - 30	
Scabblers, Cutters, and Grinders								
General Floor Scabbler	200 ft^2/hr @1/32”; 30 to 40 ft^2/hr @ 1/16”; 14 – 24	2 - 3		$2 – $16/$ft^2$		All	DF = 14 to free release on various surfaces.	Surface removal. Rate strongly depends on thickness removed

	ft^2/hr @ ¼" 7 – 12 ft^2/hr @ ½" and 3 to 6 ft^2/hr @ 1"							
General Asphalt Planer (cutter)	1000 m^2/hr at 1 cm.	4	€70,000 EUR (2003)		15 kg/m^2 for 1 cm of asphalt removal.	All	Asphalt DF = 5 to 10	Chernobyl data. Actions taken several years after deposition.
Moose	130 ft^2/hr @ 1/8" ; 275 – 450 ft^2/hr @ 1/16"	2	$165,000 (1998)	$6.68/$ft^2$ (1998)	1 ft^3 for 16.7 ft^2 @ 1/8 " removal.		DF >30 at ¼" removal.	Noise is a worker safety issue (106 dB). Rental $8125/week with $2400 parts and $65 per 23 gallon drum (1998 dollars)
Wall Walker	10 ft^2/hr @ 0.3 "; 20 ft^2/hr @0.13" for brick.	2	$255,000 (1997)		0.3 – 0.5 ft^3/ft^2 treated at 1/8" concrete removal	All		Noise is a worker safety issue (104 dB) at scabbler head; 90 dB at 10 feet). Bits need replacement every 2400 ft^2 ($300/set; 1997 dollars).
En Wav Wall Scabbler	146 ft^2/hr open walls; 23 ft^2/hr obstructed.		$390,000 (2001)	$52.74/hr (2001)	0.11 ft^3/ft^2	All		
Centrifugal Shot Blasting	18 ft^2/hr	3 + 1HP T		$34.25/$ft^2$ (2000)	1.5 gal of solid/ft^2	All		Noise is a worker safety issue
Concrete Shaver (Planer)	50 – 128 ft^2/hr	3	$20,000	$14.21/$ft^2$ (1998)		All		Replacement blades $7500 (1998 dollars). Blade life 20,000 ft^2. Noise is a worker safety issue (98 dB).
Hand-held	48 ft^2/hr @	2	$650	$2.92/$ft^2$		All		Replacement grinding wheel

Concrete Grinder	1/16”		(1998)	(1998)				$205,wheel life 500 ft^2.
Hand-held Concrete Scabbler	12 ft^2/hr @ 1/16”	1	$8800 (1998)	$10.37/$ft^2$ (1998)		All		Replacement scabbling blades $335, blade life 2500 ft^2.
Hand-Held Concrete Spaller	14 ft^2/hr @ 1/8 - 2”	2		$18.52/$ft^2$ (1998)		All		Requires pre-drilling holes on 8” centers.
Hand-Held Concrete Scaler	12 ft^2/hr @ 1/16”	1	$1250 (1998)	$10.47/$ft^2$				Replacement set of flaps $175, flap life 480 ft^2.
Roto-Peen	40 ft^2/hr	3				All	Concrete DF = 2 – 6	
Soil Sorting								
	10 – 20 acres/day (30 to 300 tons per hour)			$20 to $80 per ton.		All		Waste minimization technique. Limited to gamma radiation where detectors are fast enough; large staging area
Soil Washing								
	20 tons/hr for a small unit.	5		$200 - $500/$m^3$				Does not work well with a large fraction of fines that are typically found in the first few inches of top soil.
Fixatives								
Isofix-RC				2 L/m^2 of soil.				Not decon. Temporary fix in place that has been used for soils. Kept Cs and Co from migrating for at least 3 months.
Laundering of Clothing								
Water and Detergent						All	Cotton Cs, DF = 250; Sr,Ba, DF =140; Ce, DF = 100; I, DF = 10; Ru,	Higher values are for soluble nuclides on fabric used around Chernobyl. Particulate

							Zr, DF = 3 to 4.	contamination (UO_2 fuel fragments) was sparingly soluble and the Cs, Ce, Ru, Nb and Zr DFs were 8 to 13 and were the result of mechanical removal of particles not dissolution. The radionuclide ratios remained mostly unchanged.

Information from this table was collected from the following references:

CHEMICAL
TechXtract (formerly RadPro) [Environmental Alternatives, Inc. 2003, EPA 2006, Tripp 1996]
Radiacwash [Kuperus 2004]
Deconsolutions
Acid washing [DOE 1997, EPA 2006]
Chelators & Organic Acids [DOE 1997, EPA 2006]
Redox Solutions [DOE 1997, EPA 2006]
Foams & Gels [DOE 1997, EPA 2006]
INL Decon Foam [INL Factsheet]

HEPA VACUUMING
Dry vacuuming [DOE 1997]

STEAM VACUUM CLEANING
Steam vacuuming [DOE 1997, DOE 2000]
Kelly Decontamination SVC System [DOE 1999b, DOE 2000, EAI 2003, EPA 2006]
Hotsy Model 550B HPWC [DOE 1999a, DOE 1999a, DOE 1999b]

STRIPPABLE COATINGS
ALARA 1146 [DOE 2000, Demmer 2005, Archibald 1999]
Isotron Orion SC [James 2008b]
Stripcoat TLC [James 2008a, Demmer 2005, Archibald 1999, McFee 2002]
RADblock DB
InstaCote [McFee 2002]
Electrodecon [Demmer 2005]
Decon Gel [Sutton 2008]

PRESSURE WASHING
Hydroblasting [DOE 1994, EPA 2006, Eged 2003]

BLASTING TECHNOLOGIES
ARMS [DOE 1998f]
CO_2 Ice Blasting [Tripp 1996, Oceaneering International, Inc. 1998]
Grit Blasting [Eged 2003]

SCABBLERS, CUTTERS and GRINDERS
General Floor Scabbler [DOE 1998b, DOE 1998c, DOE 1998d, DOE 1998e, DOE 1998g, EPA 2006, Tripp 1996]
General Asphalt Planer (cutter) [Roed 1998]
Moose [DOE 1998e]
Wall Walker [Ebadian 1997]
En Wav Wall Scabbler [DOE 2001, EAI 2003, EPA 2006]
Centrifugal Shot Blasting [DOE 1998a, EPA 2006]
Concrete Shaver (planer) [DOE 1998a, DOE 1998c, EPA 2006]
Hand-held Concrete Grinder [DOE 1998b, EPA 2006, Eged 2003]
Hand-held Concrete Scabbler [DOE 1998b, DOE 1998d, DOE 2001]
Hand-held Concrete Spaller [DOE 1998d]
Hand-held Concrete Scaler [DOE 1998b, DOE 1998d]
Roto-Peen [DOE 1998g]

FIXATIVES
Isofix-RC [Fritz 2008]

LAUNDERING OF CLOTHING **[**Klochkov 1990**]**