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Conceptual Design for a Land Decontamination Robot

Gregory P. Zimmerman

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FOR THE UNITED STATES
DEPARTMENT OF ENERGY

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CONCEPTUAL DESIGN FOR A LAND DECONTAMINATION ROBOT

Gregory P. Zimmerman

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ABSTRACT

This study is directed toward the conceptual development of a machine which could be used in the cleanup and/or treatment of land areas contaminated by a nuclear accident. Specifically, a system of hardware components which could remove radioactive, fallout-type contamination from rolling terrain, such as agricultural farmland, has been identified. This concept is a mobile system which is remotely operable due to the hazard presented by gamma-emitting radioactive materials. This system could therefore be referred to as "a land decontamination robot."

A survey of vendors has identified a set of hardware components which are available "off-the-shelf;" that is, they are commercially available and not special development items. These components include: a large vacuum loader unit, a vehicle for moving the unit around the contaminated area, an industrial robot arm for moving the vacuum nozzle over the contaminated surface, an electronic remote control system, and a position determination system to assist with steering the vehicle on subsequent passes around the contaminated area. Cost estimates were developed for each component.

Two versions of the "decontamination robot" were considered: (1) a truck-mounted vacuum loader unit, and (2) a trailer-mounted unit pulled by a bulldozer-type crawler. The costs of the hardware components for the truck-mounted unit are about $450,000; the trailer-mounted unit is about 10% more expensive. These costs are only the hardware costs; the costs associated with integrating this hardware into an operating decontamination system have not been included. Also not included are the costs of programming the sweeping motion of the robot arm and of any computer equipment or software necessary to process and display information relating to the vehicle's position within the contaminated area. It is assumed that these costs will at least equal the cost of the hardware and will thus move the total cost for the complete land decontamination robot system to a minimum of $1,000,000.

EXECUTIVE SUMMARY

In the event that large areas of land were to become contaminated with radioactive material from a Chernobyl-type nuclear power plant accident, an accident involving a nuclear weapon, or some other release of fission products or fissionable material, it would be desirable to have mechanisms for safely and economically removing that contamination. A single method of performing such decontamination does not exist due to the diversity of land areas—paved areas, lawns, orchards, agricultural farmland, and woodlands—which could possibly be involved.

This study is directed toward the conceptual development of a machine which could be used to decontaminate that land area with an important long-term economical value: agricultural farmland. Specifically, a system of hardware components is sought which could remove radioactive, fallout-type contamination from rolling terrain. This system would have to be mobile and would have to be remotely operable due to the hazard presented by gamma-emitting radioactive materials. This system could therefore be referred to as a "land decontamination robot." It is highly desirable that each of the components of this system be available "off-the-shelf," that is, commercially available and not a special development item.

Because of previous experience in vacuum cleaning technology at the Nevada Test Site, a vacuum unit was selected in this study for development of a conceptual design for the land decontamination robot. Vacuuming can be used to remove only the uppermost layer of soil. Devegetation can be coupled with a vacuuming operation; the plant material can be vacuumed along with the soil. Vacuuming need not remove sufficient topsoil to create future problems with soil fertility; in addition, the spoil produced by vacuuming is significantly less than other soil removal techniques. This minimizes soil disposal problems. Furthermore, the operational concept of this machine can be applied to other decontamination methods (such as plowing or scraping) without significant impact upon the elements considered in this particular design concept.

The specific concept in this study involves the use of a commercial, truck- or trailer-mounted vacuum loader unit with an industrial robot arm (mounted on the front

bumper of the vehicle) to position a vacuum nozzle for removing the top layer of soil from a contaminated land area. The specific hardware component requirements for the decontamination system in this study include:

- Vacuum Loader Unit. Must be a large, commercially available unit [12 m^3 (16 yd^3) minimum capacity] with self-contained engine and three-stage filter for exhaust air.

- Vehicle. To be used for moving the vacuum unit across rolling, agricultural terrain. May be either a truck (for a truck-mounted vacuum unit) or a bulldozer-type crawler (to pull a trailer-mounted vacuum unit). Vehicle must be able to (1) move the vacuum unit into position, (2) stop while the vacuum unit is cleaning a small area, and (3) move the vacuum unit into an adjacent position for cleaning up the next small area.

- Industrial Robot Arm. This arm is to be mounted to the front (bumper) of the vehicle; the vacuum head (nozzle/sweeper) is to be attached to the wrist of the arm. Operation of this arm will require the same freedom of motion as can be found in a standard backhoe linkage. Once the vehicle has been moved into position and stopped, the arm is to sweep over a predefined area while removing only the top few centimeters of soil. Capability for a preprogrammed sweeping pattern is to be included in the electronic controls for the robot arm.

- Remote-Control System. Must be able to provide control of the vehicle (engine, brakes, steering, etc.) as well as the vacuum unit (engine, air flow control, dumping, etc.). Must also have some control (such as, start and stop) over the preprogrammed robot arm vacuuming operation. Audio and video feedback are required. The control unit(s) must be located at a safe distance from the contaminated area.

- Position Determination System. Since the vehicle will be used to decontaminate an expansive land area, some method must be provided to position the vehicle accurately during successive passes around that area; a tracking/positioning system is required. This system need not be automatically invoked, since some manual adjustment of the positioning sensors can be made by the operators while the vehicle is stopped and performing the vacuuming operation. Data output from this system must be coupled with maps or other geographic data to assist the operators in moving the vehicle to the next area to be cleaned. [It was found that electronic positioning and distance measuring instruments as used in modern surveying practice are the least expensive hardware items which satisfy this requirement.]

- Transportation System. Must be used to move the decontamination robot (vacuum loader, vehicle, and robot arm) from its normal place of storage to the cleanup area. This system can consist of trailers for hauling the robot, or the robot might move under its own power over existing roads, if adequate highway speeds and safety considerations can be achieved.

- Soil Off-Loading System. To be used for removing contaminated soil from the vacuum unit hopper and packaging/processing it for proper disposal.

A conceptual design and cost estimate were developed for such a system. Commercially available systems were investigated for their suitability in providing remote vehicle control, vehicle position determination/tracking, robotic vacuum operation, and dumping and handling of the collected radioactive soil. This effort was not intended to be a development project, but rather a conceptual design project to determine the feasibility and approximate costs for the hardware components of such a system. Design details, specifications, and estimated costs for each component were developed. Because of the variety of choices available, neither the transportation system or the soil off-loading system were included in this cost study.

Table S-1 summarizes the estimated, individual component costs, as outlined above, and shows the estimated total cost of this conceptual design for a land decontamination robot. Two versions are considered: (1) a truck-mounted vacuum loader, and (2) a trailer-mounted unit pulled by a bulldozer. The costs of the two versions are basically the same, except for the vehicles and the remote controls to operate them.

The truck is the cheaper of the two vehicles, but the remote controls for a wheeled vehicle are not generally available and are extremely expensive. The bulldozer is an expensive piece of machinery, but it is cheaper and easier to remotely control; it would also be more likely to successfully navigate over any type of agricultural terrain that might be encountered.

The total hardware cost of the land decontamination robot, from Table S-1, is between $411,000 and $477,000 for the truck-mounted version and between $451,000 and $522,000 for the trailer-mounted version. The range of these numbers for a

Table S-1. Summary of estimated component costs for a land decontamination robot system

Item	Truck-Mounted Unit	Trailer-Mounted Unit
Vacuum Loader Unit	$85,000 to $100,000	$85,000 to $100,000
Installation	$5,000	$5,000
Accessories	$1,500	$1,500
Safety Options	$2,500	$2,500
Vehicle	$45,000 to $60,000 (truck)	$120,000 to $140,000 (bulldozer-type crawler) $15,000 (trailer) $15,000 (engine and accessories for vacuum unit)
Remote Controls		
For vehicle control	$110,000	$45,000
For vacuum unit/video	$90,000	$90,000
Robot Arm	$50,000 to $75,000	$50,000 to $75,000
Position Determination System	$22,000 to $33,000	$22,000 to $33,000
TOTAL	$411,000 to $477,000	$451,000 to $522,000

particular version is about 15% of the total cost; however, this uncertainty should be considered acceptable for the preliminary nature of this conceptual design.

The costs in Table S-1 are only hardware costs; the costs associated with integrating this hardware into an operating decontamination system have not been included. Also not included are the costs of programming the robot arm and of any computer equipment or software necessary to process and display information relating to the vehicle's position in the contaminated area. It can be assumed that these costs will at least equal the cost of the hardware in Table S-1 and will thus move the total cost for the complete land decontamination robot system to a minimum of $1,000,000. This total cost is sufficiently high that the land decontamination robot cannot be considered to be an expendable system.

The concept and cost estimates presented in this study have included the use of both electric components and hydraulic components. It is not the intention of this study to advocate a preference for one component type over the other. Clearly, there are specific instances where one would have a marked advantage. For example, a hydraulic robot arm is cheaper and stronger than an electric one, but leaking hydraulic fluids might present more difficult equipment decontamination problems. The choice of vehicle types might also influence whether electric or hydraulic actuators are chosen for effecting the onboard remote control; for instance, a hydraulic actuator system could be readily adapted to control of a bulldozer-type crawler by connecting the actuators as a parasitic load on the vehicle's existing hydraulic system.

Some additional thought must be given to decontamination of the vehicle itself and to recovery of the unit in the event of a mechanical breakdown. Disposal of the soil from the contaminated area was not addressed in this study. It is hoped that the basic concept and cost estimates developed in this study will be used as a starting point for additional investigation into the possible development of such a decontamination machine.

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1. INTRODUCTION

The U.S. Department of Energy (DOE), the Nuclear Regulatory Commission, and the Environmental Protection Agency have responsibilities which relate to the cleanup and/or treatment of land areas contaminated by a nuclear accident. In the event that large areas of land were to become contaminated with radioactive material from a Chernobyl-type nuclear power plant accident, an accident involving a nuclear weapon, or some other release of fission products or fissionable material, it would be desirable to have mechanisms for safely and economically removing that contamination. A single method of performing such decontamination does not exist due to the diversity of land areas—paved areas, lawns, orchards, agricultural farmland, and woodlands—which could possibly be involved.

This study is directed toward the conceptual development of a unit which could be used to decontaminate that land area with an important long-term economical value: agricultural farmland. Specifically, a system of hardware components is sought which could remove radioactive, fallout-type contamination from rolling terrain. This system would have to be mobile and would have to be remotely operable due to the hazard presented by gamma-emitting radioactive materials. This system could therefore be referred to as a land decontamination robot. It is economically desirable that each of the components of this system be available "off-the-shelf;" that is, commercially available, and not a special development item.

2. BACKGROUND

Even before large-scale radioactive decontamination efforts were begun at Chernobyl in the Soviet Ukraine and at the Johnston Atoll in the Pacific Test Range (Kochen and Blakeslee 1986), and prior to the monumental facility decontamination at Three Mile Island (King and Opelka 1982), the Soviet Union had amassed an unenviable amount of experience in dealing with large areas of radioactively contaminated land.

In September 1957 in the Soviet Urals—south of the city of Sverdlovsk and closer to the city of Kyshtym—a nuclear accident involved the wide-spread release of stored, reprocessed, long-lived fission wastes from a tank at an atomic weapons plant. After years of silence on the incident, the Soviet Union has acknowledged that a radioactive trail 105 km (65 miles) long and 8 to 9 km (about 5 miles) wide resulted from the accident (Associated Press 1989). It has been estimated that 2 million curies of radioactive elements were released (Associated Press 1989) and that a contamination level of 1 mCi of Sr-90 (the chosen reference nuclide) per square meter was distributed over the affected area (Trabalka, Eyman, and Auerbach 1979; 1980).

The Soviet approach to the decontamination of land is to use equipment that is generally available in the agricultural and construction industries and to employ techniques that are the most cost effective (Medvedev 1979). One of the more effective techniques has been to completely remove the top layer of soil by mechanical scraping. Road scrapers have apparently been used for this purpose.

Soviet estimates for the decontamination of agricultural land (with good physical properties) using their most effective equipment were about 0.5 km^2 per year with about 100 working days per year due to equipment maintenance and to weather limitations (Trabalka 1981). This is equivalent to only about 4000 to 6000 m^2 (1 to 1.5 acres) per working day. The Soviets found that deep plowing (70 cm depth) was the most effective method of soil decontamination. They achieved a soil decontamination factor of about ten. However, they found that deep plowing was not a perfect technique. Plowing does not result in adequate turnover of soil layers; mixing of the layers is the result. Long-term soil fertility might also be affected by deep plowing.

There is additional evidence that large portions of the area near Kyshtym were completely abandoned and fenced in or otherwise restricted to the general public. The piles of topsoil were called "graveyards of the earth" by Soviet emigres from the area (Medvedev 1979).

Baes et al. (1986) have discussed the long-term problems associated with contaminated land. They have concluded that several decontamination methods are available which would preserve the economic value of agriculturally important land; better decontamination methods are available than those which severely affect soil fertility and/or those which are as drastic as creating "graveyards of the earth."

There are several methods for accomplishing the recovery of large areas of contamined land, including scraping, plowing, vacuuming, and the application of fixatives or other chemical agents to the soil (International Atomic Energy Agency 1979). Estimates of the costs of these techniques are available; Tawil et al. (1985) at Pacific Northwest Laboratory have developed a reference database for use in evaluating nuclear accident consequences to off-site areas. This database contains information relating to the application of decontamination methods to surfaces and to the costs of such methods. Over 340 methods have been defined for 22 different surfaces. For each method, the reference database includes:

- the costs of applying the methods;
- the efficiencies of contaminant removal;
- the rate at which the methods can be applied;
- the quantity and type of labor, equipment, and major materials required;
- the costs for labor, equipment, fuel and materials; and
- the quantity of contaminated material requiring disposal.

Using this information, Tawil and his coworkers designed a computer code, named DECON, to facilitate the planning of decontamination activities as well as to provide estimates of decontamination costs and property losses. The DECON program also contains strategy information concerning the priority which should be given to various types of simultaneously contaminated land areas and when those decontamination operations should be scheduled.

Dick and Baker (1967) conducted a study on the deposition of actual nuclear weapon fallout on vegetated areas. Plutonium concentrations on five grass pad areas (test areas subjected to nuclear fallout) were measured. The contamination was consistently higher on grassy areas than on adjacent bare soil areas. Plutonium is apparently trapped by blades of grass; grass tends to catch more plutonium, hold it more tenaciously, and prevent it from being resuspended. This report also investigated decontamination methods and found that disking is not as effective as plowing, since much of the contamination remains on the surface. Plowing tends to turn the contamination under the furrow. Burial action in plowing can be enhanced by first wetting the surface to prevent surface dust from rising into the air and resettling on an adjacent cleaned furrow.

Dick and Baker (1967) also addressed the decontamination of the equipment used to clean up the land areas. All vehicles used in the clean-up operations were decontaminated to below U.S. Atomic Enegy Commission acceptable levels. One thorough hosing with water was sufficient to do the job. Oil on truck surfaces presented the only problem. They also recommended cleaning of the engine air filters as part of the decontamination process.

Orcutt (1982) describes a test of a vacuum system to decontaminate land. A 12- by 108-m (39- by 355-ft) area was first devegetated with a Hoffco "Whizz Witch (tm)" (similar to a lawn-type string trimmer). A standard, truck-mounted vacuum loader unit, with a pavement cleaning nozzle attached to the rear of the truck, was then used for removal of the contaminated soil (see Fig. 2-1). The vacuum unit removed soil to a depth of 5 to 6.5 cm (2 to 2.5 in.). Four team members were required to operate this system (with two of these people operating the nozzle and vacuum hose). Spikes or teeth on the nozzle inlet pushed rocks away and also loosened the soil. It was found that a disc or harrow was also helpful for loosening the soil before beginning the vacuuming operation. One disadvantage of the rear-mounted vacuum nozzle was that the truck tires compacted the soil; this required additional clean-up effort.

Other methods of decontamination using existing equipment are available (International Atomic Energy Agency 1979). For example, street sweepers have been used in Costa Rica to clean up volcanic ash which had characteristics similar to nuclear weapon fallout (Clark and Lee 1965). Barbier (1981) has also presented a survey of

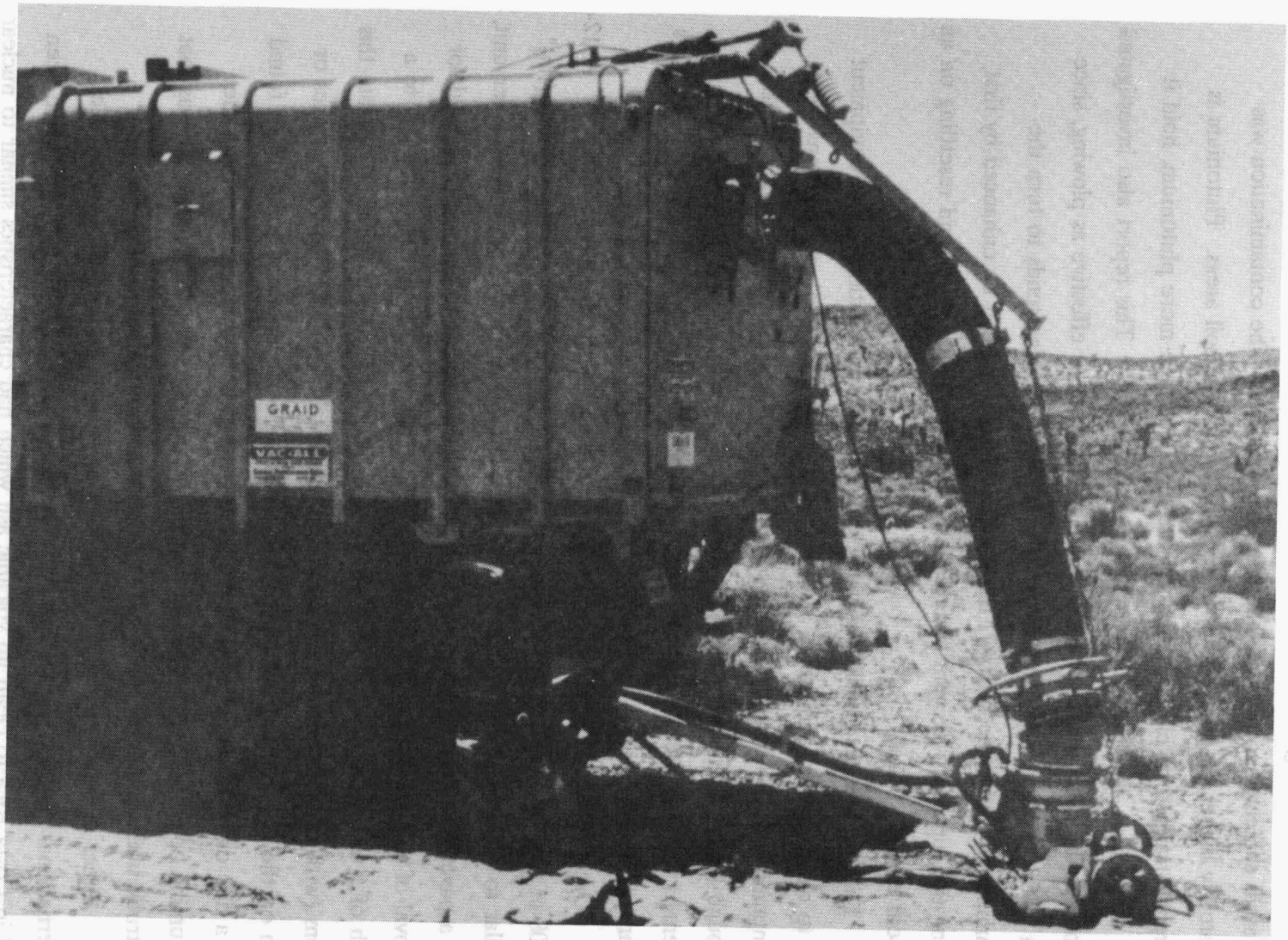

Fig. 2-1. Truck-mounted vacuum loader unit with pavement cleaning nozzle attachment in rear.

industrial, construction, and mining equipment which could be used for land decontamination.

3. CONCEPTUAL DESIGN

Because of the previous experience in vacuum cleaning technology (Manning 1986; Orcutt 1982), a vacuum unit was selected in this study for development of a conceptual land decontamination robot design. Vacuuming can be used to remove only the uppermost layer of soil; devegetation can be coupled with a vacuuming operation and the plant material vacuumed along with the soil. Vacuuming need not remove sufficient topsoil to create future problems with soil fertility; in addition, the spoil produced by vacuuming is significantly less than other soil removal techniques. This minimizes soil disposal costs which usually dominate decontamination operations. Furthermore, the operational concept of this machine can be applied to other decontamination methods (such as plowing or scraping) without significant impact upon the elements considered in this particular design.

The specific concept in this study involves the use of a commercial, truck- or trailer-mounted vacuum loader unit with an industrial robot arm (mounted on the front bumper of the vehicle) to operate a vacuum nozzle for removing the top layer of soil from a contaminated land area. The specific requirements for the decontamination system in this study include:

- Vacuum Loader Unit. Must be a large [12 m^3 (16 yd^3) minimum capacity], commercially available unit with self-contained engine and three-stage filter for exhaust air.

- Vehicle. To be used for moving the vacuum unit across rolling, agricultural terrain. May be either a truck (for a truck-mounted vacuum unit) or a bulldozer-type crawler (to pull a trailer-mounted vacuum unit). Vehicle must be able to (1) move the vacuum unit into position, (2) stop while the vacuum unit is cleaning a small area, and (3) move the vacuum unit into an adjacent position for cleaning up the next small area.

- Industrial Robot Arm. This arm is to be mounted to the front (bumper) of the vehicle; the vacuum head (nozzle/sweeper) is to be attached to the wrist of the arm. Operation of this arm will require the same freedom of motion as can be found in a standard backhoe linkage. Once the vehicle has been moved into position and stopped, the arm is to sweep over a predefined area while removing only the top few centimeters of soil. Capability for a preprogrammed sweeping pattern is to be included in the electronic controls for the robot arm.

- Remote-Control System. Must be able to provide control of the vehicle (engine, brakes, steering, etc.) as well as the vacuum unit (engine, air flow control, dumping, etc.). Must also have some control (such as, start and stop) over the preprogrammed robot arm vacuuming operation. Audio and video feedback are required. The control unit(s) must be located in a shielded area or at a safe distance from the contaminated area.

- Position Determination System. Since the vehicle will be used to decontaminate an expansive land area, some method must be provided to position the vehicle accurately during successive passes around that area; a tracking/positioning system is required. This system need not be automatically invoked, since some manual adjustment of the positioning sensors can be made by the operators while the vehicle is stopped and performing the vacuuming operation. Data output from this system must be coupled with maps or other geographic data to assist the operators in moving the vehicle to the next area to be cleaned.

- Transportation System. Must be used to move the decontamination robot (vehicle, vacuum loader, and robot arm), from its normal place of storage to the clean-up area. This system can consist of trailers for hauling the robot, or the robot could be moved under its own power if adequate highway speeds and safety considerations can be achieved.

- Soil Off-loading System. To be used to remove contaminated soil from the vacuum unit hopper and package/processes it for proper disposal.

A conceptual design and cost estimate were developed for such a system. Commercially available systems were investigated for their suitability in providing remote vehicle control, vehicle position determination/tracking, robotic vacuum operation, and dumping and handling of the collected radioactive soil. This effort was not intended to be a development project, but rather a conceptual design project to determine the feasibility and approximate costs for the components of such a system. Design details, specifications, and estimated costs for each component are discussed in Sect. 3.1.

Because a variety of choices are available, neither the transportation system nor the soil off-loading system were included in this cost study. However, a brief discussion of existing equipment capabilities and potential problem areas is included below for these systems.

Once the radioactively contaminated soil has been removed from an area, it must be safely disposed. The standard vacuum loader unit has the capability to dump the contents of its hopper in the same way a dump truck empties its load. This method of

disposal might be suitable for clean-up operations which involved the ultimate disposal of the contaminated soil in a mound or burial trench.

One optional feature offered by vendors of some vacuum loader units is a pneumatic off-loading system. The contents of the vacuum hopper can be conveyed by an air stream through a hose into an appropriate container. This system would allow the contaminated soil to be packaged for transportation from the clean-up area or for later processing. Neither of these two soil off-loading systems were costed in this study. It is obvious that, if on-site disposal is possible, mounds or burial trenches would be the most cost effective method of containing the spoil from the clean-up area.

It should be noted that the Department of Transportation has regulations regarding the transportation of Class 9 (Miscellaneous Dangerous Substances) hazardous wastes on U.S. highways. Some, if not all, of the vendors of the vacuum units mentioned in Section 3.1.1 can provide a body construction which meets the standards for such transportation. The requirement for moving the decontamination robot over long distances may affect the decision to choose a truck-mounted unit (with rubber tires) or a trailer-mounted unit (pulled by a crawler with steel treads), especially if the vehicle is to move to the decontamination site under its own power. No transportation system, for moving the decontamination robot from its normal place of storage to the clean-up site, was costed in this study.

3.1 SYSTEM COMPONENTS

3.1.1 Vacuum Loader

Table 3-1 lists several companies which currently offer large, truck- or trailer-mounted vacuum systems (vacuum loaders) that might be suitable for use in decontaminating land areas. In general, the largest of the truck-mounted units has a rated hopper capacity of 12 m^3 (16 yd^3); although, the usable capacity is closer to 10 m^3 (13 yd^3). At least one company (Super Products, manufacturer of the SUPERSUCKER truck; see Fig. 3-1) sells a 15-m^3 (20-yd^3) unit with a usable capacity of 13 m^3 (17 yd^3). Trailer-mounted units have hopper capacities as large as 23 m^3 (30 yd^3).

Table 3-1. Vendors of large industrial vacuum loading systems (for truck or trailer mounting)

Vendor	Tradename of Unit
Cannon Industries, Inc. UltraVac Division P.O. Box 09336 Milwaukee, WI 53209 phone: (414) 351-1300	ULTRAVAC
Central Engineering Co., Inc. 4429 West State St. Milwaukee, WI 53208 phone: (414) 933-4567	VAC-ALL
EL Industries, Inc. 2 North LaSalle St. Chicago, IL 60602 phone: (312) 236-0728	AQUA-TEC
Guzzler Manufacturing, Inc. P.O. Box 66 Birmingham, AL 35201-0066 phone: (205) 591-2477	GUZZLER
NFE International, LTD. 300 Beeline Bensenville, IL 60106 phone: (312) 350-1110	HI-VAC
Ormson Corporation 510 Progress Dr. Hartland, WI 53029 phone: (414) 367-2280	FAST-VAC
Peabody Myers 1621 South Illinois St. Streator, IL 61364-0908 phone: (815) 672-3171	VACTOR
Super Products P.O. Box 27225 Milwaukee, WI 53227 phone: (414) 784-7100	SUPERSUCKER

Fig. 3-1. Overall view of typical truck-mounted vacuum loader system (courtesy of SUPER PRODUCTS, Inc.).

A 10-m^3 (13-yd^3) hopper would hold about 14,500 kg (16 tons) of material, such as sand, which weighs 1450 kg/m^3 (90 lb/ft^3); a 23-m^3 (30-yd^3) hopper would hold about 33,000 kg (37 tons). A 10-m^3 (13-yd^3) hopper would be able to hold the soil removed from one acre to a depth of about 2.5 mm (0.1 in.); a 23-m^3 hopper would hold the soil removed from one acre to a depth of about 6 mm (0.25 in.).

These vacuum systems offer high-efficiency removal of the particulate material from the air stream which is pulled into the collection hopper. Most vendors employ a three-stage air cleaning system: a roughing stage (usually a cyclone separator) to remove heavy material followed by two stages of fabric bag filters inside a baghouse. The bags are cleaned by a pneumatic back purge. Most designs currently incorporate a simplified, snap-in method of installation and removal of the fabric bags for these final cleanup stages. Advertised removal efficiencies for the air streams run as high as 99.9% of all particles with diameters larger than one micron.

Unloading of the large collection hoppers in these systems is usually accomplished by dumping the material from the rear of the truck; hydraulic lifters are used in a manner similar to a standard dump truck. The dust from the baghouse is dumped at the same time through special chutes, located beneath the main collection hopper. Alternate methods of spoil handling might incorporate hopper liners that could be unloaded and sealed when full. This technique would eliminate the double handling of the spoil material. The vacuum pressure is provided by a positive displacement blower (a Roots-type blower), located downstream of the baghouse. A dedicated diesel engine must be provided for powering the vacuum loader system. (On a truck-mounted vacuum loader, the truck's engine can power the unit while the truck is not moving; however, a single engine cannot be used to operate both the vacuum loader and the moving truck at the same time.) Typical ratings of the blowers for these units are 2.1, 2.4, and 2.8 m^3/s (4500, 5000, and 6000 cubic feet per minute). The typical, generated vacuum pressure is about 50 kPa (200 inches of water). Advertised loading rates of these units are as high as 15 kg/s (1 ton/min) while picking up loose materials such as sand. The SUPERSUCKER truck has a 6-m (20-ft) boom attached to its intake hose; this boom may be "taught" to perform a repetitive set of motions from a connected, electronic control pendant.

Typical prices for these vacuum system units range from $85,000 to $100,000 without the truck chassis or trailer. The type of truck recommended by each manufacturer would add about $45,000 to $60,000 to this base price; installation of the vacuum unit on the truck or trailer would add another $5000. Vacuum hoses are available at extra cost and would run about $1500. Desired, optional features (such as fuel shutdown controls) would add another $2500.

The total price for such a truck-mounted vacuum system would therefore be between $139,000 and $169,000. A trailer-mounted vacuum unit would be about $15,000 more expensive than a truck-mounted unit, because of the need for a separate engine and accessories. The price of a typical highway trailer, without a tractor to tow it, is an additional $15,000.

3.1.2 Vehicle

A vacuum loader unit can be directly mounted onto the chassis of a large truck in the 200 horsepower class. The truck models recommended by individual manufacturers of the vacuum loader systems include such vehicles as the GMC General, International Harvester (Navistar) F2674, Kenworth C-500, and Ford F-800D. These trucks cost between $45,000 and $60,000, depending on optional equipment added to the basic vehicle. As stated above, the price of a typical highway trailer, for a trailer-mounted vacuum loader unit, is an about $15,000. The trailer could be pulled by a truck, similar in price to the models mentioned above; a steel-treaded crawler could also be used. Because the weight of the trailer and loaded vacuum hopper might be as large as 36,300 kg (40 tons), a crawler with a hefty drawbar pull would be required. Vehicles which fit this class range include 140 to 165 horsepower diesel bulldozers, such as the Case 1450B, Caterpillar D6H, John Deere 850B, International Harvester TD-15C, Fiat/Allis 14C, and Komatsu D65E8. These vehicles weigh between 13,000 and 18,000 kg (30,000 and 40,000 lb) and cost between $120,000 and $140,000. A crawler for mining use or a surplus Army tank chassis might also be suitable, but neither was priced for this conceptual design.

3.1.3 Industrial Robot Arm

There are some problems which may be encountered when using a vehicle-mounted system to decontaminate land. The area to be vacuumed must not be driven over by the vehicle before cleaning; even rubber balloon tires have been shown to compact the soil unacceptably (Orcutt 1982). Resuspension of the contaminated particles may be instigated by careless truck motion or by sloppy vacuuming. The lift capability of the vacuum line (in pounds per minute) must be also be related to the rate of motion for the vacuum head; a slowly moving head may remove more depth of soil than is necessary. For these reasons, it is desired that the vacuum head be operated by a programmable industrial robot arm which is mounted to the front (bumper) of the vehicle.

Many types of programmable industrial robot arms are currently available. Either an electric or hydraulic robot arm could be used for this particular application. The motion pattern of this arm would be the same as a standard backhoe linkage; that is, the vacuum head (nozzle) would be moved back-and-forth across the soil surface, in line with the axis of the vehicle. The shoulder of the robot arm would provide left and right pivot motion; the elbow would provide the back-and-forth motion for the vacuum head. There are no requirements for any rotational capability (i.e., roll) of the proposed linkages. The left-to-right motion would best be accomplished by mounting the (shoulder of the) arm to a gantry or rail support on the front bumper of the vehicle. The normal operation of the robot arm would be to sweep the vacuum head over the area immediately in front of the vehicle; this area would be at least as wide as the vehicle and would extend as far forward of the vehicle as the robot arm could reach. A gantry mount would also allow the arm to be moved to the side of the vehicle for clean-up of areas with difficult access.

The wrist of the robot arm could be attached to the vacuum head. The vacuum head housing could also contain some sort of mechanism for mechanical agitation of the surface, such as a sweeper brush. The robot arm capable of lifting this vacuum head and housing would have to lift at least 50 kg (100 lb). Industrial robot arms in this capacity range have a maximum reach of about 3 m (10 ft), which would be sufficient for this task. The weight of such an arm would be around 500 kg (1000 lb). The

operating rate of motion for these arms is 30 to 60 cm/s (1 to 2 ft/s), about the same as that used when operating an upright household vacuum cleaner.

Table 3-2 contains a partial list of vendors of industrial robot arms which meet the above criteria. Electric robot arms are more expensive than hydraulic ones; tremendous cost savings can be achieved for hydraulic arms because of the similarity of the desired arm to a standard hydraulic backhoe. When the standard, programmable electronics are included, a gantry-mounted industrial robot arm would cost between $50,000 and $75,000 with the electric models being the most expensive.

It was initially thought that some sort of proximity sensor might be incorporated into the robot arm motion in order to have it follow rolling terrain. However, the computer control required to accept continuous feedback on the existing terrain and take corrective action with the vacuum head would be rather complex and is beyond the capability of "off-the-shelf" robotic equipment. Current robot arms can be taught to follow a set of simple predefined motions, including vacuuming or sweeping (Hanna et al. 1985); altering those motions by continuous input (as from terrain sensors) is a much more complex operation.

It is simpler to manage terrain-following by carefully choosing the manner in which the vacuuming operation is performed. The robot arm could first lift the vacuum head into position as far away from the vehicle as possible. The nozzle could then be lowered to the ground and pulled back toward the vehicle. If a freely pivoting linkage is provided between the robot's wrist and the vacuum head (such as suspending the vacuum head on chains), then the head will "float" on the ground and will closely follow the terrain without any need for proximity sensors. Of course, some method of controlling the rate of soil removal would still need to be developed for this, or any other, vacuuming strategy.

The optional attachments for the vacuum head (nozzle) were not included in the cost for this conceptual design. A sweeper brush is available from vendors of street cleaning equipment. An attachment, such as a lawn-type string trimmer, for removal of vegetation could also be installed in the vacuum head.

Table 3-2. Selected vendors of industrial robot arms

Vendor	Address
Bio-Compuneering, Inc.	718 Washington Ave. Elyria, OH 44035 phone: (216) 366-6100
Cayuga Manufacturing Co.	4981 Lake Ave. Buffalo, NY 14219 phone: (716) 823-5600
Cincinnati Milacron	215 S. West St. Lebanon, OH 45036 phone: (513) 841-6200
General Electric Co., Robotics and Vision Systems	P.O. Box 17500 Orlando, FL 32860 phone: (305) 889-1200
Westinghouse Electric Corp., Unimation Division	Shelter Rock Lane Danbury, CT 06810 phone: (203) 744-1800

3.1.4 Remote Control System

Remote control equipment is available for use in a variety of industries which use several different types of vehicles: locomotives, bulldozers, overhead cranes, mining equipment, and fork lifts. Remote control of a vehicle involves sending electronic signals across specific frequency bands to engage actuators which operate the normal vehicle controls (throttle linkage, brakes, etc.).

There are two types of actuators which can operate the controls inside the vehicle: electric and hydraulic. The electric actuators are motors which are connected by gears into the normal vehicle controls; when the motor turns the gear, a specific linkage is adjusted. Hydraulic actuators (Keir 1982) are actually electric/hydraulic hybrids; the electronic activating signal engages an electric solenoid valve which operates a hydraulic cylinder connected to the normal vehicle controls. Electric actuators are more reliable but require a high-current supply of electricity to operate the motors. Hydraulic actuators can be operated from the existing hydraulic system of such vehicles as bulldozers.

Most of the existing applications of remote control for vehicles employ some type of fixed track or path along which the vehicle is allowed to move. The remote control problem then simply becomes a matter of starting the vehicle's motion, adjusting its speed and applying the brakes at the appropriate times. Steering a vehicle presents more difficult control problems; although, steering algorithms have been developed and tested for tractors pulling farm implements (Smith, Schafer, and Bailey 1979; Smith, Schafer, and Young 1979).

No one currently manufactures a unit which is capable of remotely controlling a wheeled vehicle such as a truck; the steering is too difficult and the demand for such units is low. Bulldozers and crawlers do not present the same steering problems, since they are basically steered by forward and reverse movement of independently operated treads. CatTron, Inc. (29 N. Second St., Sharpsville, PA 16150; phone: 412/962-3571), Telemotive, Inc. (6460 W. Cortland St., Chicago, IL 60635; phone: 312/889-9035), and the Vectran Corp. (261 Kappa Drive, Pittsburgh, PA 15238, phone: 412/963-1221) offer a set of remote controls suitable for operating a crawler or bulldozer. The control

package for a Caterpillar D9 bulldozer is approximately $45,000 and includes control of steering, brakes, and all engine functions.

For wheeled vehicles, a commercially available unit is offered on a custom basis by the Vectran Corporation. In a recent application involving a John Deere 690C excavator, a wheeled vehicle was controlled by Vectran from a portable, suitcase-sized control panel; although, skid-steering (which is similar to bulldozer or crawler steering) of the vehicle was the only motion control provided for the vehicle. A video link was included to remotely observe the excavation process. The unit was sold for about $95,000. Other contacted vendors stated that they had no similar unit currently available but offered to custom-make such a unit; estimated prices ranged from $45,000 to $125,000 with $110,000 as a best guess for the quantity of control circuits needed in this application.

If remote control is to be used successfully, it must also include control of the vacuum system functions (blower speed, baghouse purges, engine control, and dumping control). Remotely controlling the vacuum system is possible, but it will add complexity to the remote control panel. Most vendors suggested including feedback—both visual and audible (for observing gauge readings and detecting engine strain or other noises)—from the truck to the control panel. This would result in a more costly control package, but it would also allow a more normal operation of the heavy equipment, regardless of the situation encountered in the field. Based on the cost of the Vectran/John Deere unit, a remote control unit for the vacuum loader system would probably cost about $90,000, including the video link for use with the positioning of the vehicle.

Currently, radio control vendors limit the range of their units to about 150 m (500 ft). This limitation comes from safety considerations, as well as from concerns about extraneous signal interference in the frequency bands used. There are no technical reasons why such a remote control unit could not be used to operate equipment from greater distances; repeater stations can extend the range of such a control signal to several kilometers. If a video link is included, the repeaters must be line-of-sight microwave links, or else they must be connected by co-axial or fiber optic cables.

One final consideration of configuring a vehicle to operate by remote control is whether it is also desirable to operate the vehicle normally, that is, with a human driver. If, for example, the vehicle is a bulldozer and it is remotely controlled by hydraulic actuators, then the actuators can be readily disengaged, and the vehicle can be operated normally. If, on the other hand, the actuators are configured so as to interfere with normal, human driving of the vehicle, then this might become part of the decision criteria against using that particular type of actuator system.

3.1.5 Position Determination System

Since the vehicle is intended for use in decontaminanting a large land area, some method must be provided to position the vehicle accurately and continuously during successive clean-up passes around that area; a tracking or position determination system will be required. Electronic instruments available in the surveying industry appear to offer the necessary accuracy for determining angles and distances at the most reasonable price.

Table 3-3 lists vendors of electronic position and distance measuring instruments as used by surveyors. All of these companies are foreign owned (Swiss), and the instruments are imported to the U.S. The basic angle measuring instrument is called a "theodolite;" a transit is a special type of theodolite. Electronic theodolites can measure both horizontal and vertical angles (from some reference point) to well within one minute of arc. A "total station" combines the theodolite with an electronic distance measurement (EDM) instrument into a single package. These total stations weigh about 7 kg (15 lb). Distances are determined by using an infrared laser beam with a retroreflector; range can be determined to within 1 cm (0.5 in.), even at distances of 1.6 km (1 mi.). The maximum range for these distance measurement instruments is 20 km (12.5 miles) in a slightly hazy atmosphere.

Typical prices for a total station range from $15,000 to $25,000. The reflector prism, which would have to mount on to the decontamination vehicle, would cost about $1000.

All of the vendors in Table 3-3 supply electronic connectors which can feed data from their systems into a computer. The use of a computer system could simplify the

Table 3-3. Vendors of electronic position and distance measuring instruments

Vendor	Address
Kern Instruments, Inc.	Geneva Road Brewster, NY 10509 phone: (914) 279-5095
The Leitz Company	9111 Barton Box 2934 Overland Park, KS 66201 phone: (913) 492-4900
Wild Heerbrugg, Ltd.	465 Smith St. Farmingdale, NY 11735 phone: (516) 293-7400

manual positioning of the decontamination vehicle by presenting graphical or map-like display on a monitor. This is particularly important with respect to positioning the vehicle on subsequent passes around the contaminated area. An alternate positioning strategy might be to mark the decontaminated region (for example with paint or with powdered limestone) so that the operator could easily identify the adjacent still-contaminated areas. This simpler method has one major disadvantage: it requires a fatiguing operator involvement in visually identifying such areas on subsequent passes.

The Leitz Company sells a package which can be directly connected to the RS-232 port (the serial/communication port) of an IBM Personal Computer. Data from the total station can be recorded, stored, and/or processed by the personal computer. These specialized electronics will add $6,000 or $7,000 to the cost of the total station. Thus, the price of a complete system would be between $22,000 and $33,000.

It should be noted that typical operation of the total station requires manual operation of the adjustment knobs to align the target (the reflector prism on the decontamination vehicle) with the infrared beam. This should present no problem, since the vehicle will not be moving while the actual vacuuming operations are in progress. However, it is likely that an automated acquisition method could be easily developed for alignment of the beam and the prism. This automated system would have the advantage of eliminating all routine, manual tasks associated with obtaining the position and distance of the vehicle.

Other candidate systems include satellite positioning systems (e.g., NAVSTAR) and "beacon" systems (such as those used to position mobile factory robotic equipment). These alternate systems were neither included nor costed in this study.

3.2 CONCEPT COST

Table 3-4 summarizes the estimated, individual component costs, as outlined above, and shows the estimated total cost of this conceptual design for a land decontamination robot. Two versions are considered: (1) a truck-mounted vacuum loader, and (2) a trailer-mounted unit pulled by a crawler. The costs of the two versions are basically the same, except for the vehicles and the remote controls to operate them.

Table 3-4. Summary of estimated component costs for a land decontamination robot system

Item	Truck-Mounted Unit	Trailer-Mounted Unit
Vacuum Loader Unit	$85,000 to $100,000	$85,000 to $100,000
Installation	$5,000	$5,000
Accessories	$1,500	$1,500
Safety Options	$2,500	$2,500
Vehicle	$45,000 to $60,000 (truck)	$120,000 to $140,000 (bulldozer-type crawler) $15,000 (trailer) $15,000 (engine and accessories for vacuum unit)
Remote Controls		
For vehicle control	$110,000	$45,000
For vacuum unit/video	$90,000	$90,000
Robot Arm	$50,000 to $75,000	$50,000 to $75,000
Position Determination System	$22,000 to $33,000	$22,000 to $33,000
TOTAL	$411,000 to $477,000	$451,000 to $522,000

The truck is the cheaper of the two vehicles, but the remote controls for a wheeled vehicle are not generally available and are extremely expensive. The crawler is an expensive piece of machinery, but it is cheaper to remotely control; it would also be more likely to successfully navigate over any type of agricultural terrain that might be encountered.

The total cost of the land decontamination robot, from Table 3-4, is between $411,000 and $477,000 for the truck-mounted version and between $451,000 and $522,000 for the trailer-mounted version. The range of these numbers for a particular version is about 15% of the total cost; however, this uncertainty should be considered acceptable for the preliminary nature of this conceptual design.

The costs in Table 3-4 show only the hardware costs; the costs associated with integrating this hardware into an operating decontamination system have not been included. Also not included are the costs of programming the robot arm and of any computer equipment or software necessary to process and display information relating to the vehicle's position in the contaminated area. It can be assumed that these costs will at least equal the cost of hardware in Table 3-4 and will thus move the total cost for the complete land decontamination robot system to a minimum of $1,000,000.

4. FINDINGS AND CONCLUSIONS

This study has investigated the feasibility of using "off-the-shelf" hardware to assemble a land decontamination robot. This robot would use vacuum technology to remove the top few centimeters of soil from a radioactively contaminated area. An industrial robot arm would operate the vacuum nozzle. The entire unit would be remotely controlled from a safe distance.

Two conceptual versions of this system were developed: (1) a truck-mounted unit and (2) a trailer-mounted unit pulled by a bulldozer-type crawler. The estimated hardware costs for the truck-mounted unit ranged from $411,000 to $477,000. The cost estimates for the trailer-mounted unit were $451,000 to $522,000. The truck is the cheaper of the two vehicles, but the remote controls for a wheeled vehicle are not generally available and are extremely expensive. The bulldozer is an expensive piece of machinery, but it is cheaper to remotely control.

The costs above are only for the system hardware. The costs of integrating this hardware into an operable system might easily result in a total cost for the complete land decontamination robot system near $1,000,000. This cost is high enough that the land decontamination robot cannot be considered to be an expendable system.

Four organizations have current experience with integration of similar hardware into remotely controlled vehicular equipment. The U.S. Navy has an Explosive Ordnance Disposal Technology Center in Indian Head, Maryland. They have a vigorous program to develop mobile remotely controlled equipment to do dangerous tasks (i.e., ordnance disposal) (Butler and Nelson 1986). They are also responsible for the Navy's HERC (Heavy Equipment Remote Control) program and are applying industrial robotics to some of their tasks. The following three companies have recently been involved in the Navy's HERC program; each company can provide the custom design services needed to create a system similar to the land decontamination concept:

(1) American Northwest, Inc. (3446 W. Hacienda Ave., Las Vegas, NV; phone: 702/739-0101) manufactures a variety of bolt-on remote control systems for industry and military applications. They have provided remote control for such vehicles as forklifts, drum handlers, concrete cutters, and backhoe dozers. They prefer electrically operated systems and mechanical

actuators to hydraulics which they feel are high mortality devices (i.e., hydraulic devices are more frequently in need of repair or replacement).

(2) Foster-Miller (360 Second Ave., Waltham, MA 02254; phone: 617/890-3200) has experience with remotely controlled excavators, mine sweeping equipment, and mining equipment. They have a contract with the U.S. Air Force to develop dedicated reconnaissance-type robot vehicles. They have some recent experience with the development of remote controls for a Chevrolet truck (Blazer).

(3) Ametek (P.O. Box 6447, 41 Aero Camino, Santa Barbara, CA 93160; phone: 805/683-2151) has developed conceptual designs for remotely controlled excavation equipment and reconnaissance vehicles and is conducting a feasibility demonstration for a fire fighting robot for the U.S. Air Force. This remotely controlled fire truck (a wheeled vehicle) contains a video link and a robot arm to safely fight aircraft fires which involve ordnance. Of all currently existing equipment, Ametek's fire truck is the most closely similar to the land decontamination robot concept in this report; however, it does not have a manipulator arm.

The concept and cost estimates presented in this study have included the use of both electric components and hydraulic components. It is not the intention of this study to advocate a preference for one component type over the other. Clearly, there are specific instances where one would have a marked advantage. For example, a hydraulic robot arm is cheaper and stronger than an electric one, but leaking hydraulic fluids might present more difficult equipment decontamination problems. The choice of vehicle types might also influence whether electric or hydraulic actuators are chosen for effecting the onboard remote control; for instance, a hydraulic actuator system could be readily adapted to control a bulldozer-type crawler by connecting the actuators as a parasitic load on the vehicle's existing hydraulic system.

Some additional thought must be given to decontamination of the vehicle itself and to recovery of the unit in the event of a mechanical breakdown. Disposal of the spoil from the contaminated area was not addressed in this study. It is hoped that the basic concept and cost estimates developed in this study will be used as a starting point for additional investigation into the possible development of such a decontamination system.

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81. Bernard H. Weiss, Office of Analysis & Evaluation of Operational Data, U.S. Nuclear Regulatory Commission, Washington, D.C. 20555

82. Martin Williams, Professor, Department of Economics, Northern Illinois University, DeKalb, IL 60115

83. William F. Wolff, Office of Safety Policy, and Standards (EH-35) U.S. Department of Energy, Washington, D.C. 20545

84-129. Given distribution as shown in OSTI-4500 Health and Safety Category UC-407.