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Environmental Restoration and Waste Management Robotics Technology Development Program Robotics 5-Year Program Plan

Volume II
Program Plan

Department of Energy
Office of Environmental Restoration and Waste Management
Office of Technology Development

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Washington, D.C. 20585

ROBOTICS TECHNOLOGY DEVELOPMENT PROGRAM
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1.0

BACKGROUND

1.0 BACKGROUND

In March 1989, DOE Secretary James Watkins established a plan of action to strengthen the Department's nuclear waste management activities. In letters discussing his plan of action, he outlined a four-pronged set of research initiatives to develop new technologies. One of the four areas is a program to "develop robotic applied technologies to reduce the potential hazard to the public, remediation technicians, and decontamination-decommissioning crafts." In accordance with the Secretary's direction, the ER&WM
Five-Year RDDT&E plan places emphasis on the development and standardization of robotics technologies to be used broadly across all areas of environmental restoration and waste management operations.

In August 1989, DOE issued its first annual Five-Year Plan for ER&WM. That plan expressed DOE's commitment to achieving compliance with laws, regulations, and agreements aimed at protecting human health and the environment. In order to carry out that commitment, DOE stated that it would focus its resources to (1) assess and clean up inactive waste sites and facilities,
(2) continue safe and effective waste management operations, and
(3) coordinate an aggressive applied waste research and development (R&D) program keyed to developing innovative technologies to yield permanent disposal solutions and lower costs. The Five-Year Plan for ER&WM established the agenda for compliance and cleanup against which progress will be measured.

In November 1989, DOE issued a draft RDDT&E Plan, which is the first of many annual documents delineating the current state of environmental restoration, waste management, and waste minimization technologies. An update of this plan was issued in July 1990. The RDDT&E plan addresses the focus on an aggressive applied research program and sets milestones for research to fulfill DOE's objectives of reduced risk to human health and the environment, decreased costs, and a 30-year restoration goal. The RDDT&E Plan is needs driven, addressing the requirement to provide faster, safer, less expensive technologies to site remediation and waste management operations.

This 5-Year Program Plan discusses the overall approach to be adopted by the RTDP to aggressively develop robotics technology and contains discussions of the Program Management Plan, Site Visit and Needs Summary, Approach to Needs-Directed Technical Development, Application-Specific Technical Development, and Cross-Cutting and Advanced Technology. Integrating application-specific ER&WM needs, the current state of robotics technology, and the potential benefits (in terms of faster, safer, and cheaper) of new technology, the Plan develops application-specific road maps for robotics RDDT&E for the period FY 1991 through FY 1995. In addition, the Plan identifies areas where longer-term research in robotics will have a high payoff in the 5- to 20-year time frame.

2.0

INTRODUCTION

2.0 INTRODUCTION

2.1 PROGRAM OBJECTIVES

The objective of the RTDP is to develop and apply robotics technologies that will enable ER&WM operations at DOE sites to be:

- Safer
  Reduced worker exposure and increased safety through remote operation and control of equipment,

- Faster
  Increased speed and productivity for ER&WM operations through enhanced capabilities and automation, and

- Cheaper
  Faster, more productive systems resulting in quicker completion of remediation operations that in turn reduces life-cycle costs.

2.2 PURPOSE AND SCOPE OF THE PLAN

Purpose: This Plan supports DOE's RDDT&E Plan in the area of ER&WM activities, and specifically focuses on development and application of robotics technology. It defines and promotes an innovative and aggressive technology development program for robotics covering FY 1991 through FY 1995 and outlines the management process for implementing and funding the development.

ER&WM activities at DOE sites often involve work in the hazardous environments of chemicals, radioactive contamination, radioactivity, etc. These and hazardous materials must be contained while the work is performed. Workers associated with these activities must be protected from the hazards. Performing the work remotely is often the most effective way to maintain containment and protect workers.

When work with hazardous materials in confined spaces is performed manually it is usually slow and expensive. Worker efficiency is low due to protective clothing and, in some cases, exposure limits. Fatigue is often induced by the need to perform difficult tasks without adequate access to the work location. Additional wastes are generated in the form of contaminated clothing, rags, tools, etc. The cost of a given task or project is increased by the special materials needed to protect workers and the environment, low work efficiency, and extended time for completion. Application of robotics technology can increase the speed of performance and reduce costs by minimizing and eliminating many of these factors. Some activities (analysis of samples to characterize sites and wastes, for example) involve large numbers of repetitive operations using hazardous materials. Automation of these activities can remove workers from the hazards and still provide the capacity needed to handle the very large volume of procedures projected for ER&WM work.

Existing robotics technologies can be applied to ER&WM needs, to a limited degree, but cannot begin to meet all of the needs identified, particularly where the needs are unique to ER&WM and require specialized system configurations capabilities. Thus, RDDT&E must look to current robotics technology for near-term applications and a technology base, and provide technology development directed at the needs of ER&WM operations at DOE sites.

Scope: Robotics technology is not a specific solution to any one ER&WM need. Rather, it cuts across, and is applicable to, many needs and potential applications.

Six major, cross-cutting ER&WM applications, which are of immediate importance and priority to DOE, have been identified by the OTD. They provide a center of focus for the preparation of this initial 5-year Program Plan for robotics RDDT&E. These applications are: (1) Waste Storage Tanks (above ground and underground), (2) Buried Waste Retrieval, (3) Contaminant Analysis Automation, (4) Waste Minimization, (5) Decontamination & Decommissioning (D&D), and (6) Waste Facilities Operations.

Additional applications will be defined during the evolution of the Plan as their importance and priority are established by DOE.

This Program Plan will be updated annually to support DOE budget planning and funding allocations. Each annual update will reflect actual accomplishments and will advance the Plan's horizon on a DOE Fiscal Year basis. Thus, the Plan will always cover a 5-year span, with emphasis on near-term detailed plans.

Planning Premises: This plan is based upon several premises regarding the implementation of robotics RDDT&E and ER&WM activities at DOE sites. These premises are necessary to establish planning bases where alternative approaches or uncertainties exist.

- Site Needs
  The planning team visited five DOE sites prior to the preparation of this Plan. The principal needs identified at the sites are assumed representative of ER&WM needs at other DOE sites.

- Priorities and Schedules
  For this initial 5-year Plan, individual compliance dates (in Federal Facility Agreements at the DOE sites) were the principal factors considered for priorities and schedules.

- Technology Concepts
  Identification of technology development needs, and the bases for that development, requires a technical concept as a point of reference. For this Plan, general technical concepts and approaches to meet each need were selected and are described. In general, these concepts were selected from a number of alternative approaches under consideration at each site.

- Closure Alternatives
  For purposes of this Plan, closure is the completed remediation of a project as defined and accepted in the applicable Federal Facilities Agreement. Alternatives for closure of waste storage tanks, buried waste, and contaminated soil units are being evaluated by DOE

site personnel. For this Plan, retrieval and disposal of waste materials (and contaminated soils) is assumed to be the alternative of choice for closure of most units, although this may not be the eventual solution.

2.3 STRUCTURE OF THE PROGRAM AND THE PLAN

DOE Program Structure: DOE's ER&WM Office of Technology Development has established RTDP to integrate robotics RDDT&E activities and to provide needs-driven, timely, and economical robotics technology to support ER&WM activities at DOE sites.

The program promotes the availability of the technology and supports its deployment and use at DOE sites. The program further serves as a bridge between the ER&WM robotics RDDT&E and the basic robotics research carried out by DOE's Office of Energy Research, providing guidance for the basic research program and integrating the results in applied research and advanced technology development projects. The Program is structured to focus robotics technical expertise from DOE national laboratories, prime contractors, private industry, universities, and other Federal agencies upon parallel lines of development. All have existing robotics work under way, which is a strong basis for initiating an aggressive RDDT&E program. New emphasis is placed on identifying and combining the best expertise from these organizations into teams. A well-coordinated team approach will lead to a correct and comprehensive integration of existing technologies with candidate technologies. The program structure also provides a strong interface between organizations developing robotics technology and potential users of the technology in ER&WM projects at DOE Sites. Research, development, and some demonstrations (typically subsystem or critical features demonstrations) are carried out by the technology development community. Once a system is at the prototype stage, then cold and hot demonstrations, tests, and an evaluation are carried out by ER&WM operations at the site, with technical support from technology development teams. In addition, specific applications development will be coordinated by DOE site staff with a strong need for the robotics technology.

Plan Structure: This Plan describes the initial makeup of the RTDP. It is based on needs identified at five DOE sites: Fernald, Hanford, Idaho, Rocky Flats, and Savannah River.

Section 3.0 discusses the Program Management Plan. Section 4.0 summarizes the needs for robotics technology at the sites. Needs-directed technology development and application-specific technical development are then described in Sections 5.0 and 6.0 respectively for five technology areas selected to meet needs at the sites. Each technology development section highlights needs, discusses benefits to be derived from application of the technology, describes concepts for robotic systems, and defines the technology development activities planned. Time-phased logic diagrams illustrate how the technology development will be carried through to demonstrations and applications, meeting needs and compliance dates at each site.

Section 7.0 discusses cross-cutting and advanced technology development. Cross-cutting technology development provides a cost effective means to pursue technology, such as control system elements and software, which can be used for widespread application. Advanced technology development assures sustained long-term development of high payback technologies which can be applied in decades to come.

2.4 ROBOTICS DEFINITIONS

The Robot Institute of America defines a robot as follows, "a robot is a programmable, multi-functional manipulator designed to move material, parts, tools, or specialized devices, through variable programmed motions for the performance of a variety of tasks".

The term robots, as used in this document, includes: (1) mechanical subsystems such as servomanipulators, mobile platforms, remotely-operated heavy equipment (bridge cranes, excavators), and special remote tooling, and (2) sensing and control systems associated with the operation of these mechanical devices.

The term robotics, as used in this document, spans a broad range of technology from human-in-the-loop controlled remote systems to advanced autonomous systems.

The control of robots and robot systems spans the field from human operator to fully computer controlled (with human programming). Typically, both human operators and computers share in the control of robots. The operational control of robot systems include the following:

- **TELEOPERATOR:** A teleoperator is a general purpose, dexterous, man-machine system that augments man by projecting his manipulatory and pedipulatory capabilities across distance and through physical barriers into hostile environments. Typically, manipulation is performed by a movable mechanism (crane hooks, servomanipulator), and vision is direct or indirect (protective window, periscope, or camera).

  Man is always in the control loop in a teleoperator system. The historical use of teleoperator systems has been in the nuclear reactor industry utilizing master/slave manipulators and remotely operated cranes. There has been minimal use of computer-aided support in these systems.

- **TELEROBOT:** A telerobot system is an extension of the teleoperator system which utilizes a shared control system where the computer is assisted by human control. Due to the unstructured environments typical of hazardous waste sites, it is anticipated that teleoperator systems will be common in waste management and remediation.

- **AUTONOMOUS**: An autonomous robot system performs the same functions as a teleoperator system, except that the human control is oversight and very minimal. The action instructions and decision responsibility are computer controlled. An example of an autonomous robot is the Defense Advanced Research Projects Agency (DARPA) sponsored autonomous land vehicle research robot.

For purposes of the RTDP, the term robot system encompasses systems with any of the three aforementioned control approaches.

2.5 FY 1990 ACCOMPLISHMENTS

Planning: The RTDP has prepared two planning documents. The draft ER&WM Robotic Technology Development Program Site Needs and Requirements Document describes the results of planning team visits to five high priority DOE sites and is summarized in Volume III of this plan. The RTDP Robotics 5-Year Program Plan (this document) addresses the site needs and plans for technology development and applications to meet those needs, defines schedules for implementation of the defined program, and sets out a plan for robotic technology development based upon the assessment of site needs.

Initiating Interactions with the Robotics Technology Community: In July 1990, a forum was held announcing the robotics program. The forum was attended by more than 200 individuals. Over 60 organizations (industrial, university, and federal laboratory) made presentations on their robotics capabilities. The information gathered forms part of the assessment of the technology base that exists to support the robotics program.

Technology Demonstrations: As part of its effort to stimulate early interactions with the site ER&WM technologists as well as with the robotics community at large, the RTDP has sponsored four early technology demonstrations focused upon specific ER&WM needs. They are characterization and clean up of waste storage tanks, rapid movement of waste containers using bridge cranes, subsurface mapping of buried waste sites, and a robotic system for Pu production lines. These demonstrations integrate commercial technology with advanced robotics concepts developed over the past years by DOE in support of areas such as nuclear reactor maintenance and the civilian reactor waste program.

The demonstration of rapid movement of simulated waste containers applied model-based control algorithms developed at SNL combined with technology in computer control of large gantry bridges at ORNL to provide swing-free movement of large suspended payloads. This system demonstrates that rapid movement using bridge cranes can be achieved without inducing significant swing in the payload. This technology greatly decreases the time for materials movement (two orders-of-magnitude reduction in time) and increases safety by eliminating the potential for collisions of swinging payloads with objects in the work space. Sites such as WIPP and Hanford have indicated an interest in applying such technology to waste handling operations. Results of testing this system were reported in the 1990

Summer National American Nuclear Society Conference. A videotape of this demonstration was prepared and provided to the OTD.

The scaled waste tank remediation demonstration at SNL integrates sensors and advanced computer control into a commercial gantry robot. This system employs the equivalent of engineering drawings of a laboratory-scale simulated waste tank to automatically program collision-free robot motions. The robot system uses sensors (ultrasonics, lasers, ground penetrating radar, and metal detectors) to verify the information in the original drawings as well as to detect and map (in three dimensions) unknown objects such as pipes and the surface of the waste. The extensive use of models for robot system control allows graphical programming of the system complete with operator-supervised path planning. Automatic collision detection and avoidance provides enhanced system safety during all man-in-the-loop operations. Programmed operation speeds repetitive waste removal tanks. The RTDP is actively working with Hanford to integrate these technologies into early remote systems addressing the cleanup of single-shell tanks. Results of testing this system were reported at the 1990 Summer National American Nuclear Society Conference. A videotape of this demonstration was prepared and provided to the OTD.

ORNL has also demonstrated the integration of an advanced teleoperated controlled vehicle with advanced sensing technologies to speed the mapping of buried waste sites. A teleoperated all-terrain vehicle, on loan from the DOD Soldier-Robot Interface Program, is being used as a mobile sensor platform. This vehicle is equipped with a manipulator arm that will be used to position radiation detectors. Navigation technologies were coupled with the sensing information (from radiation, gas and subsurface large objects sensors) to automatically build sensor specific maps of subsurface materials. Such maps are critical to the successful remediation of buried waste sites. Robotic technology allows systematic generation of the audit trails necessary for quality assurance (QA). Successful testing of this first system was completed at a small buried waste site at ORNL. A video tape of this demonstration was prepared and provided to the OTD.

A team consisting of LLNL, SNL, LANL SAIC, and IBM demonstrated a robotic system for loading powder into a furnace in a plutonium production line, and then transferring the product to the next operation in a mock-up facility. The system demonstrated is an adaptation of an IBM commercial robot. This robotic system eliminates the need for operator hands-on transfer operations and reduces the generation of operator-associated waste materials such as wipes, protective clothing, gloves, and transfer bags. A videotape of this demonstration was prepared and provided to the OTD.

3.0

PROGRAM MANAGEMENT PLAN

3.0 PROGRAM MANAGEMENT

3.1 PROGRAM ORGANIZATION

The organization of the robotics technology development program is illustrated in Figure 3.1.1.

The RTDP is an element of the DOE ER&WM Applied RDDT&E program. It is administered by the ER&WM OTD through the Robotics Program Manager (RPM).

To ensure the responsiveness of the program to the needs of the DOE complex, the RPM will be assisted by an Operations Office Review Group (ORG). This group will have familiarity with the ER&WM issues facing the DOE complex. The RPM will also receive assistance from a Technical Review Group (TRG) of robotics and automation experts from DOE laboratories and sites, universities, industry, and other federal agencies. A Program and Budget subcommittee of the TRG will be appointed by the RPM.

The RPM will appoint several Robotics Applications Coordinators who will develop robotics program implementation plans with concurrence of the respective field office Technical Program Officer (TPO). The implementation plans will focus on each of the major ER&WM issues as identified in the scope. The RPM will also appoint an Advanced Technology Coordinator (ATC) who will develop a program plan for advanced robotics technology and cross-cutting technologies that are applicable to the major ER&WM issues. This plan will also have TPO concurrence.

3.2 FUNCTIONS AND RESPONSIBILITIES

Robotics Program Manager: The RPM is responsible for formulating, implementing, updating, and evaluating the RTDP. To discharge this responsibility, the RPM has the authority to allocate available resources for RDDT&E of robotics technologies for DOE's Office of Environmental Restoration and Waste Management.

The RPM has the responsibility to make sure that the RTDP draws on existing expertise both inside and outside of the DOE Complex. The RPM also initiates basic R&D as appropriate to meet the RTDP objectives. Participation will be based on technical capabilities and the needs of the program.

Technical Program Officer Review Group: The TPO RG, chaired by the Robotics Program Manager OTD, DOE-HQ, and made up of the Technical Program Officer from each of the eight DOE Field Offices or a designated site representative, will provide information for, and participate in, the development of the Plan's technical requirements and schedules.

The TPO RG insures that the site needs are addressed by the RTDP and will promote the application at the user sites of the systems developed.

The field office TPO has the responsibility to review and approve robotics program plans for their respective sites plus any changes

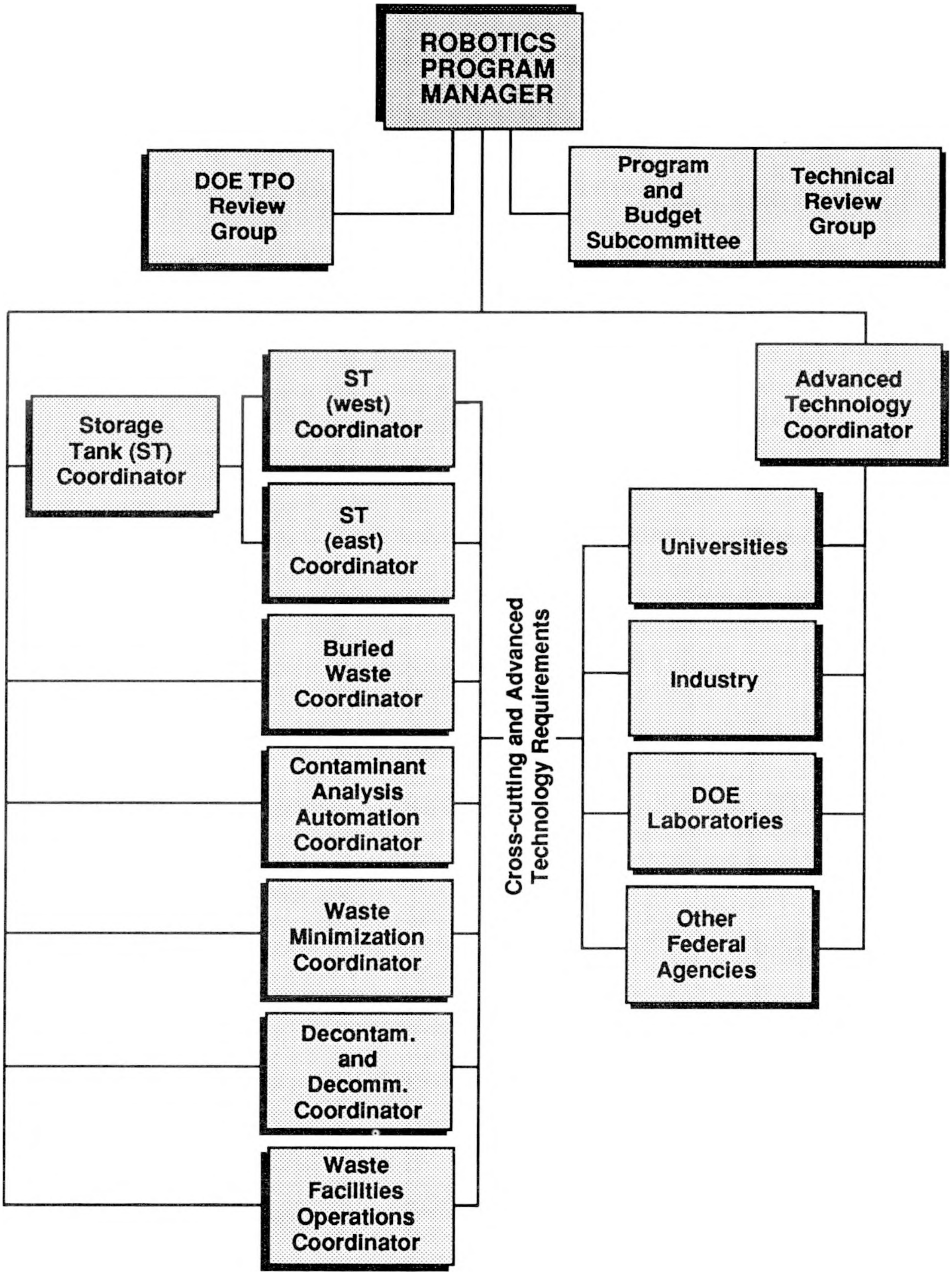


Figure 3.1.1 - RTDP Organization

thereafter. Programmatic directions to the field office contractors will be through the TPO. The TPO will interface with the OTD Robotics Program Manager on issues concerning progress reports, program/funding decisions, directions to field office contractors, and financial statusing.

Technical Review Group: The TRG, which is chaired by the RPM, is composed of technical experts from DOE laboratories and sites, universities, private industry, and other federal agencies. It is charged with the responsibility to evaluate RDDT&E proposals submitted to the RPM. The members have expertise both in robotic technologies and/or in environmental restoration and waste management issues. The RPM assigns TRG members to one or more subcommittees that will be responsible for evaluating proposals in basic research or in each of the applications areas supported by the RTDP. One such subcommittee will be appointed to recommend resource allocation among technology development areas to the RPM.

It should not be anticipated that support for robotics applications will be divided equally; rather, it will be concentrated in those areas where the need is the greatest or where DOE support will quickly lead to success in the development of robotics technologies for ER&WM applications.

Robotics Applications Coordinators: A coordinator has been appointed for each robotics application area reporting to the RPM. This person is responsible for coordinating the flow of technical information relevant to the applications area among those groups having an interest in the area, avoiding duplication, encouraging compatibility, interaction and cooperative efforts. (Financial reporting on RTDP grants should be made directly to the RPM.) Accordingly, all technical reports resulting from RTDP funding should be sent to the applications coordinator as well as to the RPM. The coordinator is responsible for keeping the other groups in the relevant applications areas appraised of the results of RTDP funded activities in that area. The coordinator, with the approval of the RPM, will also convene occasional conferences on the applications area.

The coordinators function as the advocate for the technologies applicable to their particular problem area. To facilitate the application of the best technology with a high probability of success to the particular problem area, the coordinator actively solicits proposals from the entire robotics and automation community for routing to the RPM. A thorough familiarity with the ER&WM problems and issues is required of the coordinators. This familiarity will be maintained through site visits, personal contacts, and symposia where appropriate.

Cross-cutting and advanced technology requirements will be funded through the applications coordinator who has identified the technological need. This will help insure that the applied R&D is responsive to the needs of the sponsoring group. Coordinators who put together a team approach with industry, laboratories, universities, or other agencies will be most favorably reviewed.

Advanced Technology Coordinator: The ATC reports to the RPM. He is responsible for coordinating the flow of technical information other than applied R&D. He is familiar with all aspects of the RTDP, identifies cross-cutting technology needs applicable to most or all of the major ER&WM issues identified in the scope, and is able to identify areas of future need in robotics and ancillary systems, that are not being addressed in the applied R&D areas. He is responsible for coordinating with universities, industry, DOE laboratories, and other federal agencies to bring proposals for needed advanced technology, to the TRG and RPM.

3.3 INTERFACES

Robotics Program Manager: The RPM will maintain close contact with the DOE sites and the environmental restoration projects and waste management operations at those sites. The Manager will have a formal top level interface with the ORG and the TRG. In addition, the RPM interfaces directly with project and operations staffs at the sites through the Robotics Applications Coordinators.

Technical Program Officer Review Group: The TPO RG is the primary interface to the end-user sites. The members of the TPO RG are closely involved in the ER&WM programs at their sites and provide site specific assistance to the RTDP staff. The TPO RG also provides an interface to the necessary support disciplines (e.g., industrial safety, maintenance, etc.) to insure a completed integrated system is delivered as the end product.

Technical Review Group: The TRG serves as the interface to robotic and automation systems development programs underway in other government agencies and the private sector in addition to DOE. RTDP staff who interface with the various key programs will periodically review relevant programs and report their status to the entire TRG and the RPM for consideration for inclusion in the RTDP. The TRG reviews proposals coming into the RTDP and makes recommendations for support to the RPM. It is anticipated that in some cases it will be advantageous to invest in some of these programs on a leverage basis. Thus programs which leverage funds from non-OTD/ER&WM sources and from other agencies, if they are technically applicable, will be given special consideration.

Robotics Application Coordinators: Each Coordinator communicates directly with the involved user group throughout the course of approved tasks to assure development of rigorous requirements, continued understanding of applications issues, design reviews, functional demonstrations, and final acceptance of advanced robotics systems by the end-user group. Interfaces will be identified with the user group to assure that testing and evaluation are performed most expeditiously and effectively. The user group must be directly involved in the performance of these tasks to facilitate end-user acceptance of the new systems. Each Coordinator communicates development status with the other Coordinators to assure that useful development information is communicated between projects. Coordinators are funded to provide the logistical/administrative support involved in coordinating of the input of other sites with the same need.

Advanced Technology Coordinator: The advanced technology coordinator communicates with the applications coordinators individually and as a group to identify technology needs that are cross-cutting applications, and integrates these into the advanced technology program plan. Furthermore, the advanced technology coordinator communicates with the applications coordinators to develop their interest in advanced technologies that can make application-specific systems faster, safer and cheaper. Plans for development of these advanced technologies are integrated into the advanced technology program plan.

The advanced technology coordinator interfaces with technical groups in the DOE laboratories and operating contractors, in other federal agencies, and with universities to bring forth proposals for advanced technology development. These interfaces will occur in many forums, workshops, seminars, and site visits.

3.4 PROGRAM PLANNING

A comprehensive technical program plan was developed during the first year of funding. This initial plan development was a significant effort since the plan is based on the needs of the environmental restoration and waste management operations as identified by the eight DOE field offices and the sites they administer. A major portion of the initial plan development was assessment and understanding of those needs. The technical program plan covers a five-year period with primary emphasis on the one-year plan and secondary emphasis on the two and three-year projections. The plan covers technical work and schedules and is tied closely to the requirements and schedules of individual site environmental restoration and waste management projects.

Six major cross-cutting ER&WM applications, of immediate importance and priority to the DOE, were used to provide the initial focus for the development of the 5-Year Program Plan for robotics RDDT&E. These are (1) Storage Tanks, above and underground; (2) Buried Waste; (3) Contaminant Analysis Automation; (4) Waste Minimization; (5) Decontamination & Decommissioning; and (6) Waste Facilities Operations. Additional applications will be developed during the evolution of the Plan as their importance and priority is established by DOE.

The technical Program Plan will be updated annually to support DOE budget planning and funding allocations. Each annual update will reflect actual accomplishments and will advance the Plan horizon by one fiscal year. Thus the Plan will always cover a five-year span with emphasis on near-term detailed plans.

Development of the Plan will include problem identification by the TPO RG. The TPO RG will obtain from each of the DOE sites a description and definition of their ER&WM projects.

The TRG will review these projects and identify potential robotics applications and will highlight problem areas and needs where robotics technology may have potential to do the job faster, cheaper, or safer. The TRG will assist the RPM in identifying the initial planning bases and resource requirements.

Development of detailed plans will begin with a series of interactive discussions among the Robotics Applications Coordinators. In these discussions the site project needs will be discussed, potential robotics application concepts will be identified, and the status of robotics technology relative to those applications will be defined. Applicable existing technology and technology development needs will be identified. These discussions will result in the identification of robotics technology projects which will be the planning basis for the program. The RPM, with assistance from the TRG, will assemble the individual robotic systems development activity plans into an integrated Program Plan. Each activity within the Program Plan will include a definition of objectives, resource and funding needs, schedules, and deliverables. Each activity will also specify a protocol, derived jointly with the end user, for measuring its success.

The Plan will be reviewed relative to site ER&WM project needs to identify common applications and to determine what changes in the technical approach would be needed for a cross-cutting technology application at multiple sites versus a specific application at one site. These individual robotic technology development activity Plans will be reviewed by the TRG and approved by the RPM.

The annual update of the Program Plan will follow the same logic as the Plan preparation discussed above. In many cases, the update will be a review and extension of existing plans. Each annual update will be a rigorous planning exercise with emphasis on understanding and meeting site ER&WM project needs with robotics technology which will enhance that project by improving safety, shortening overall schedules, and/or reducing costs.

4.0

SITE VISITS AND NEEDS

4.0 SITE VISITS AND NEEDS

4.1 SITE VISITS

In March 1990 RTDP planning teams visited five DOE sites. These sites were selected by the OTD to provide a needs basis for developing a 5-Year Plan. Visits to five DOE sites provided identification of needs for robotics technology development to support ER&WM projects at those sites. Additional site visits will be conducted in the future to expand the planning basis.

The purposes of these visits were (1) to understand the needs and requirements of the highest priority environmental restoration projects and waste management operations at the sites, (2) to obtain information for use in planning the Program, and (3) to describe the RTDP to personnel at the site and discuss development of the Program Plan. Emphasis was placed on both technical and schedule (i.e., compliance dates) needs and requirements.

The results of these visits are discussed in Volume III which summarizes the findings at each site and highlights priority needs. An overview of the findings from each site visit is provided in the following sections. These findings form the basis for the 5-Year Program Plan discussed in Section 6.0.

4.2 FERNALD SITE

Fernald is operating under the requirements of a CERCLA 120 Consent Agreement (CA) with the State of Ohio, U. S. Environmental Protection Agency (EPA), and DOE. Compliance dates in the agreement require that remediation efforts begin in 1993 for the silos and for stored and buried waste.

<u>Waste Storage Tank Remediation</u>: Fernald has four storage tanks (called "silos"), three in use and one unused and empty. Two of the silos contain pitchblende, which is the residue from 1950s uranium production. The third silo contains thorium oxide. The silos are approximately 80 ft in diameter, have walls 26 ft in height, and are filled to a depth of 18 to 22 ft. The silo walls have indications of external spalling and cracking, and radioactive contamination has leaked from the pitchblende-filled silos into the surrounding berm.

Alternatives are being evaluated for remedial action for the silos and the surrounding contaminated berm. The radiation levels within the silos are from 600 to 800 mrem/h, mostly from radon. If the waste materials are to be retrieved from the silos, then robotics technology will be needed for these operations.

<u>Buried Waste Retrieval</u>: Operable Unit No. 1 contains six pits designated as waste storage units. These pits have been characterized but the method of remediation has not been determined. Remediation options include retrieval and repackaging and in situ stabilization. The pits contain contaminated slurries and soils. One pit is designated as hazardous medical waste because of the presence of barium chloride. Robotics technology may be needed for waste retrieval operations to remove workers

from potential hazards at the excavation site.

Other Potential Needs: A significant inventory of thorium is stored in steel drums and containers at the Fernald site. The radiation field around the drums has a range of 100 to 190 mrem/h, so that shielding is required for any drum handling or inspection. There are about 13,000 drums in warehouse storage in this category. Robotics technology may be needed to support handling and repackaging operations.

There are about 100,000 drums of waste, stored around the Fernald site, that contain chemical and/or radioactive hazardous material. The physical condition of many of the drums is poor because of deterioration. Robotics technology may be needed for inspection, handling, and repackaging operations.

4.3 HANFORD SITE

The Hanford site is operating under the requirements of the FFCA with the State of Washington, EPA, and DOE. The conditions of the FFCA require that remediation efforts begin in 1994 for the remediation of single-shell storage tanks (SSTs). Later dates have been agreed to for completion of SST remediation, as well as remediation of stored and buried waste.

Waste Storage Tank Remediation: There are 149 SSTs located on the Hanford site and grouped according to EPA designations. The tanks are underground vertical cylinders with few penetrations. The internals of the tanks have several obstacles consisting of pumps, thermal wells, inlet and outlet piping, and cooling coils around the walls and the floor of the tanks. In general, the SSTs are 75 ft in diameter, with wall heights of 18 to 33 ft. A few of the tanks are smaller. The SSTs collectively contain 37 M gal of waste.

The types of waste contents are liquid, salt cake, and sludge. Currently, liquids are being removed from SSTs. Composition of the wastes ranges from hard crystalline structure to thermally warm viscous material. The contents of all of the tanks are both chemically and radioactively hazardous. Robotics technology will be needed to support sampling and retrieval of the tank contents, since the high radioactivity and hazardous chemicals preclude any but remote operations.

Stored and Buried Waste Retrieval: Hanford has about 1100 sites applicable to EPA's Operable Unit category. These sites contain Low-Level Waste and pre-1970 Transuranic (TRU) wastes. The sites first must be characterized, and methods of remediation developed and agreed upon. A determination then must be made on a site-by-site basis whether to retrieve and repackage or to stabilize in situ and cap with a near-impermeable cap. Robotics technology may be needed for remote retrieval operations.

Other Needs: There are several caissons and other storage sites at Hanford that contain solid wastes. These wastes are designated as extremely hazardous from its unknown material characteristics. They are chemically hazardous, have high curie content, and are classified as "mixed waste." Robotics technology may be needed for characterization and retrieval of these materials.

Waste tanks and contaminated sites must be sampled to determine the nature of, and chemical composition of, the materials. The procedure of characterization helps to determine the type of remediation and specify the processes to be performed on the waste to stabilize it for long-term storage. The samples take from 2 to 4 weeks to retrieve, and up to 6 months to analyze. Hazardous components of the samples can be lost during the long pre-analysis time, making resulting data questionable. These process times and sample integrity concerns will severely impact the efforts for remediation within the time constraints of the FFCA. Data reduction and report preparation are extremely time-consuming. These activities could be enhanced through application of advanced robotics.

4.4 INEL SITE

The INEL is operating under an FFCA with the State of Idaho, EPA, and DOE. There is a significant amount of buried waste on the INEL reservation that has potential for contaminating an aquifer under the site.

Buried TRU Waste: The buried waste consists of TRU wastes received from the Rocky Flats Plant and buried prior to 1970. The volume of waste in this category is estimated to be 2 M ft^3 of contaminated, hazardous, radioactive material and 6 M ft^3 of similarly contaminated soil, all contained in an area designated as the "Subsurface Disposal Area" (SDA). This waste was received in cardboard boxes, steel drums, plywood boxes, and as loose material. Sampling wells in the area of the SDA have indicated traces of plutonium and carbon tetrachloride in subsurface water at about a 100-ft depth. A large aquifer is located at 550 ft below the surface of the ground.

Typical wastes in the burial ground are TRU, Remote Handled TRU (RH-TRU), highly volatile contaminated liquids, low viscosity contaminated lubricants, contaminated particulates, low flash point combustible liquids, acid and alkaline byproducts, pyrophoric materials, chemically active compounds, various radionuclides, and contaminated large solids (e.g., vehicles, machinery, piping, etc.).

INEL is conceptually designing a facility that will retrieve, process, and package buried wastes remotely. Remotely operated sensing systems used to characterize the wastes prior to excavation are included in the pre-conceptual planning.

Waste Storage Tanks: INEL has single-shell waste storage tanks similar to those at Hanford, but INEL does not have the quantity of tanks to remediate. Hanford and INEL are collaborating on the development of technology for SST tank remediation.

Stored Retrievable Waste: Stored waste (as opposed to buried waste) is contained in metal drums and plywood fiberglass-reinforced, plastic-coated boxes. These containers have been received since 1970 and contain TRU waste with partially known contents. The Transuranics Storage Area (TSA) contains 130,100 barrels and 11,500 boxes of stored waste. There are 35,200 containers of waste stored in weatherproof fabric/poly air-supported buildings. The remaining waste is stored on asphalt pads and covered with plywood, polyethylene, and earthen berm. The total volume of the stored TRU waste is 2.4 M ft^3.

INEL is currently designing new storage buildings for the stored waste.

All stored waste is considered to be in interim storage. EPA requires weekly inspection of waste containers in interim storage, which will detect indications of gross deterioration or gross leakage of the primary container.

Taking advantage of remote sensing and vision systems could eliminate the need for personnel access between stored waste containers. Containers could be configured in a close-packed array, which would reduce both the number of storage buildings needed and, significantly, the cost of storage construction.

Much of the stored waste may have to be repackaged for permanent disposal. Typical wastes to be repackaged are highly volatile contaminated liquids, low viscosity contaminated lubricants, contaminated particulate, low flash point combustible liquids, acid and alkaline byproducts, pyrophoric materials, chemically active compounds, and various radionuclides. Safety issues specifically related to handling of pyrophoric materials will have to be addressed and met. Remote ways to safely handle and repackage this waste will be required.

Other Site Needs: Sampling and analysis will have to be performed on all waste tanks, sites, and stored waste. Sample taking and analysis is time-consuming, and thus will impact FFCA remediation dates unless automation is used to reduce both time and costs.

4.5 ROCKY FLATS SITE

The Rocky Flats Site is operating under the requirements of a Draft FFCA with the State of Colorado, EPA, and DOE. The conditions of the FFCA have not yet been negotiated; therefore, remediation schedule dates for the 881 Hillside, Old Burial Sites, and Stored Residues are not available. The Solar Evaporation Ponds are to be closed by October 1991.

Solar Evaporation Ponds: Located at Rocky Flats Plant are five Solar Evaporation Ponds that are used to retain and control contaminated process water. They allow solids to settle and liquids to evaporate pending contaminated material disposal. The sludge in the ponds principally contains heavy metals such as cadmium, and may contain some radionuclides.

The Solar Ponds are being dewatered, and the remaining sludges are being mixed as part of the aggregate in a concrete mixture and formed into 4- × 4- × 4-ft blocks. The "pondcrete" blocks are then readied for shipment to the Nevada Test Site for permanent retention. The pondcrete blocks must met the land disposal limits for cadmium in order to be shipped to Nevada. However, some of the blocks prepared to date do not meet pending EPA Land Disposal criteria.

The contents of the ponds include the heavy metals that comprise part of the solids in the sludge. Additionally, since it is probable that the asphalt liner for the ponds will have to be removed, the heavy equipment necessary for that operation may stir up considerable airborne contamination. For worker health and safety, this will require that workers wear full air suits during the pond remediation. Automatic Guided Vehicles (AGVs) could, however, support these remediation activities and counter the need for air suits.

Stored and Buried Waste Retrieval: The 881 Hillside and the groundwater at the base of the hill are contaminated with volatile organic compounds (VOCs) and heavy metals. Each rainfall/snowfall and eventual water runoff results in additional contamination washing off the hillside and extending the contaminated groundwater plume zone.

Several burial sites on the east end of the plant contain wastes that have been buried since the early 1950s. The wastes consist of depleted uranium, plutonium, carbon tetrachloride (which has migrated), lithium, sodium, and some americium (decay product of plutonium). The level of hazard is not well defined.

Stored residues are a class of waste which may be determined to contain materials with value. The Rocky Flats residues were generated from the incineration of glove box operation wastes and are stored in drums in buildings on site. The residues contain plutonium which may exceed 5 g/bbl. These residues are presently classified as "speculative retention" and a decision must be made within a specified time period as to the disposition of the residue (i.e., reclaim the plutonium and process the waste). If such a decision is not made, the law mandates the residues be classified as "waste" and must be treated as such.

Robotics may be needed for remote retrieval and handling operations.

Other Needs: Rocky Flats has designed, and is installing, a supercompactor for shredding and compacting waste materials generated at the plant. There may be a need for some robotic applications that will enhance glove box operations.

Another area that could benefit from robotics support is effluent line location and remediation. The Rocky Flats Plant has a considerable number of abandoned waste effluent lines emanating from production facilities. It is probable that these lines will have to be dug up along with the surrounding contaminated soil. This problem is common to several facilities. To minimize the amount of soil removal, a method of real-time sensing for multiple contaminates will have to be developed. The soil removal operations could be enhanced with the use of AGVs.

4.6 SAVANNAH RIVER SITE

The Savannah River Site (SRS) is presently negotiating an FFCA between the State of South Carolina, EPA, and DOE. The Resource Conservation and Recovery Act's (RCRA) Facility Investigation (FI) Program is active and scheduled for completion in FY 1992. Remedial Investigation (RI) and Feasibility Studies (FS) investigations are planned to start in FY 1990 and will continue through FY 1996. Firm reclamation dates will be published when negotiations are complete.

Waste Storage Tank Remediation: There are 51 high-level radioactive waste tanks at the SR site that either have received, or are receiving, liquid wastes from operations in the *F* and *H* canyons. The wastes in the tanks are allowed to settle, and the supernate is decanted off and then treated. The sludge settling out of the liquid wastes have remained in the tanks.

All of the tanks are constructed of carbon steel and are 75 to 85 ft in diameter. All have some form of secondary containment, such as carbon steel or concrete catch pans. The SR site operations staff consider the materials in the waste tanks to be well characterized because of the hundreds of samples taken.

All tanks have been inspected. Nine tanks show signs of leakage to the secondary containment (catch pan). One tank (No. 16) overflowed its catch pan in 1960 and the tank was emptied at that time. The materials (in the catch basins and annulus areas of the nine tanks that have leaked) are high-level waste salt crystals.

Retrieval of wastes from the tanks will be performed by mobilizing and pumping. Clean out of residual materials and decontamination of the tanks may need robotics technology support since the high radioactivity, hazardous chemicals, and remote/limited access preclude hands-on operations.

Stored and Buried Waste Retrieval: Interim storage for post-1970 TRU waste is provided outdoors on concrete pads. The TRU waste is contained in drums, boxes and large concrete culverts. Some of the stored waste has been covered with earth. This storage arrangement was set up 20 years ago.

There are about 24,000 drums currently in interim storage and additional containers of waste are being received at a rate of about 2000/year. The SR site has the largest inventory of waste by curie content in the DOE complex. Before CY 1995, a portion of the stored waste will exceed the 20-year design storage limit. A facility for certifying newly generated waste for WIPP has been built. A new Transuranic Waste Facility to retrieve, repackage, and certify waste for WIPP will start up in 1998. The robotics technology planned is generally commercially available equipment.

The SR site seepage basins receive low-level radioactive waste water from the Savannah River Plant. The current proposed closure method consists of stabilization of basin liquids followed by backfilling and capping of the basin. Other closure options are being evaluated.

The five reactor areas at the SR site use earthen seepage basins to dispose of low-level radioactive purge waters from the reactor disassembly basins. There are fourteen reactor seepage basins on the site of which seven (six in *R* area and one in *K* area) are inactive. Six of these inactive basins (Nos. 1 through 6) were deactivated and backfilled from 1958 through 1977. Options for permanent closure of these basins are being evaluated.

One method being considered, which could become the preferred method, is retrieval of settled materials for packaging and disposal. This method would require remote systems and robotics to support remediation of these sites.

Other Needs: Savannah River has numerous glove box, canyon, and stet facilities. Remediation of the facilities will require D&D, which will require the use of robotics due to the extreme radiation fields.

5.0

APPROACH TO NEEDS DIRECTED TECHNOLOGY DEVELOPMENT

5.0 APPROACH TO NEEDS DIRECTED TECHNOLOGY DEVELOPMENT

Site needs provide the focus for the RTDP. The RTDP 5-Year Plan will be updated annually in order to reflect completion of technology developments as they occur as well as to reflect evolving priorities within the ER&WM program itself. In this first plan, six areas have been identified as having priority for development and application of advanced robotics and automation technologies:

- Waste storage tanks have reached the end of their design life at many sites around the DOE complex and are leaking radioactive and chemically hazardous materials into the environment.

- Buried waste sites are releasing radioactive and chemical hazards into the environment at a number of DOE locations.

- The shortage of analytical laboratory facilities and trained chemists is a barrier to meeting the site characterization requirements of the ER&WM.

- Waste generated during production operations needs to be minimized.

- Inactive nuclear facilities, such as canyons, glove boxes, reactors, hot cells and gaseous diffusion plants, must be decontaminated and decommissioned.

- Wastes stored at sites must be inspected weekly and, in some cases, repackaged.

Visits to five DOE sites (Hanford, INEL, Rocky Flats, Fernald, and Savannah River Site) have been made by a DOE robotics planning team. The results of these visits were used to identify the five areas of potential need for robotics technology and to develop needs-driven requirements for robotic systems. This information, when integrated with an assessment of currently available technology and the potential payoff for advanced robotics, results in a focused plan for robotics RDDT&E.

5.1 APPROACH

The basic RTDP approach to developing technology is to meet near-term remediation needs while fostering Cross-cutting and Advanced Technology Development to solve difficult long-term ER&WM needs.

Attention to solving near-term needs, as well as developing advanced technology:

- provides credibility by helping to solve critical site cleanup problems early on in the program on a schedule that supports ER&WM;

- stimulates early teaming and trust through the combined involvement of the industrial, remediation, and research communities early in the program;

- provides focus for cross-cutting and advanced technology development efforts; and

- stimulates faster adoption of newly developed technologies that reduce overall costs and increase safety as they become available by encouraging meaningful participation of all sectors from the beginning.

Near-term remediation needs can be met by integrating available commercial technologies with emerging technologies available in R&D laboratories to produce early system technology demonstrations (Figure 5.1.1) at DOE sites performing ER&WM activities. These include cold demonstrations (non-radiation environments) that, when successfully completed, lead to hot demonstration, test, and evaluation of the robotics applications to waste management and remediation activities. As needs for new technology are defined through the interactions of the industrial and R&D communities with the site remediation technologists, the R&D talents existing within universities, industry, DOE sites and laboratories, and other government laboratories are directed toward the development of cross-cutting and advanced technology.

Cross-cutting and advanced technology development has two important products, as shown in Figure 5.1.1:

- new robotics technologies applicable to the cleanup and management of waste, and

- advanced R&D capabilities in the form of degreed researchers, enhanced laboratory capabilities, and an increased knowledge base.

Early involvement of the industrial community with the teams addressing near-term waste management and remediation needs for robotics fosters an environment for accelerated technology transfer. Transfer of new technology out of the R&D laboratories provides the new commercial products that form the base of new technology approaches needed for solving site cleanup problems faster, safer, and cheaper. Similarly, the advanced R&D capabilities resulting from the performance of cross-cutting and advanced technology development form the foundation necessary to support further advances in technology. The continuing involvement of the R&D community with commercial suppliers and site ER&WM organizations supports the early integration of emerging, pre-commercial technology into early systems for accelerated robotics application to site ER&WM needs.

This cyclical process continues throughout the life of the technology development process, feeding the applications requiring new technology both by developing new products and by fostering the institutional interactions and infrastructures needed to aggressively implement new technologies as soon as they become available. In addition, the close interaction of the R&D and industrial communities with the site ER&WM organizations helps ensure that cross-cutting and advanced technologies with the highest potential payoff are developed first.

5.2 PRIORITIZING RTDP TECHNOLOGY OPTIONS

The goal of the RTDP is robotics technology which will help ER&WM activities at DOE sites to be "faster,

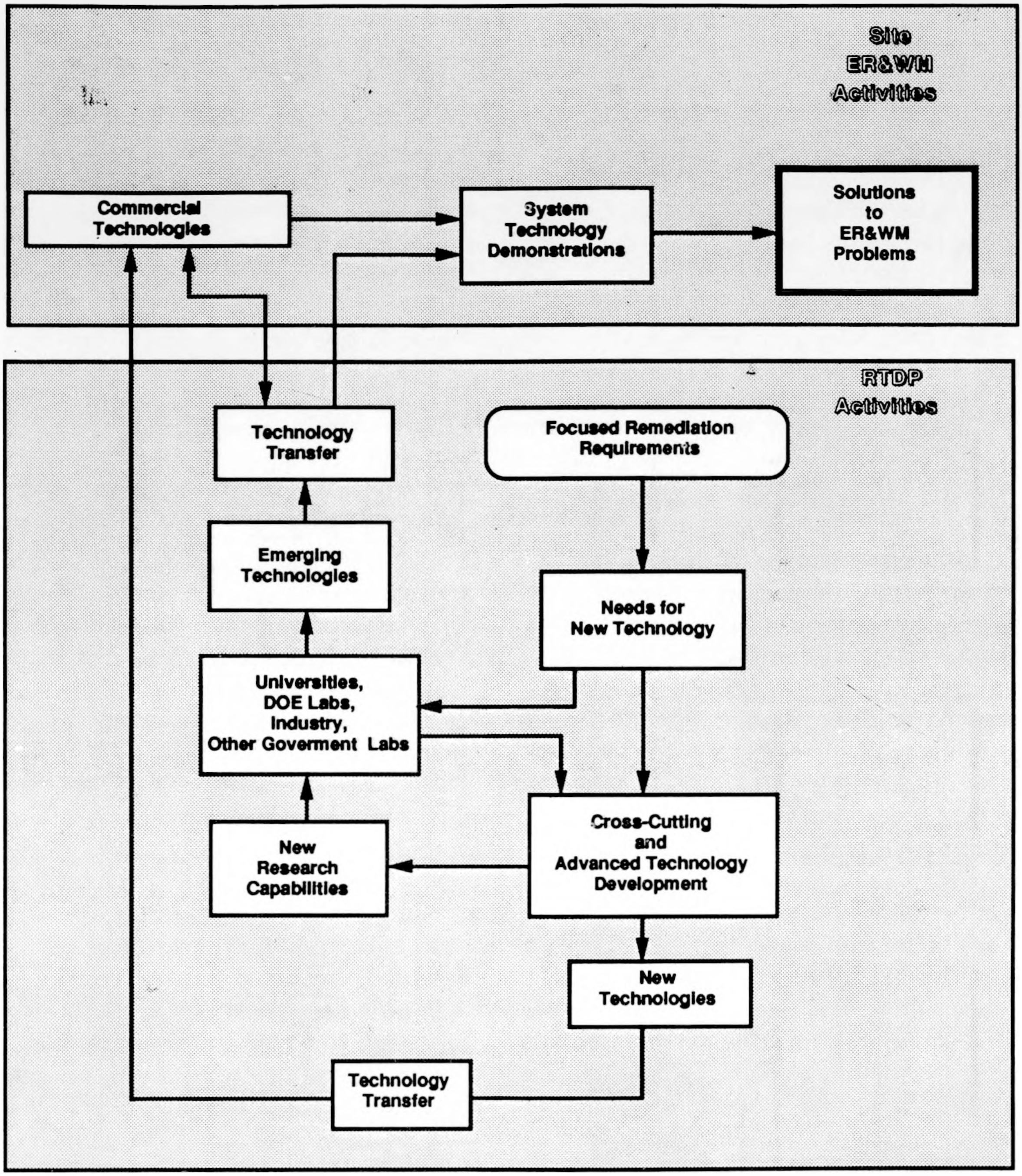


Figure 5.1.1 - RTDP Approach to Technology Development

safer, and cheaper". The Program will develop a cost/benefit methodology which will allow options to be prioritized in regard to the "faster, safer, cheaper" goal. The methodology will take into account capital, operating and disposal costs of robotic systems. Although these estimates of cost and benefit are incomplete at the time of preparation of this plan, the basic characteristics of robotic systems do provide insight into their potential impact on ER&WM.

Faster - Due to the hazardous nature of many ER&WM environments, human entry may be proscribed. Past experience has shown that tasks in which the use of conventional remotely operated equipment is required typically take 8 to 50 times longer to complete than if the task were performed hands-on by unencumbered skilled humans. However, recent tests at DOE laboratories have shown that programmable devices (robots) can perform many of the remote tasks similar to those anticipated in ER&WM projects at speeds comparable to unencumbered humans. Thus, robotics technology should significantly decrease the time required for many remote ER&WM operations, and therefore has significant potential to lower the life cycle operating costs. In applications were the same task must be carried out many times, such as remediation of the 149 underground storage tanks at Hanford, important system optimization is enabled by the faster operation of robotic systems. For example, if a comparison is made between robotic systems and standard teleoperators, the same number of robot systems can complete the cleanup significantly faster, whereas fewer robot systems are required to complete the cleanup in equal time. In other words, tradeoffs can be made between capital and operating costs.

Safer - Two safety issues are important in the consideration of remote systems. First, remote systems can reduce the exposure of personnel to levels near zero. The cost of personnel exposure will be accounted for in the cost/benefit methodology being developed by the program.

Second, robotic systems have the potential to significantly increase the safety of remote operations. By carrying out programmed, autonomous operations in some cases and by providing assistance to human operators, robotic systems can significantly reduce the operator fatigue normally associated with remote systems. Fewer operators will thereby be required, thus lowering system operating costs.

In addition, sensor-based telerobotics, operating with knowledge of their environment and proper procedures, can monitor and evaluate operator instructions and not perform those potentially resulting in dangerous operation or violating established procedures. Computer monitoring of robotic operations (even when operated in predominantly manual modes) allows automatic generation of QA audit trails.

Cheaper - In addition to potential cost savings already mentioned, remote systems can produce additional savings by minimizing waste production and thereby minimizing the cost of

transporting and storing waste. For example, it is estimated that 70% of the radioactive waste generated at Rocky Flats derives from protective clothing and packaging materials associated with direct human handling.
The benefits mentioned are not free of course. When compared to remote manual systems, the principal cost increase associated with robots is the cost of the computing systems and sensors. This extra cost is expected to be in the range of $25,000 for simple systems to $300,000 to $500,000 for complex systems. Many of the remote ER&WM systems are expected to cost many millions of dollars. Thus, the decreased time of ER&WM operations resulting from a relatively small percentage increase in cost to provide computer controlled robots can result in dramatic ER&WM cost savings.

Experimental verification that robotic systems are faster is critical to the credibility of the RTDP prioritization process. Experiments will be carried out as part of the development of the methodology for use in assessing the costs and "faster, safer, cheaper" benefits of the robotic technology options.

5.3 THE AVAILABLE TECHNOLOGY BASE SUPPORTING THE RTDP

The Department of Energy will make use of the existing U.S. technology base in executing the RTDP. In many cases, industrial robotic technologies can be adapted for early applications in ER&WM operations. Technology developed in DOD and NASA programs has the potential to be modified and applied to DOE problems. Finally, the federal laboratories and DOE sites have been focusing their efforts on the development of remote technologies for a number of years and have robotics technology and technical expertise suitable for ER&WM applications. The Department is actively seeking participants in the program.

6.0

APPLICATION-SPECIFIC TECHNOLOGY DEVELOPMENT

6.0 APPLICATION-SPECIFIC TECHNOLOGY DEVELOPMENT

The following sections describe both the near-term and advanced technology developments needed to decrease the time, improve the safety, and reduce the life cycle costs of ER&WM operations. Six major ER&WM areas are discussed:

- Waste Storage Tanks,
- Buried Waste,
- Contaminant Analysis Automation,
- Waste Minimization, and
- Decontamination and Decommissioning.
- Waste Facilities Operations

This first RTDP 5-Year Plan should be considered a starting point. It will be updated annually as the five-year planning horizon shifts into the future.

6.1 WASTE STORAGE TANKS

There is a large amount of radioactive waste stored in tanks across the DOE complex. The following discussion is based on present knowledge of this area and early engineering assessments of the potential for applying robotics technology to cleaning up these tanks.

6.1.1 Description of the Need

As discussed in Section 4.0 the DOE has significant amounts of radioactive waste stored in single-shell storage tanks and silos. The large majority of these tanks is buried. Waste generation began in the 1940s as a by-product of the production of nuclear weapons. Many of these storage tanks have reached their design life and are of questionable seismic stability. In addition, some are deteriorating structurally and are leaking to the environment.

Waste storage tanks range in size up to approximately 85 ft in diameter and contain up to 1 million gallons of waste each. The wastes are chemically and radiologically hazardous with radiation levels ranging from slightly above background to thousands of rads/hr. The consistency of the waste ranges from pumpable liquids and slurries to thick sludges and large crystalline masses.

Access to the tanks is typically limited to existing risers and man ways. Although the addition of entry ways to gain better tank access is being studied, it is highly desirable to maintain the integrity of the tank in order to minimize the potential for release of hazardous material to the atmosphere. Finally, it is anticipated that some of the tank domes may not be able to support the weight of inspection and remediation equipment and that external bracing and support will be required during remediation operations.

While all DOE production sites have waste storage tanks, the two most critical sites are Feed Materials Production Center in Fernald, Ohio, and the Hanford Site in Washington. Both sites face early EPA compliance milestones for waste tank remediation. The SRS and INEL are also facing environmental compliance regulations although at the time of this writing, the agreements are in draft form.

6.1.2 Planned Remediation Tasks

Remediation tasks planned by the DOE sites include the determination of the physical, chemical, and radiological characteristics of the waste. Due to the difficulty and expense of obtaining and analyzing samples, only limited sampling is currently being performed. Photographic techniques are used to examine in-tank structures and solid waste formations. INEL is purchasing a specially designed robot (payload of 30 lb) to spray wash the interior walls of their waste storage tanks to allow examination of these tank walls for deterioration.

Once characterization has been completed, the waste will either be treated in situ or removed for treatment and subsequent storage. Currently, the Tri-Party Agreement at Hanford requires removal of the waste, at least in early demonstrations. SRS is planning to pump waste slurries from the tanks to a vitrification facility. Other sites are evaluating alternatives for remediation of waste storage tanks and silos. In the case of pumpable waste, removal is relatively straightforward. However, as discussed above, many waste forms are not directly pumpable and will have to be mobilized using technologies employing high pressure water, air, or other fluids or more conventional digging technologies. Large objects (e.g., pipes and recirculating pumps) or other solids may have to be cut and removed in pieces. In all cases, the hazardous nature of the waste requires that containment be maintained to prevent escape of hazardous material to the environment.

6.1.3 Technology Development Plan

The DOE sites have just begun the process of cleaning up the wastes currently stored in tanks. As a result, concepts for remediation of these waste tanks are preliminary. Several basic concepts are emerging, however, that appear to be broadly applicable. A concept used as the reference from this plan is illustrated on Figure 6.1.1.

The 5-Year Plan for robotics RDDT&E to support waste storage tank remedial actions is illustrated in Figure 6.1.2. This logic chart shows the major elements of technology development with respect to ER&WM projects at DOE sites. The timing of results from technology development activities is shown by the arrows. These results are keyed to specific needs at DOE sites, which are shown on the project lines for each site. Significant dates for the site projects are shown in the ovals.

The principal thrust of the technology development plan illustrated in Figure 6.1.2 is robotics support for K-65 Silos Remedial Actions at the Fernald Site and the Single-Shell Tank Waste Retrieval Project at the Hanford site. In both cases the technology development plan is strongly influenced by compliance dates and support for demonstrations at the sites. The plan is oriented toward integrating robotics technology into the project-related demonstrations at the sites. Key dates driving the schedule are the start of K-65 silos remedial actions at Fernald in FY 1993 and the completion of the cold demonstration design at Hanford in FY 1994.

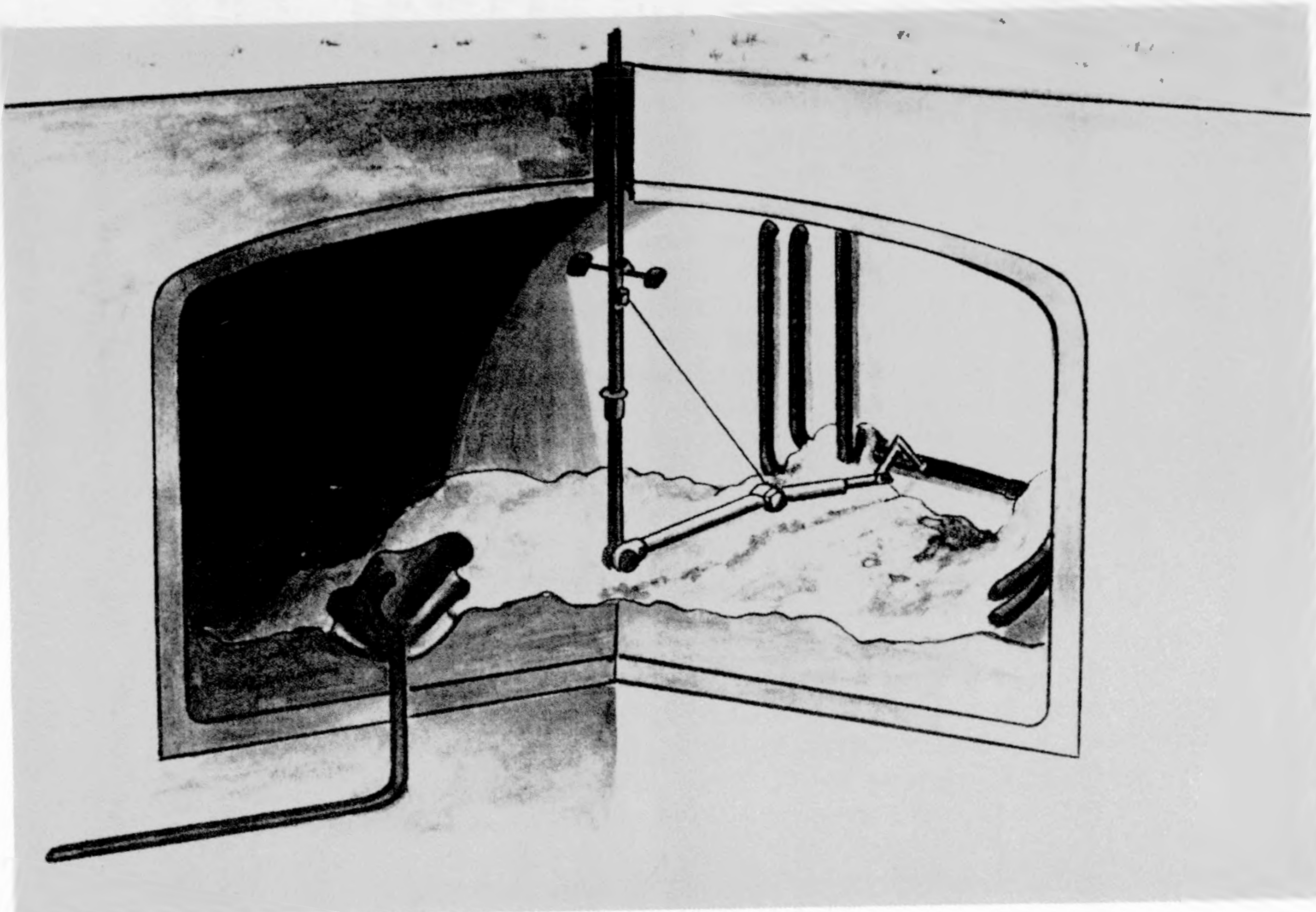
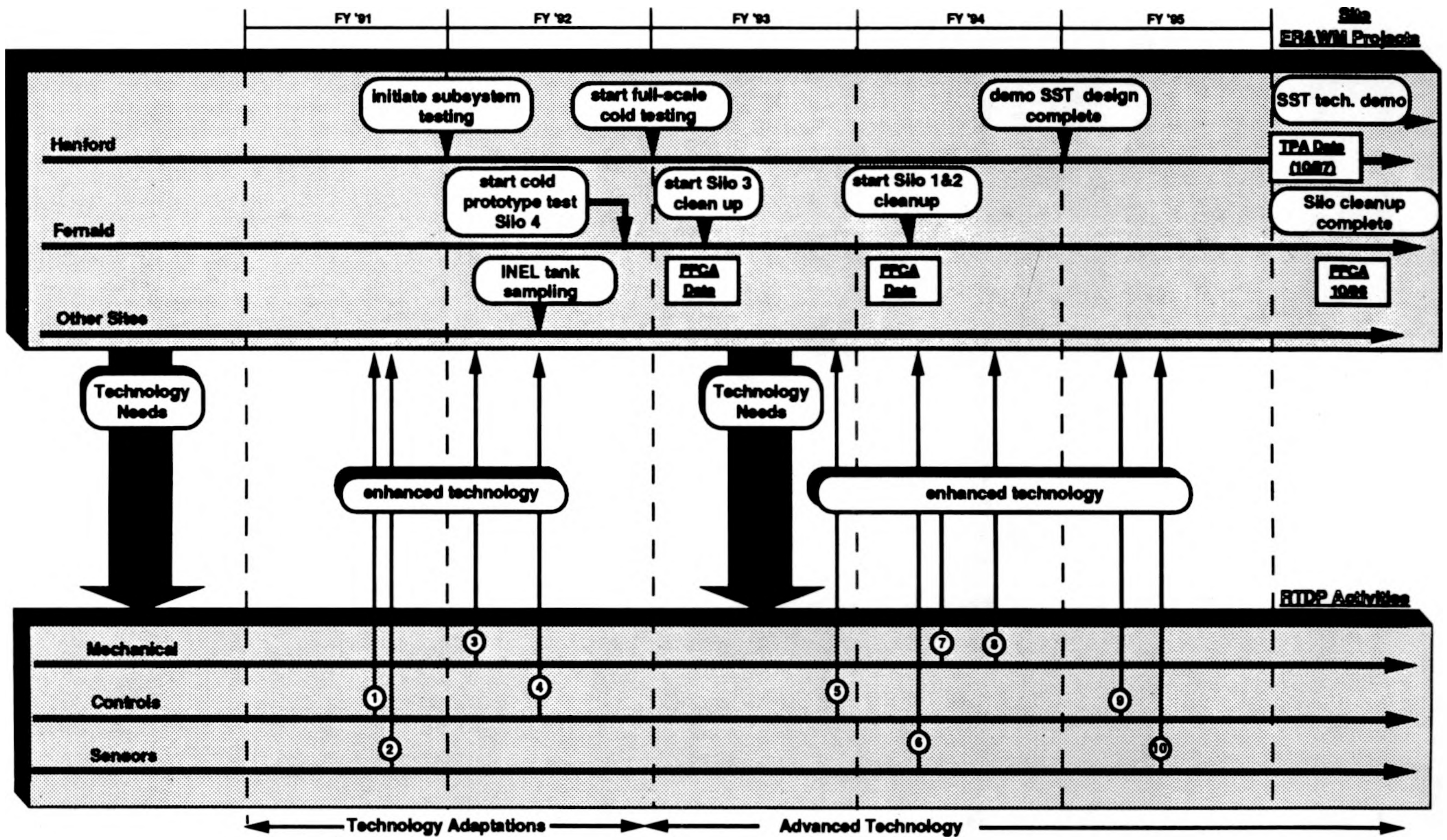


Figure 6.1.1 Robotic System Concept - Waste Storage Tank Remediation

Figure 6.1.2

ROBOTICS TECHNOLOGY DEVELOPMENT - WASTE STORAGE TANKS



① - force, proximity, graphic control

② - proximity, force/torque sensors

③ - high strength positioner/ dexterous manipulator

④ - 3-D viewing systems

⑤ - advanced world modeling, servo oscillation damping, force reflection

⑥ - hardened sensors

⑦ - high dexterity manipulator/end-effector, passive oscillation damping

⑧ - environmental hardening

⑨ - parallel computing, adv. servo damping, standard robot programming lang.

⑩ - real-time computer vision, whole arm collision detection

Figure 6.1.2 Robotics Technology Development - Waste Storage Tanks

In summary, Figure 6.1.2 provides a road map and framework to guide detailed planning for the robotics technology development supporting waste storage tank remedial action projects.

6.1.3.1 Mechanical Subsystems

Near-Term Technology Adaptations: In almost all cases, there is a need for a large articulated manipulator or other robotic device that can enter a tank through a limited number of existing openings (preferably one) to minimize the potential for atmospheric contamination. Adaptation of existing manipulator and other remote systems technology coupled with focused development can support remediation of the silos at Fernald and the full-scale testing activities scheduled for Hanford. Early engineering concepts have focused on long-reach, high-strength robotic arms that can enter through the existing man ways in the center of the silos and tanks and then extend out to reach all locations. The size of existing openings presents a significant technical challenge. Since the tops of the tanks and silos may not support the weight of a robot, an external superstructure to support the robot's weight would most likely be employed. The robot manipulator would either fold upon itself or telescope. Motion would include rotation around the vertical tank axis, as well as radial and vertical extension, to allow access to all locations.

Due to the difficulty of deploying very long-reach articulated robotic arms through small openings, some concepts envision locking the joints after gross positioning to ensure that the characterization and/or retrieval equipment are stably positioned. Alternatively, should the development of long-reach, high-strength arms prove impractical in the near term, shorter-reach articulated arms or other robotic devices that are moved to different tank access ports may be needed. Thorough engineering design studies must be performed to assess the best near-term technology to use. First-generation robot manipulator technologies for tank entry are expected in FY 1992. Environmental hardening technologies existing in research laboratories will be coupled with commercial technologies to prolong the in-tank life of mechanisms.

Positioning of waste characterization and retrieval devices may require end-effectors with dexterity. It is anticipated that existing end-effector technologies can be adapted to the needs at Fernald. High-dexterity, environmentally hardened end-effectors may be needed for the in-tank environments at Hanford. Commercial, multiple degree-of-freedom robot manipulators may be adapted to these needs and integrated into early cold demonstrations. For manipulation of objects that may be found in the tanks, end-effectors with mechanical jaws may be required. Cutting and breaking operations are not anticipated at this time for the early cleanup operations involving the Fernald silos.

Modularity will be required in all mechanical systems (drives and structures) to facilitate repair and maintenance. It is expected that any system entering the waste tanks will become contaminated. Design for decontamination is very important. Maintenance will be done either remotely or manually, using glove box handling technology.

Technology Development: A primary focus for technology development will be the complex SST environments at sites such as Hanford and INEL. The RTDP will parallel the ongoing SST cleanup programs to accelerate integration of advanced technology into planned testing and demonstration programs. Large mechanical manipulators of increased dexterity may be required because of the complex geometric interior structures of the Hanford tanks. Even if internal pipes and structures are removed during the tank cleanup process, the removal process itself may require arm dexterity. Currently, it is anticipated that an advanced version of the high-strength positioner envisioned for early demonstrations will be required. It is expected that the payload of the arms used in the Hanford SSTs will be higher because of the more complex nature of the waste in the Hanford tanks. Advanced, passive vibration-damping technologies will be developed to assist the control technologies employed in the operation of these large positioning mechanisms. This technology is expected to be available in FY 1994 in time to support the Hanford cold test demonstration.

In addition to advanced robot arms to position waste characterization and retrieval equipment, high dexterity end-effectors may be required for fine motion control. Operations such as cutting, grinding, and positioning of high-pressure air jets for breaking up large solid waste masses will require careful control. High degree-of-freedom, high-strength end-effectors that can be operated under sensor control and reach into confined locations can be developed by FY 1994. Since no single end effector is expected to be able to perform all anticipated operations, technologies for rapid, high-reliability end effector changing will be required. High-reliability hydraulic systems may be required to deliver the power needed for many of the anticipated remediation operations.

Because of the anticipated difficulty of maintaining contaminated systems, development of reliable, low maintenance, robotic systems is very important. Hardening of mechanical subsystems against both chemical and radiation effects (e.g., use of resolvers instead of the more common optical encoders) will be an important part of the advanced technology development activities. This work will build upon existing environmental handling expertise within the nuclear and chemical industries. The first hardened systems should be available in FY 1994. Advanced technology developed within this element of the RTDP would be ready for testing in the proposed Hanford Cold Test Facility in time to impact the design of the remediation systems used in the SST cleanup demonstration in FY 1997. These hardened systems would also serve as prototypes for the even more advanced systems employed for future closure of SSTs.

This technology, while focused on the needs at Fernald and Hanford, would also find application in cleaning up the sludge around the cooling coils of the INEL waste tanks and the residues anticipated to remain in the SRS tanks.

6.1.3.2 Control Subsystems

The system control for robotic systems deployed in the cleanup of the waste storage tanks and silos at Hanford and Fernald, as well as other sites across the DOE complex, will need the technology attributes discussed in Section 7, Cross-Cutting and Advanced Robotic Technology Development. Technology for robotic systems control is typically quite generic, with the same basic technology meeting the needs of a large variety of applications. Thus, only those technology development needs specific to the remediation of waste storage tanks will be discussed here.

Near-Term Technology Adaptation: Technologies for preparing highly-structured software architectures functioning in multi-processor, real-time control systems can be merged with commercial robot control technologies to produce early model-based, sensor-directed robot system controllers in late FY 1991. These near-term technology adaptations will be available in time to support both the start of silo cleanup at Fernald and the full-scale cold testing at Hanford. Application of this technology will focus on adapting structured software programming techniques to existing computing and operating systems. Technology in computer graphics will be used to allow graphical programming of robot actions by the operator. Whole arm collision detection will be implemented using this system to allow basic robot trajectory planning. This system will provide collision detection and warning both during computer operation and manual control. Algorithm development will focus on force and proximity control. These sensing modalities will also be used during the initial mapping operations which supplement information from engineering drawings to provide the world model. Sensory feedback to the operator will initially be limited to displays from two-dimensional remote viewing systems providing multiple view angles.

Technology Development: Technology development will focus on developing new modeling technologies for use in world model construction and use in real-time system control. This system will include monitoring and preventing operator mistakes. There will be continuing development to increase the speed and safety of the in-tank robot systems. Technology to allow real-time error detection and recovery will be an important focus of these advanced technology development efforts.

In addition, servo control algorithms for detecting and eliminating vibrations in large multi-link robot manipulators will be developed. It is anticipated that oscillations in the large in-tank manipulator systems will be at higher frequencies than current robot control and servo actuator systems can control. Higher speed robot servo control and servo actuator systems will be needed. Also, since the large in-tank robot systems may not be easily modeled, adaptive control algorithms that dynamically adjust control algorithm parameters will be developed. It is anticipated that a first generation of such advanced servo control algorithms will be available in late FY 1993 for testing in the Hanford Cold Test Facility with improved versions ready in FY 1995 in time to support the Hanford SST demonstration.

New parallel computing technologies such as neural networks and hypercube concepts will be adapted to the needs of in-tank robot system control. Parallel computing technologies allow faster computing of advanced control algorithms allowing faster and safer system control. Parallel approaches to world modeling will also be examined. Given the current research status of these computing technologies, initial applications to waste tank remediation could occur in the FY 1994 to FY 1995 time frame, potentially impacting the Hanford SST demonstration.

Improved viewing systems, including three-dimensional for use within the limited-lighting environments of the Fernald and Hanford tanks, are expected to be available in the FY 1991 to FY 1992 time frame. Three-dimensional viewing systems are currently available but need to be adapted for human operator control of large robot systems in waste tanks. Human factors considerations such as fatigue and eye strain need to be fully evaluated. Computer interpretation of video images would improve overall system speed and reliability. High-speed computer vision systems for use in real-time system control is anticipated in FY 1995.

Development of force-reflecting telerobotic control technology is expected to be difficult but extremely useful, especially in the degraded viewing conditions expected in the tanks during waste removal operations. Existing force-reflecting control technology development at national laboratories will serve as a baseline for this technology development. Initial force-reflection technology is expected to be available in late FY 1993.

6.1.3.3 Sensor Subsystems

Knowledge of the in-tank environments is expected to be incomplete when remediation tasks begin. Because of this incomplete knowledge, sensing technology will be critical to the successful application of robot systems to waste tank remediation. Sensors are widely applicable to many ER robotics applications and are discussed further in Section 7, Cross-Cutting and Advanced Robotic Technology Development.

Near-Term Technology Adaptation: Both force and proximity servo control of robots have been demonstrated in the research laboratories and can be integrated into the Fernald silo cleanup and Hanford full-scale testing projects in the FY 1991 to FY 1992 time frame. Proximity sensing can also be used, together with laser-based systems for mapping the location of unknown obstacles. Existing sensing technologies must be adapted to survive in the cleanup environments where damp sludge material is expected to be splattered about.

Technology Development: Technology development in these sensing areas involves further hardening for radiation and chemical effects for use in the FY 1993 to FY 1994 time frame in the cleanup of the Fernald silos and later Hanford SST demonstration. Whole arm sensor systems for collision detection are needed to ensure safe operation of the in-tank manipulator systems. Although the world model is the first line of system safety, real-time proximity sensors that envelop the arm provide a very important back-up system. The first versions of such whole arm collision detection systems are anticipated in FY 1994, with second generation systems ready in FY 1995 to support the Hanford SST demonstration.

In situ waste characterization is a very important long-term technology development area. This area is discussed further in Section 6.3. Sensors for sensing safer operating conditions (e.g., presence of flammable constituents) will be employed as a normal part of remote systems operation.

6.2 BURIED WASTE RETRIEVAL

There is a large amount of buried waste and contaminated soil across the DOE complex. The following discussion is based on present knowledge of this area and early engineering assessments of the potential for applying robotics technology to retrieval of buried wastes or contaminated soil.

6.2.1 Description of the Need

Buried waste within the DOE complex typically refers to low level radioactive waste buried prior to 1970 in pits and trenches and covered with soil. Although low-level radioactive waste was buried after 1970, the post-1970 waste was typically placed on asphalt pads and buried more carefully than the pre-1970 waste. The post-1970 buried waste is designated stored retrievable waste. To date, there has been no indication that the stored retrievable waste is leaking to the environment. Sampling at pre-1970 buried waste sites has indicated that leakage to the environment has occurred and that remediation is needed to prevent further environmental impact. Although several sites within the DOE complex have pre-1970 buried waste, the most extensive site is at the INEL and it is a known release site.

The pre-1970 buried waste at the INEL is located in the subsurface disposal area (SDA) and primarily consists of materials contaminated with transuranic (TRU) radionuclides originating from a number of sites throughout the nation including the weapons production facility at Rocky Flats. Currently, there are no Federal Facility Compliance Agreements (FFCAs) or other agreements with regulatory agencies in place at the INEL. However, the INEL is actively discussing such agreements with local and Federal environmental agencies and mandatory site remediation actions are expected to be forthcoming in the near future. A demonstration of buried waste retrieval from a portion (Pit 9) of the SDA at INEL is scheduled for FY 1995. The SDA demonstration schedule is still uncertain pending a decision on what to do with the retrieved waste. In addition, the results of the CERCLA-mandated review of technologies such as in situ vitrification have not been completed.

Technologies developed for the INEL site will be applicable to the remediation of contaminated soils and buried wastes at other DOE sites as well. For the purposes of this 5-Year Plan, the term "buried waste" will also include contaminated soils that may exist at DOE sites and may have to be excavated and removed for treatment.

6.2.2 Planned Remediation Tasks

An important early remediation task will be the subsurface characterization and mapping of the SDA at the INEL and other buried waste sites within the DOE complex. Thorough site characterization is critical to the formulation of safe, efficient cleanup methodologies for these sites. Historical manifests of the chemical and radiological contents of the wastes placed in the pre-1970 buried waste sites are known to be incomplete and/or inaccurate. Exploratory excavation of a limited area at the INEL SDA indicated that approximately 70% of the secondary containers (mostly wood and cardboard boxes) were breached, while most of the primary containers (i.e., plastic bags) were intact.

After characterization, a decision will be made on the proper approach to remediation. The INEL is in the process of performing preliminary site remediation concept evaluations. While in situ processes such as vitrification and weather capping (such as that being done at Hanford - see Volume III, Section 4.2) are being evaluated by several sites, excavation and retrieval of at least some of the pre-1970 waste will likely be required.

Waste excavation and retrieval operations are planned to be performed remotely due to the radiological and chemical hazards present at the SDA. The design concept for the SDA waste retrieval demonstrations includes a mobile containment building enclosing the excavation operations to minimize the spread of airborne contaminants during excavation. A co-located waste sorting and packaging facility to repackage the waste for storage and eventual disposal is also part of the concept. Sorting and repackaging are planned to be remote operations due to potential radiological and chemical hazards.

6.2.3 Technology Development Plan

The development of robotic systems for site surveys and excavation that can operate safely in the hazardous environments at the buried waste sites such as the SDA is needed. In addition, there is a need for remotely operated and automated sorting and packaging technologies to support the repackaging requirements anticipated prior to the safe long-term storage of the retrieved buried waste. It is anticipated that there will be a wide range of object sizes and geometries, placing a high requirement for flexibility on any developed systems. Concepts used as a reference for this plan are illustrated in Figure 6.2.1.

The 5-Year Plan for robotics RDDT&E to support buried waste retrieval is illustrated in Figure 6.2.2. This logic chart shows the major elements of technology development for ER&WM projects at DOE sites. Results from technology development activities are

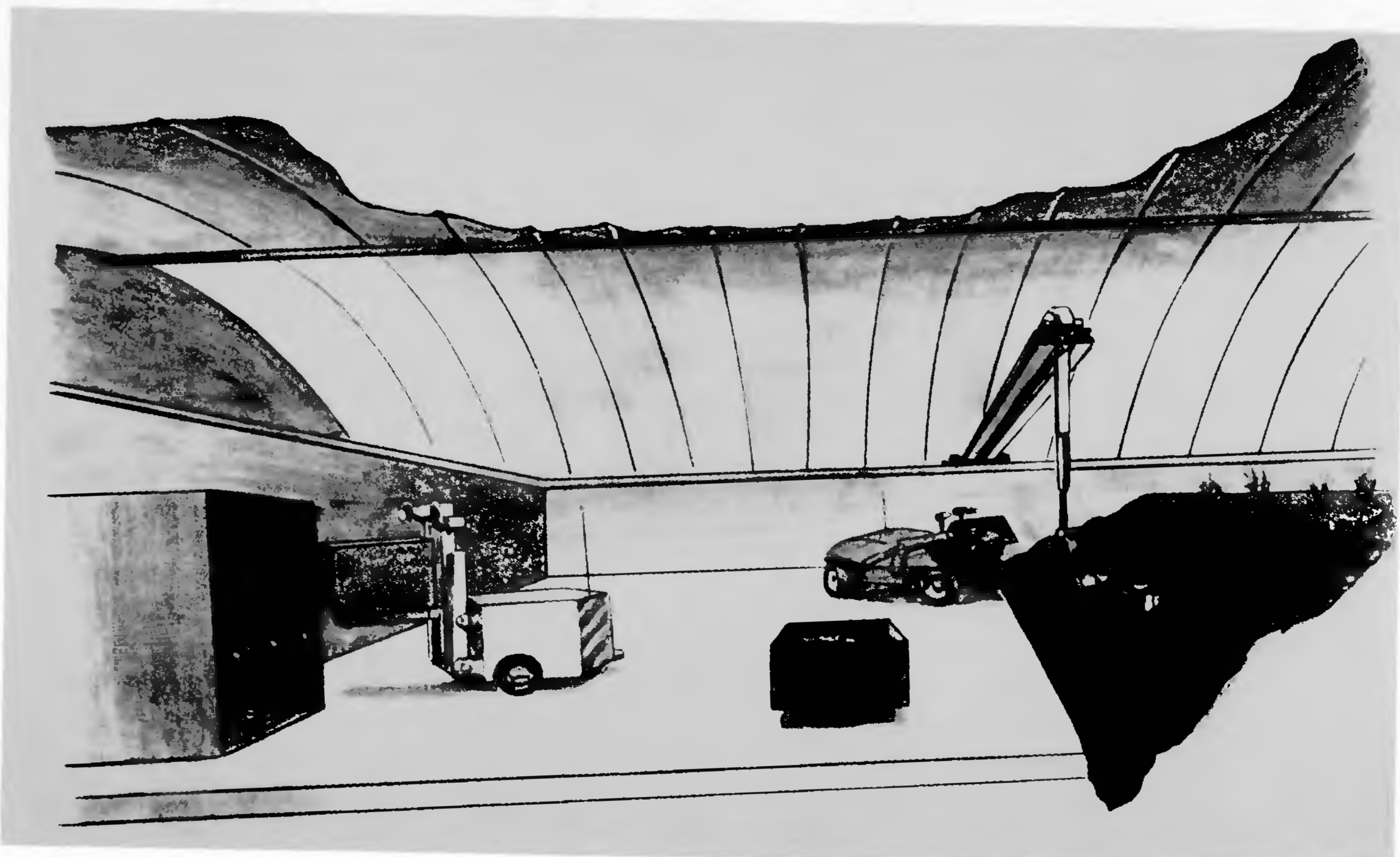
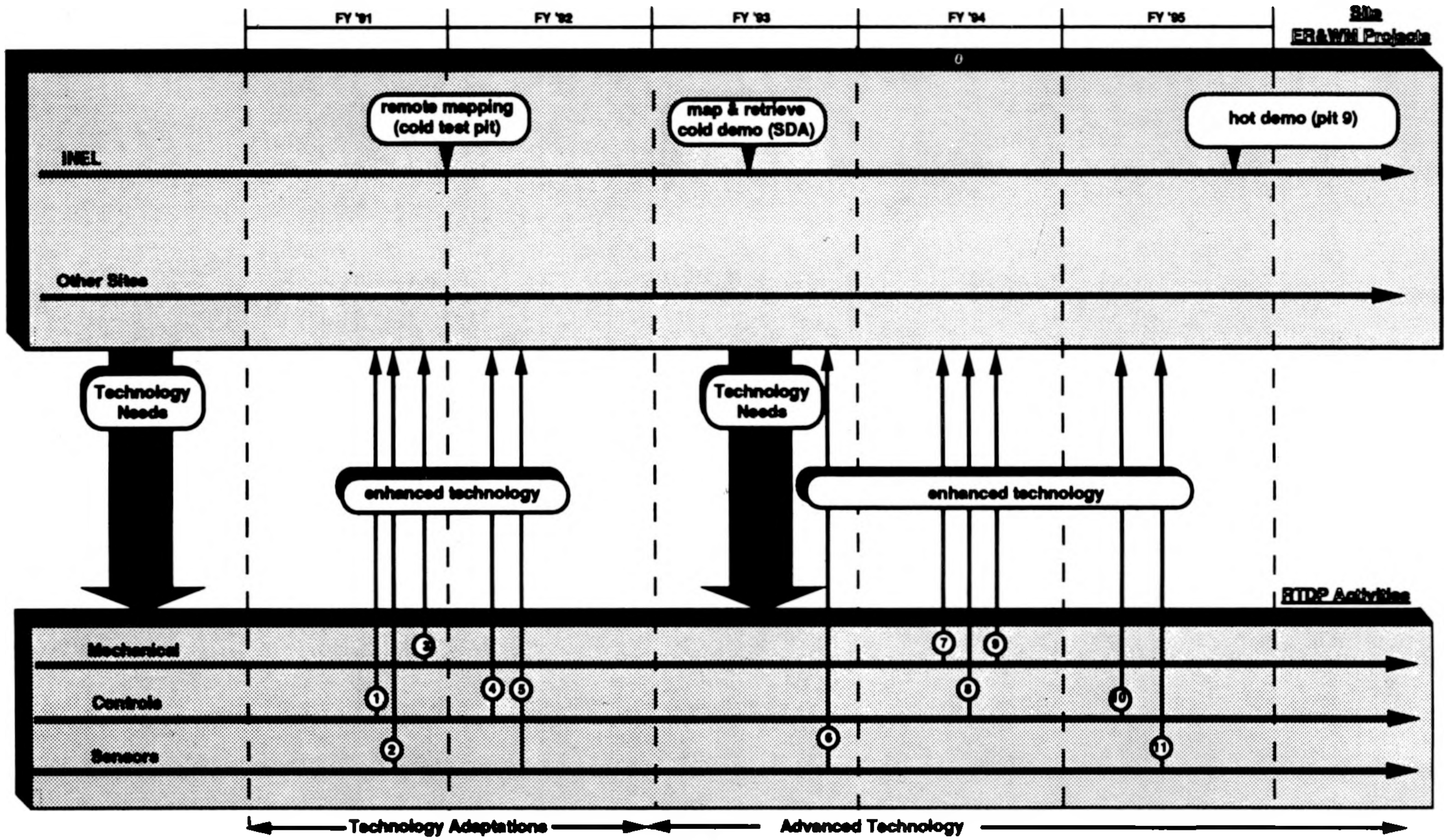


Figure 6.2.1 Robotic System Concept - Buried Waste Excavation

Figure 6.2.2

ROBOTICS TECHNOLOGY DEVELOPMENT - BURIED WASTE



(1) - model assisted teleoperated control

(2) - proximity, force/torque sensors, gpr, seismic

(3) - teleoperated mobile sensor platform

(4) - graphical control, sensor based control

(5) - enhanced subsurface mapping sensors, 3-D viewing systems

(6) - hardened robot control sensors

(7) - combined mobile vehicle and robot manipulator, dexterous end-effectors

(8) - feedforward force control of large excavator

(9) - environmental hardening

(10) - parallel computing, adv. servo damping, standard robot programming lang. force reflection

(11) - real-time computer vision, whole arm collision detection

Figure 6.2.2 Robotics Technology Development - Buried Waste shown by the arrows. These results are keyed to specific needs at DOE sites, which are shown by the large project lines for each site. Significant compliance dates for individual site projects are given in the ovals.

The technology development plan for buried waste retrieval is currently tied very closely to support for the SDA Waste Retrieval Demonstration at INEL. Other sites are evaluating remedial action alternatives for buried wastes and contaminated soils; annual updates of the Plan will reflect needs for robotics technology development as the site plans and needs emerge. The SDA Demonstration is also in the planning stage and is likely to change as approaches and concepts are evaluated; this plan will be modified to support the technology needs and schedules for the project as they are identified by INEL.

The principal emphasis in this plan is application of existing robotics technology and development of new technology for waste excavation and retrieval as well as waste handling, processing, and packaging. Figure 6.2.2 provides a general road map and framework to guide detailed planning for robotics technology development in the support of buried waste retrieval projects.

6.2.3.1 Mechanical Subsystems

Near-Term Technology Adaptations: Most of the near-term activities in the cleanup of pre-1970 buried waste are expected to involve site characterization and mapping. Mobile off-road vehicles exist which can be adapted for robotic control and used to carry sensor packages (see Sensor Subsystems, Section 6.2.3.3) to map the subsurface environment of the SDA. To support the planned INEL demonstration program as outlined in Figure 6.2.2, the first area to be mapped would be a Cold Test Pit at the INEL representative of the SDA. Conventional robotic manipulators can be integrated with these robotic vehicles to assist in sample retrieval and placement of sensing packages if necessary. Robotic mapping of the SDA can provide automated execution of the tedious site survey tasks (e.g., driving a defined grid pattern) with automated generation of a high quality audit trail as defined by regulatory requirements for QA purposes.

Technology, which is being developed by existing programs within the DOE, DOD, and other institutions sponsoring mobile robot research, provides a foundation to allow aggressive, early application to the buried waste problem. Also, drilling technology within the DOE's energy research programs can be adapted, if appropriate, to the needs of drilling and sampling within the SDA. In addition to robotic technology for site characterization, existing commercial excavation technologies can be adapted for use in early technology feasibility demonstrations in time to support design and construction of the SDA waste retrieval demonstration at the INEL. The INEL is actively evaluating robotic technology concepts for the SDA demonstration.

Technology Development: Retrieval of buried waste is a challenging problem that may require significant robotics technology. It is anticipated that this technology will be applicable to a broad class of site remediation problems involving the excavation and recovery of contaminated soil and buried waste. Technology development will be focused by site remediation needs and goals for safer, faster, and cheaper ER&WM activities.

Due to the hazardous nature of the waste and the existence of large objects (such as ambulances) which may require on-site cutting, conventional mining and excavation technologies may prove to be inadequate. As indicated in Figure 6.2.1, early concepts developed by the INEL for waste retrieval envision remote mechanical subsystems such as backhoes and front-end loaders. Some concepts envision gantry robots that span the buried waste trench. The gantry robots would be used for detailed dig-face characterization and the application of foams to the dig face to reduce dust generation. Such gantry robots could also be used for object lifting and moving operations during excavation. These mechanical subsystems would require significant development to provide highly reliable, hardened (protection from abrasive dust, chemicals, etc.) systems applicable to the unique problems of retrieving buried hazardous waste.

Robot manipulators may be combined with large mobile devices used for excavation and retrieval if dexterous manipulation is required. Hydraulic systems may be needed to deliver required power to the site of excavation. Proper design of the mechanical subsystems of such robot arms is important to minimize vibrations and simplify control. Passively damped vibration stabilized manipulators are anticipated by FY 1994. This technology development effort is expected to be supported by similar development efforts focused on waste storage tank remediation.

During the sorting and repackaging of recovered waste, robotic systems for grasping and manipulating odd-shaped objects of varying sizes will be needed. It may not be possible to employ the parallel jaw grippers commonly used in current robot systems to grasp such ill-defined objects. While special-purpose end-effectors may be developed to handle many situations, dexterous end-effectors with grasping capabilities similar to simple hands may also need to be developed. Although focused upon the needs of the buried waste remediation at the INEL, dexterous grasping mechanisms are somewhat generic and would serve the needs of a wide variety of applications in the D&D areas in particular. Such technology may also support remote excavation activities if objects that require careful handling are to be recovered intact without damage. Dexterous end-effectors could be available in the FY 1994 time frame, if a vigorous development program is pursued.

Environmental hardening of the mechanical subsystems deployed during all excavation and retrieval operations is extremely important for the success of buried waste remediation. Although there is uncertainty about the hazards in buried waste sites such as the SDA, mechanical systems must at least withstand the effects of dust and potentially chemically corrosive environments. Resolvers may have to be used in place of encoders to protect against radiation and dust. Finally, all mechanical systems employed in buried waste cleanup must be developed so as to not cause significant sparking. The potential for fires is high, given the presence of low flash point organics in the buried waste sites such as the SDA.

6.2.3.2 Control Subsystems

Control subsystem concepts for robotic systems deployed in the cleanup of the buried waste sites such as the SDA at INEL will have many of the technology attributes outlined in Section 7, Cross-Cutting and Advanced Robotic Technology Development. Technology for robotic systems control is typically quite generic with the same basic technologies meeting the needs of a large variety of applications. Thus, only those technology development needs specific to the remediation of buried waste sites will be discussed here. In addition, robotic system control development support for planned SDA remediation activities at the INEL will also be discussed.

Near-Term Technology Adaptation: As shown in Figure 6.2.2, system control technology development is expected to support buried waste retrieval cleanup programs. Technologies for preparing highly-structured software architectures functioning in multi-processor, real-time control systems would be merged with commercial robot control technologies to produce early model-based, sensor-directed robot system controllers in late FY 1991. These near-term technology adaptations would be available in time to support both the characterization of the SDA at the INEL as well as the design process for the SDA Pit 9 demonstration planned for start up in FY 1995.

Technology adaptation will focus on applying structured software programming techniques to existing computing and operating systems. Technology in computer graphics could be used to develop animated graphics models of the robots for automating the programming of repetitive buried waste characterization operations. This requires accurate computer models of all remote devices and their work space. Techniques for validating these models need to be developed. The maps generated as part of the Pit 9 characterization process could be merged with the graphic control systems to provide graphic control interfaces to allow graphical programming of robot excavation actions by the operator. If accurate models exist, collision detection in the graphics system could be implemented using this system to allow basic robot trajectory planning and to provide collision detection and warning both during programmed operation and manual control. Algorithm adaptation would focus on force and proximity control of the robot systems deploying site characterization sensor packages, as well as site excavation robots. In the near term, sensory feedback to the operator would probably be limited to displays from two-dimensional remote viewing systems providing multiple view angles. In addition, graphic displays and audio would also assist operators. Other technologies to enhance operator feedback are discussed later.

Technology Development: Technology development will focus on developing advanced modeling technologies for use in world model construction and real-time system control, including monitoring and correcting operator errors. Of particular importance is the control of the multiple devices anticipated to be operating simultaneously during excavation and retrieval operations. There will be a continuing effort to increase the speed and safety of the site cleanup robot systems. Technology to allow real-time error detection (e.g., sensory detection of a potential collision not anticipated by the world model or operator) and recovery will be an important focus of these technology development efforts.

In addition, advanced servo control algorithms to permit controlled interactions of the very large robot excavators will be developed. It is anticipated that predictive servo control algorithms (e.g., control algorithms that model and compensate for delays in system response) may be required to ensure safe operation of these large systems. Force control algorithms coupled with non-contact proximity and subsurface sensors may be required to permit the robotic excavators to remove soil and buried objects in a controlled fashion that prevents damage of the robotic system or the waste containers buried within the soil. First integrated system demonstrations of this technology are anticipated in FY 1993.

Development of sensor feedback to the operator is also needed. High-fidelity force feedback from the very large robotic excavators is needed to provide the operators with a feel for the robot's interaction with materials in the buried waste pits and trenches. Development of force-reflecting telerobotic control technology by the FY 1994 time frame is expected to be difficult yet extremely useful, especially in the degraded viewing conditions expected in the SDA during waste removal operations.

A significant problem expected in current concepts for buried waste cleanup is that of communication with multiple robotic devices operating simultaneously. For example, remote excavation may involve the simultaneous operation of robot excavators, dig face characterization and spraying robots, large object graspers, and transporters to remove the excavated waste from the vicinity of the dig face. Communication with these devices from a single remote control room could be a significant challenge involving advanced technology development in both high-speed, high-bandwidth hardwire (e.g., fiber optics) and wireless (e.g., microwave) communication. Such technology development should be as general as possible due to its potential application to other site remediation projects such as tank cleanup and D&D.

As indicated in Section 7, cross-cutting and advanced technologies such as three dimensional viewing systems and parallel computing are applicable to many ER&WM tasks. Figure 6.2.2 illustrates how these technologies can support buried waste cleanup at the INEL and other sites.

6.2.3.3 Sensor Subsystems

Near-Term Technology Adaptation: Site characterization sensors represent an important class of buried waste sensors. For example, two standard geophysical tools for seismic and electromagnetic measurements can be adapted and applied to the mapping of buried waste sites. At low frequencies, seismic surveying is used extensively in the oil and gas industries for exploration and mapping. Optimizing sonic imaging for buried wastes will require a hybrid technology that uses both acoustic mapping and the acoustic tomography technologies common to the medical industry. The basic hardware and analytical tools to optimize seismic imaging for buried waste is thought to exist. Initial seismic sensors optimized for buried waste mapping could be available in late FY 1991 to early FY 1992.

Electromagnetic methods can detect buried metal objects, fluid with total dissolved solids different from ground water, clay layers, and resistive or low dielectric fluids such as oils or other hydrocarbons. Ground penetrating radar has been employed in a variety of waste site applications. With today's technology, ground-penetrating radar surveys can be highly variable because of the sensitivity of the technology to attenuating soil conditions near the surface. Analysis of ground-penetrating radar results can also be difficult. An alternative to surface-based ground-penetrating radar approaches employs borehole techniques. In this approach, ground-penetrating radar is used for cross-borehole measurements. The results of this approach have been quite encouraging in some cases. Use of this type of survey in a routine fashion would require refinement of hardware systems and tomographic imaging software. Initial adaptations of electromagnetic sensing systems to buried waste mapping could be accomplished by late FY 1991 or early FY 1992.

Evaluation of the chemical and radiological characteristics of buried waste sites may require borehole drilling and logging technologies. These technologies are commonplace within the oil and gas industry and should be employed in any attempt at complete site characterization. Based upon technologies used in the oil and gas industry, pulsed neutron logging technologies can detect concentrations of approximately 0.1% fissile materials. Pulsed and steady-state neutron sources can also be used for activation analyses to detect many elements. Neutron sources can also detect water. A precise determination of water content is dependent upon knowledge of the neutronic properties of the soil material. Such properties can be measured at, for example, the Advanced Reactivity Measurement Facility at the INEL.

Near-term adaptation of existing sensing technologies such as proximity, force, and vision sensing can also support the early buried waste remediation programs at the INEL as shown in Figure 6.2.2. Both force and proximity servo control of robots have been demonstrated in the research laboratories and can be integrated into the SDA Pit 9 characterization and cleanup demonstration program. Tests of these concepts in the INEL Cold Test Pit could be accomplished in the FY 1991 to FY 1992 time frame. Enhanced control enabled by the development of predictive, feed-forward control algorithms is anticipated in FY 1993. Existing sensing technologies may need to be adapted to survive in the cleanup environments where much dust (containing radioactive contaminants and chemicals) may be present. Dust control technologies may reduce these problems significantly.

Technology Development: While sensing technologies such as the previously discussed electromagnetic and seismic sensors exist which can be adapted to the needs of site characterization at buried waste sites, advanced sensing technologies with general applicability need development. Continuing development will improve the imaging capabilities of traditional electromagnetic and acoustic imaging technologies and automated data interpretation technologies will continue to improve. Development of systems and components hardened to resist deleterious effects of radiation and chemicals is needed. The development of integrated sensing packages for the in-situ determination of physical and chemical properties represents a long-term goal of advanced technology development and is discussed further in Section 6.3.

Whole robotic sensor systems for collision detection may be needed to ensure safe operation of multiple devices during excavation operations. The excavation robots will have to contact each other during materials transfer operations and remediation actions (e.g., partitioning of large objects) requiring cooperative actions by more than one device. Sensors which warn of the encroachment of one robotic device on the work space of another may be required for safe control. Although the world model is a first line of system safety, real-time sensors which envelop the robots provide a very important backup system. First versions of such whole robot collision detection systems are anticipated in FY 1994. High speed computer vision systems for use in real-time system control are also anticipated in FY 1995, potentially supporting the SDA Pit 9 demonstration.

6.3 CONTAMINANT ANALYSIS AUTOMATION

DOE has significant amounts of radioactive and hazardous wastes stored, buried, and still being produced at many sites associated with DOE activities. Historical waste disposal and storage manifests have been found to be incomplete or incorrect at many DOE sites. Therefore, stored and buried wastes need to be analyzed for element, isotope, and compound content. Contaminant analysis must occur before efforts can begin to remediate, or to develop techniques to remediate, the wastes to meet EPA guidelines.

6.3.1 Description of the Need

Some of the ER&WM activities that require sample collection, preparation, analysis and data interpretation include remediation of:

- the burial trenches and pits at INEL, Fernald, Hanford, and ORNL;
- the storage tanks at Fernald, Hanford, INEL, ORNL, and SRS;
- the solar ponds at Rocky Flats; and
- the waste water retention ponds at SRS and Rocky Flats.

The requirements for sampling and analysis will increase sharply as the DOE is required to devise and defend environmentally sound site remediation plans. It has been established that historical manifests of the contents of the DOE waste sites are incomplete and/or inaccurate in many cases. The DOE processes 2 to 3 million samples per year and this is expected to grow to approximately 10 million samples per year by FY 1995.

The analysis time and costs will be enormous. For example, at present, it takes two weeks to obtain a sample from an underground storage tank at Hanford and can require between four and six months to analyze and provide results to the requester. The cost for this process can be as much as $300,000.

Due to the unique characteristics of the DOE waste (e.g., the presence of radionuclides), most commercial analytical laboratories are not equipped to perform the required remote analytical processes. The projected work load far exceeds the current capacity of certified DOE and commercial laboratories. Productivity in the analytical laboratories must be increased while the cost of analysis is reduced. In addition, potential hazards to the analytical technicians (even when the waste is not radioactive) must be minimized, since many of the samples and reagents used are in themselves hazardous. Many of the EPA-approved protocols are labor intensive, requiring frequent and direct manipulations by the analysts.

The primary bottlenecks to sample analysis are the preparation of samples for analysis and the interpretation of the resulting analytical data. Another major concern is the loss of key contaminants from cumbersome techniques for obtaining, storing, and handling samples.

6.3.2 Planned Analysis Automation Tasks

Intelligent systems for analytical laboratories that automate essentially all of the time, risk, and cost intensive steps required to take a sample and produce interpreted results must be developed. In automated laboratories, samples would be received, prepared, and analyzed by highly integrated equipment with minimum human intervention.

Many individual analytical procedures such as chemical separation using chromatography, measurement of pH and electrical resistivity, and mass spectral analysis are already highly automated. However, preparation of a field sample for use of the standard analytical techniques is typically performed manually. Sample preparation can involve operations such as grinding for size reduction, digestion of solids to prepare solutions for subsequent analysis, buffering of liquid solutions to achieve the proper pH, emulsification to uniformly suspend nonmiscible liquids, or modification of the chemical nature of reactants to adjust the solubility of the chemical substituents of individual samples. Preparation of samples for determination of physical properties is also critical to the thorough characterization of waste sites.

A long-term goal is the full automation of required analytical characterization techniques to allow complete instrumentation packages to be delivered to the waste sites for on-site characterization. This not only speeds the characterization process and reduces the concomitant waste associated with sampling, transport, and sample manipulations in a laboratory but may provide more accurate information as well. Many of the important bulk physical properties of waste, for example, may change during the process of sampling and laboratory preparation. On-site determination of these bulk properties would be extremely beneficial. In-situ analysis would be extremely useful both for screening analyses as well as for final EPA-approved analyses.

6.3.3 Technology Development Plan

The approach to laboratory automation recommended by a DOE laboratory automation study group calls for the development of automated laboratory systems to perform standard analysis methods (SAMs) according to standard specifications. The system performing a SAM would receive a sample and produce interpreted analytical data as output while automatically maintaining necessary records for quality assurance and quality control. The automated laboratories would be assembled from standard laboratory modules (SLMs) that can be programmed to perform the SAMs. A concept used as a reference in this plan is illustrated in Figure 6.3.1.

There are three classes of SLMs: sample preparation modules, analysis instrumentation modules, and data interpretation modules. Typically, a complete SAM will involve sample preparation, analysis, and data interpretation and thus will require SLMs from each class. The initial efforts in the automation of contaminant analyses will focus on the definition of a highly modular and open architecture (both hardware and software) with well defined interfaces for the assembly and integration of the SLMs in the automated analysis systems.

As shown in Figure 6.3.2, a first protocol identified for automation is EPA Method 3550, sonication extraction. Method 3550 extracts nonvolatile and semivolatile organic compounds from solids such as soils, sludges, and other waste forms. In addition, it includes some cleanup steps that are common to many extraction protocols. Identification of this protocol as a candidate for early automation was based on the fact that it is widely used, employs several common laboratory unit operations, and represents a significant part of the overall analysis cost.

EPA Method 3540, soxhlet extraction, for semivolatile analyses, is a strong candidate for the next protocol to be automated. It is time-consuming, commonly performed, and could use many of the SLMs developed for the automation of Method 3550.

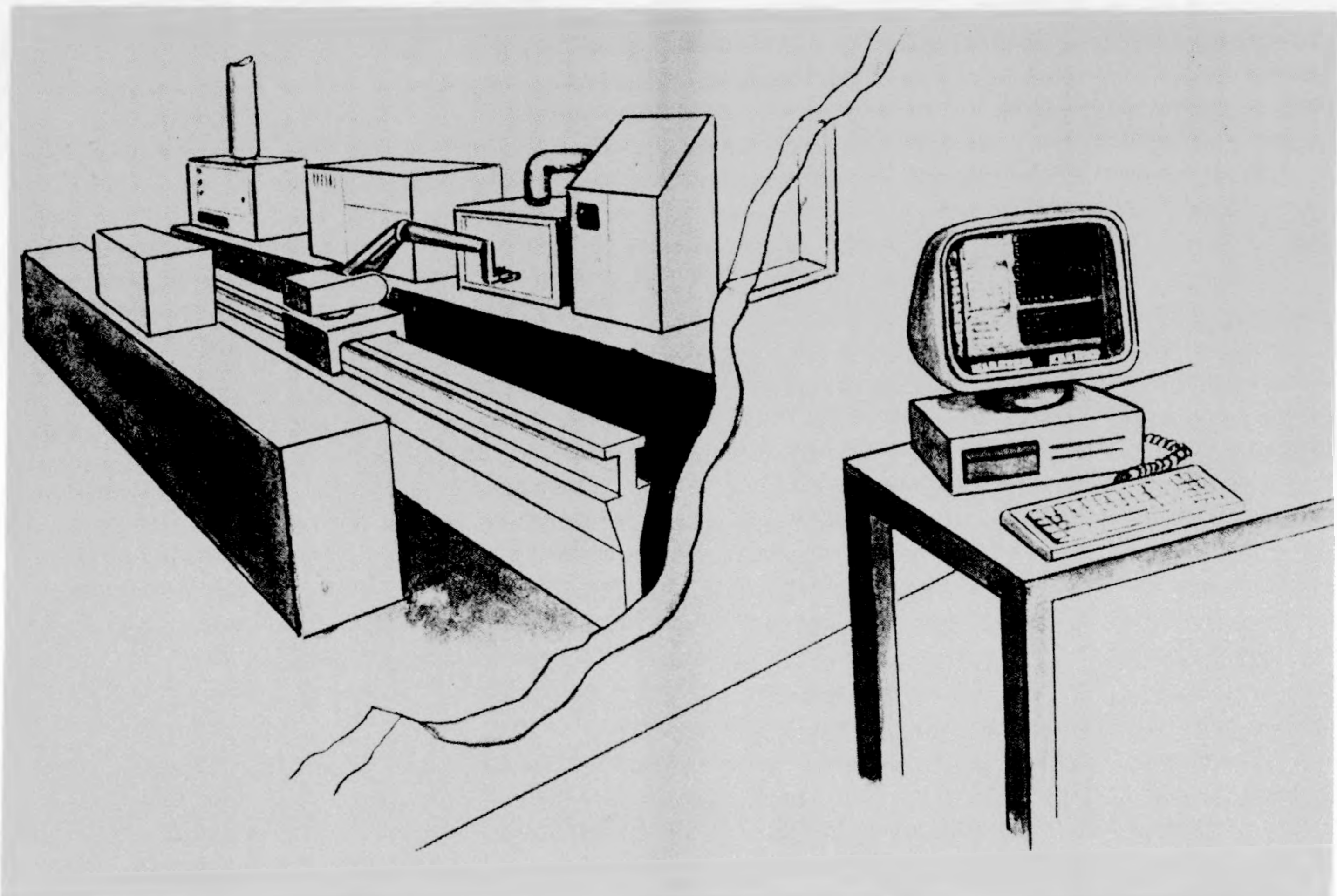
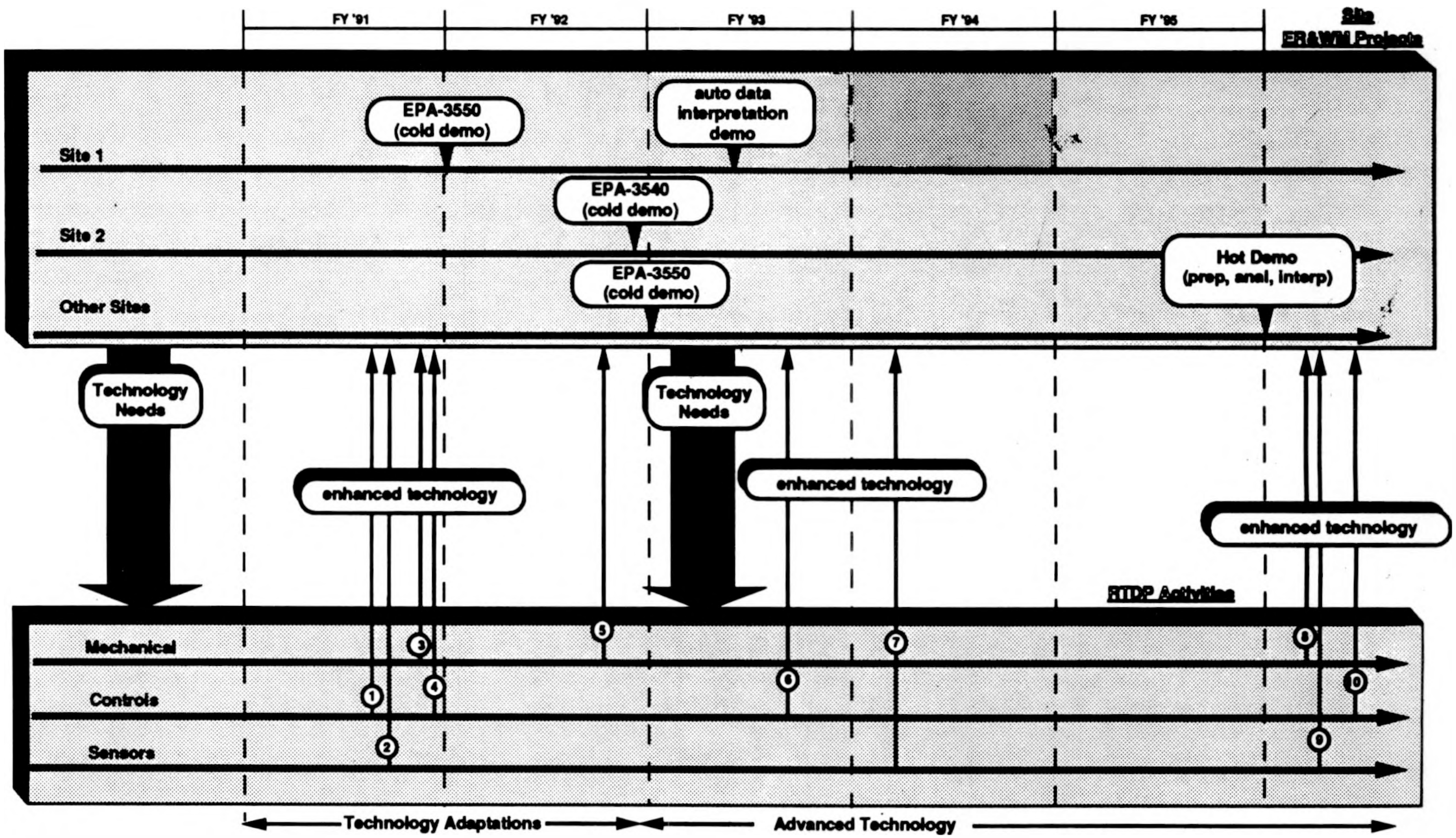


Figure 6.3.1 Robotic System Concept - Contaminant Analysis Automation

Figure 6.3.2

ROBOTICS TECHNOLOGY DEVELOPMENT - CONTAMINANT ANALYSIS AUTOMATION



① - initial modular, open architecture control concept developed

② - proximity, force/torque sensors

③ - SLMs for EPA Method 3550 sample preparation completed

④ - graphical control, sensor based control

⑤ - SLMs for EPA Method 3540 sample preparation, dexterous manipulation, hardened for hot cell use

⑥ - automated interpretation of mass spectral data

⑦ - first demonstration of intelligent GC silicon chip

⑧ - environmentally approved mobile laboratories

⑨ - second generation silicon based intelligent sensor

⑩ - second generation automated interpretation of analysis results

Figure 6.3.2 Robotics Technology Development - Contaminant Analysis Automation

Automation of sample preparation protocols through the use of SLMs can provide significant benefits even before the automated laboratories are able to perform complete SAMs (sample in, interpreted data out). EPA Methods 3550 and 3540 represent a major part of the sample preparation costs for semivolatile analyses. Automation of EPA Methods 3550 and 3540 would provide a basis and a test bed for the definition of a modular and open architecture for use in developing automated analysis laboratories for SAMs, as well as provide a set of SLMs that would be useful in the automation of additional sample preparation protocols.

Data interpretation modules (DIMs) are a special type of SLM required for complete automation of a SAM. The interpretation of the data resulting from analytical procedures is perhaps the most difficult automation task. DIMs evaluate the data resulting from the performance of one or more analytical methods to produce an interpretation of the amounts and types of chemical species present and/or the physical properties of the materials being analyzed.

The modular approach described here for laboratory automation ensures system flexibility so that the extension of existing capabilities and the addition of new tasks can be accomplished without redesign of whole systems.

It is highly desirable to encapsulate the systems to perform SAMs in mobile laboratory systems capable of moving to a waste site. This would greatly reduce the potential transportation hazards associated with shipping waste samples to a centrally-located laboratory complex. A goal should be the transmission of only data (not materials) to a central repository. At the very least, on-site analytical laboratories could perform screening analyses with only the final candidate samples being sent to a central laboratory.

The RTDP will take advantage of the extensive technology base at DOE sites and laboratories. Experience at these sites will be used in the development of contaminant analysis automation technologies.

The 5-Year Plan for robotics RDDT&E to support contaminant analysis automation is illustrated in Figure 6.3.2. This logic chart shows the major elements of technology development with respect to ER&WM projects at DOE sites.

The timing of results from technology development activities is shown by the arrows. These results are keyed to needs at DOE sites, which are shown on the lines for each site. Significant dates for the sites are shown in the ovals.

The principal thrust of the technology development plan is robotics support for EPA Methods 3550 and 3540 as a first priority. Key dates driving the schedule are

- demonstration of EPA Method 3550 in FY 1992, and
- demonstration of EPA Method 3540 in FY 1993.

6.3.3.1 Mechanical Subsystems

Much of the technology in the form of mechanical and instrumentation subsystems for implementing the sonication protocol exists and adaptation of this technology should allow construction of the SLMs required to demonstrate EPA Method 3550 in early FY 1992. Force- and proximity-sensing technologies to ensure safe operation of robotic transport devices should also be ready in late FY 1991 or early FY 1992.

It is anticipated that the analysis of many hazardous waste samples may be done in glove boxes or hot cells due to radiation hazards. Environmental hardening of mechanical systems used in dry atmosphere hot cells will also be required. Environmental hardening to protect equipment against caustic, acidic, abrasive, or radioactive substances will also be important to ensure long life of the SLMs. Such hardened systems are expected to be available in FY 1993. Development of technology for environmental hardening is discussed further in Section 7.0, Cross-Cutting and Advanced Robotic Technology Development.

6.3.3.2 Control Subsystems

Near-Term Technology Adaptations: Much of the control technology needed to support laboratory automation is available in research laboratories and commercial products which can be adapted for use in the automation of EPA Method 3550 in FY 1992. Advanced software engineering techniques will be used to develop highly modular, reliable system-control software. Graphical programming techniques will be developed for the SLM interfaces comprising the EPA Method 3550. This graphical programming technology will provide the technology base for easily reconnecting SLMs into new protocols and methods as the library of SLMs grows. Advanced operator interfaces will allow senior chemists to program the automated laboratory methods without detailed knowledge of system level software. The interactive control system will also automatically deposit relevant information including quality assurance and quality control information into an archival portion of the information management system.

Technology Development: Some laboratory protocols, such as Soxhlet, currently require assembly and disassembly of glassware. It is anticipated that redesign of glassware, modification of protocols, and hard automation of systems will simplify control systems. However, some sophisticated algorithms that incorporate sensor-based servo control may still be required. As indicated in Figure 6.3.2, the control concepts for these operations will be developed by late FY 1992.

Automation of data interpretation for the various analyses performed in DOE's analytical support laboratories represents a major challenge and is a main focus of advanced technology development efforts. Hybrid software systems for data interpretation will incorporate conventional interpretation methods such as chemometrics in an expert system environment together with the rapid pattern recognition capabilities of neural networks.

The development of a complete DIM which is capable of handling all output spectra from GC/MS analyses, together with a full featured data interpretation user interface, will be an activity that will require several years of effort. The first operating GC/MS DIM is expected to be available in the FY 1993 time frame. A follow-on effort of two years will allow the development of a DIM for at least one other analysis method.

6.3.3.3 Sensor Subsystems

Near-Term Technology Adaptation: Sensors and instrumentation for monitoring and control of the in-laboratory processes employed in SLMs to perform chemical and physical properties measurements are generally well established and supported in the commercial sector. Thus, they are not considered part of the development responsibilities of the RTDP, except for the development of the communication interfaces required to support integration into the automated SLMs.

Technology Development: Micro-analytical sensor packages for the performance of in situ characterization represent a long-term sensor technology development effort with a high potential payoff. These sensors integrate transduction and computing to provide compact intelligent sensor systems (i.e., SAMs on a chip) which can be delivered remotely to hazardous environments. These intelligent sensor packages can be left in place to monitor waste over time or used immediately to assist in the formulation and execution of remediation activities.

Although analytical sensing systems have been coupled to silicon-chip technology using micro-machining technologies for applications such as space probes which have been sent to other planets by NASA, this technology is quite new. However, recent advances in micro-machining of silicon and hardening of silicon-based technologies offer great hope for the development of more advanced technologies. An important aspect of this work will be the development of new protocols approved by EPA (as well as other regulatory agencies).

This is a new technology area with significant risk. As a result, the technology development in this area is focused on providing a silicon-based analytical system for proof-of-concept demonstration in FY 1994. Based upon the results of this first technology development effort, the direction of further technology development will be assessed and approaches to next-generation intelligent sensors formulated. The first intelligent sensor system would be a gas chromatograph for the identification of volatile organics. This sensor system builds upon the experience in the space program and ongoing research in the chemical sciences areas. Successful development of a volatile organics sensor system addresses a large number of characterization needs within the DOE.

6.4 WASTE MINIMIZATION

A current focus of DOE is to eliminate waste at the source. Waste minimization is required by Federal regulations, RCRA as amended, and by DOE guideline orders. Waste minimization at DOE sites will progress from immediate to long-term actions. Efforts will be prioritized by the Waste Management Minimization Group (WMMG) currently managed by the DOE Albuquerque Operations Office. The goal of the WMMG is to eliminate or greatly reduce, though design materials and process changes, both current and future waste steams associated with the production of nuclear weapons.

Robotics technology could contribute to minimizing waste in a large number of areas within the DOE complex.

6.4.1 Description of the Need

Potential areas for waste minimization include processing modifications, advanced intelligent control concepts, advanced processing equipment, recycle of process waste, and automation of materials handling operations and process flows. There are needs for robotics and automation technology development in each of these areas.

Specific needs for robotics technology in production operations involving Special Nuclear Materials (SNM) have been identified in uranium machining at the Y-12 facility and in plutonium handling and processing at Rocky Flats.

At Y-12, uranium parts fabrication currently generates waste equivalent to 95% of the starting material. Much of the waste generation results from poor capability to characterize blanks which thus must have excess starting wall thicknesses (frequently eight times that of the finished part). Use of robotics vision systems and edge and surface finishing technologies can reduce the required wall thicknesses for blanks.

Handling and processing of plutonium in the DOE complex is currently performed manually in glove boxes. Such manual operations generate substantial quantities of combustible waste materials (gloves, bags, wipes, rags, tenting materials, and personnel protection clothing). These materials are necessary to control operator dose and contain the spread of contamination.

This waste comprises about 70% of TRU waste from Rocky Flats at present. In addition, inefficiencies and failed runs during plutonium machining and processing operations produce residues, which correspond to roughly 20% of the processed material. These residues require aqueous recovery, which generates the major portion of the TRU processing wastes. Modern chemical processing and handling equipment, largely based upon automation, is needed to improve process efficiencies and to reduce or eliminate operator handling of plutonium materials. Such improvements can reduce the current loss from inefficient processing from about 20% to less than 3%, with a corresponding reduction in plant TRU process waste generation.

No firm regulatory driven milestones for waste minimization currently exist.

6.4.2 Planned Waste Minimization Tasks

Robotics and automation technologies can reduce waste generation by:

- reducing operator-generated waste (e.g., gowns and shoe scuffs) by replacing hands-on glove box operations with automated operations;

- reducing the number of failed parts through improved control and repeatability;

- reducing the size of material blanks, and thus the machining waste, through improved characterization and control capabilities;

- improving process control and yield to increase mainline processing efficiencies, thereby reducing waste generation from recovery operations;

- automating product breakout to reduce operator generated waste;

- developing bagless transfer/transport systems, thereby reducing plastic bag waste; and

- controlling dust from oxide handling operations, thereby reducing waste from cleanup and recovery operations.

In addition, automation technologies that eliminate the need for human entry into potentially hazardous environments allow design of well controlled containment facilities. Such controlled environments, designed to minimize contamination spread, minimize waste cleanup in the event of contamination.

6.4.3 Technology Development Plan

Automation and waste minimization are strongly coupled to plant modernization issues. Although several automation concepts have been identified that look promising for minimizing waste within the nuclear weapons complex (NWC), it is recognized that this is a very complex problem requiring a fully-integrated systems approach to manufacturing. Thus, an early milestone in FY 1991 is the initiation of a study of high waste generation manufacturing processes. An important part of this study will be a workshop to discuss waste production in the NWC. The product of this workshop will be a draft Waste Minimization Through Automation plan.

Several concepts for near-term applications to existing production operations form the principal basis for the current plan. These will be modified according to the Waste Minimization Through Automation plan when it becomes available.

Two robotic system concepts with potential to reduce waste generation in uranium parts fabrication are being considered. Optical techniques can be applied to the characterization of machining blanks to provide two orders-of-magnitude improvement in the measurement of blank dimensions. Robotic edge and surface finishing technology can be applied to machining parts in a closed environment.

Three robotic system concepts are also being considered for plutonium processing. First, tilt and pour furnaces for oxide reduction, americium removal, and electro-refining operations can be automated to reduce glove box operations in production lines. Second, equipment and methods for bagless transfers can use robotic assists to eliminate bag waste. Third, robotically assisted operations for plutonium oxide handling and dust control can reduce operator generated waste during cleaning and residue recovery operations. A concept used for this 5-Year Plan is illustrated in Figure 6.4.1.

Robotics technology development for waste minimization applications will take advantage of the extensive technology base at DOE laboratories, including a bag in/bag out robotic system for glove box operations and a gantry robot for applications in glove boxes. The RTDP effort in waste minimization will build on the technology developed by these efforts. The 5-Year Plan for robotics RDDT&E to support waste minimization efforts is illustrated in Figure 6.4.2. This logic chart shows the major elements of technology development to address identified needs at DOE sites.

Development of robotics technology for waste minimization in uranium machining operations is planned to support cold laboratory demonstrations in FY 1991 and both cold and hot demonstrations in the Y-12 production facilities in FY 1992 and FY 1993, respectively. These demonstrations will include both robotic vision systems for improved characterization of machining blanks and robotic edge and surface finishing technology.

The plan for robotics technology development to reduce wastes generated in plutonium handling and processing operations is keyed to demonstrations of the technology. Application of the developed technology will be integrated with plant modernization activities to reduce the cost and impact of applying new technology to production operations.

6.4.3.1 Mechanical Subsystems

Near-Term Technology Adaptations: Pneumatic transfer systems have already been developed and demonstrated in the laboratory at sites such as Rocky Flats. Coupled with advanced control and sample tracking systems, this technology could be implemented and in use in plutonium glove box production facilities such as Rocky Flats in FY 1992 as shown in Figure 6.4.2.

The development of a first prototype plutonium glove box robotic manipulation system could be accomplished by FY 1991 with a hot demonstration of this technology in FY 1994. This technology would build upon the existing commercial robot manipulator technology and sensor based control technologies recently demonstrated in research laboratories. Computer-controlled plutonium-powder handling procedures could greatly reduce the spreading of plutonium dust common in many plutonium glove box operations. Migration of plutonium dust is a major source of contamination, for example, in the glove box ventilation systems at Rocky Flats.

Substantial mechanical systems development may be required to integrate robotics hardware with existing process equipment.

Technology Development: As stated above, not enough is currently known to formulate a complete long-term

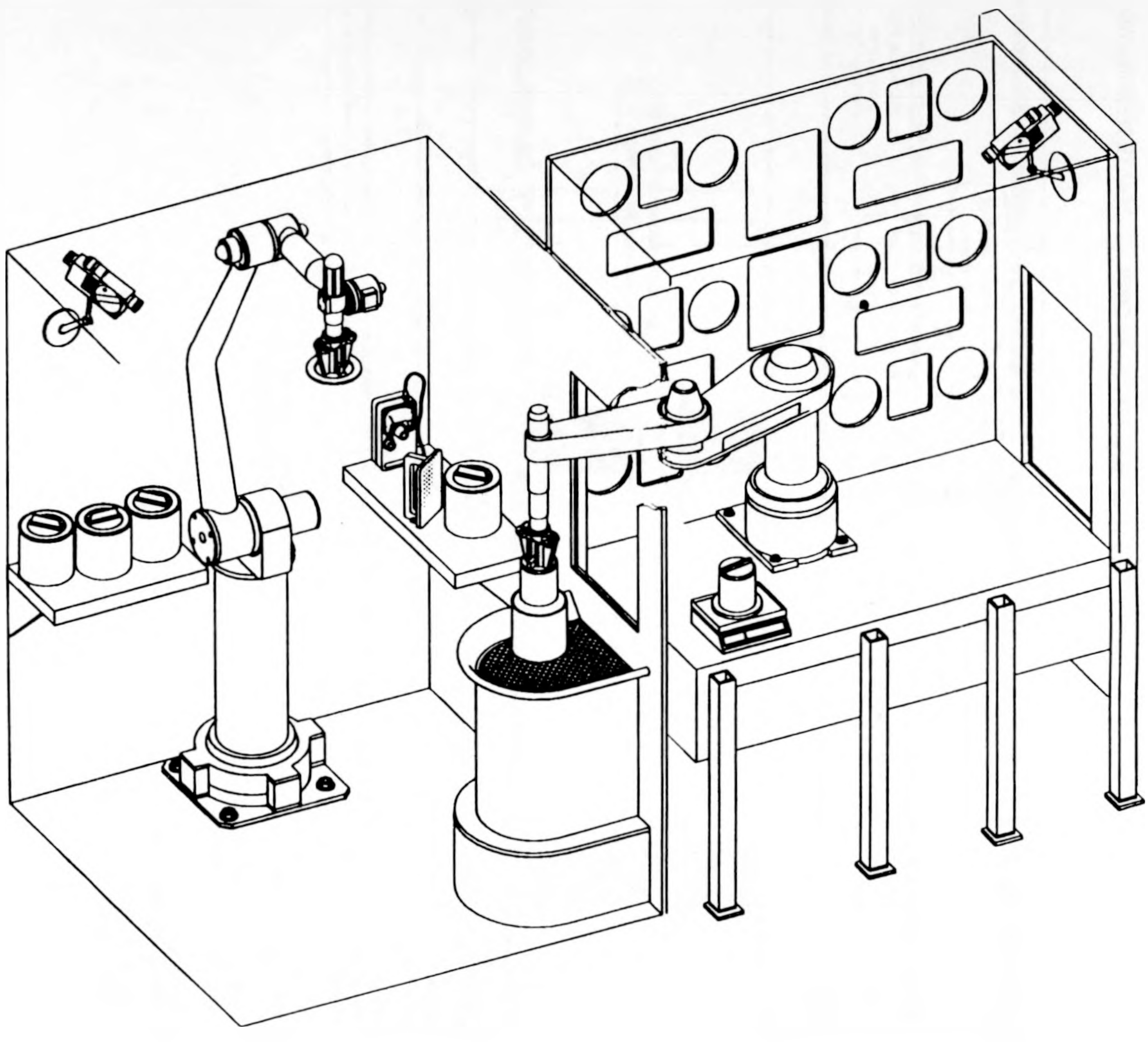
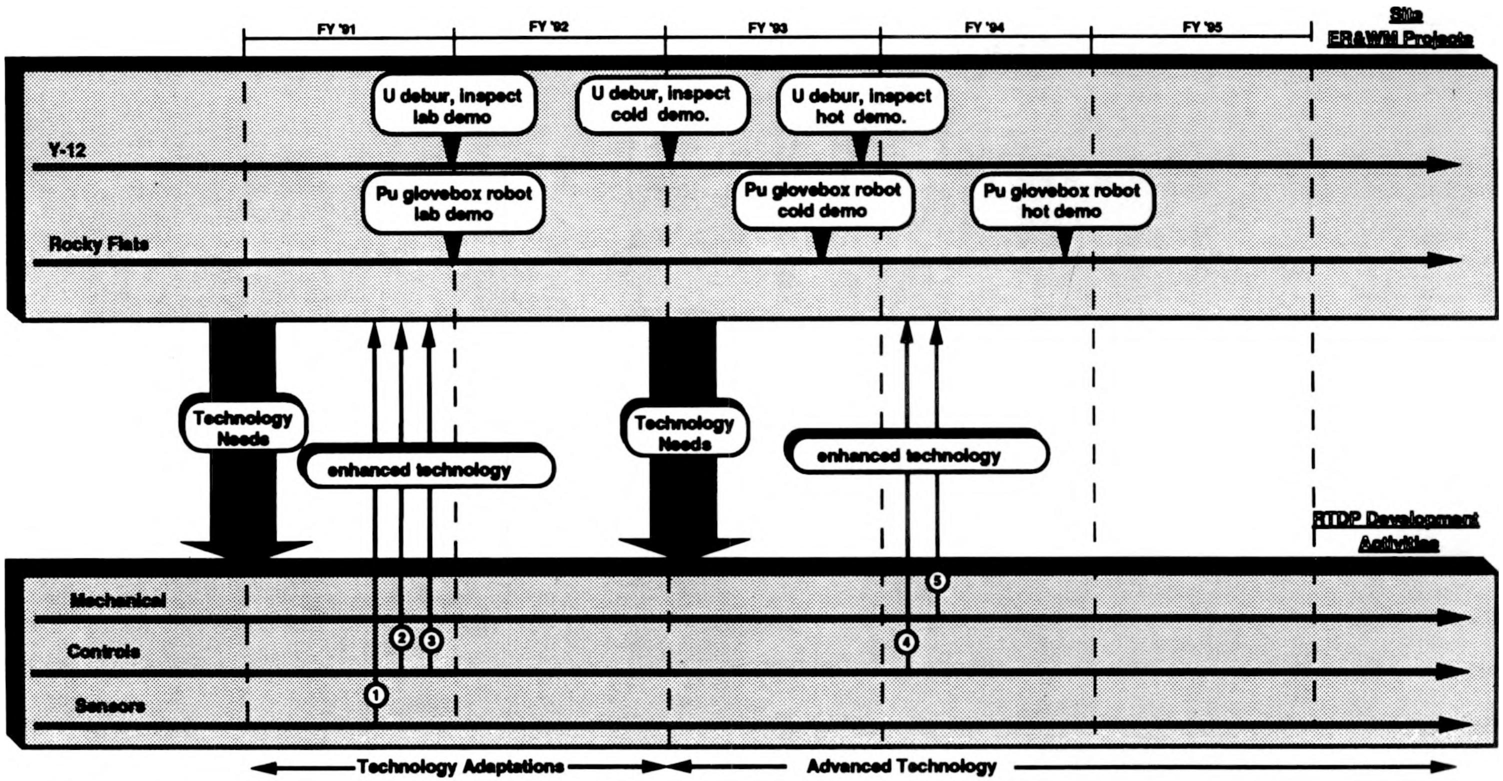


Figure 6.4.1. Robotic System Concept Waste Minimization

Figure 6.4.2

ROBOTICS TECHNOLOGY DEVELOPMENT - WASTE MINIMIZATION



① - proximity, force/torque sensors

② - modular, structured software and system control concepts

③ - model based control, sensor based control, automatic inspection

④ - force reflection teleoperation control, error detection/recovery

⑤ - high dexterity end-effectors, glovebox hardened systems

Figure 6.4.2 Robotics Technology Development - Waste Minimization technology development plan at this time. However, one area that is well known to require technology development is the further development of glove box robots. Generalized robot systems applicable to a large variety of DOE glove box environments are needed. These systems should be highly modular, have high payloads, and have all high-maintenance subsystems outside the glove box for easy maintenance. Other technology development needs will be identified as part of the waste minimization study planned for FY 1991 and will be incorporated in the FY 1991 update to the RTDP plan.

6.4.3.2 Control Subsystems

The system control concepts envisioned for automation systems directed towards minimizing waste are similar to those described in Section 7, Cross-Cutting and Advanced Robotic Technology Development. Model-based control using graphical programming and human-assisted computer control to ensure safe operator interactions with the system will be developed and used. Structured software concepts operating in commercially available computer systems will form the basis for the computer controlled systems. Sensors for force and proximity control will allow safe interaction between the robot and its environment. Figure 6.4.2 shows the anticipated availability dates for these control technologies.

A related area is intelligent process control. Advanced computer models of processing technologies should allow better control with significantly less waste. While these intelligent process systems may not be classical robotics systems, the basic controls technology is expected to be very similar to model based intelligent robot controllers.

6.4.3.3 Sensor Subsystems

Near-Term Technology Adaptations: One application of automation to waste minimization which has been identified at Y-12 is on-line inspection of uranium machining blanks. Technology for high speed geometric inspection of as-formed machining blanks coupled with automated, numerically controlled (NC) machine programming technologies would allow near net forming of machining blanks. Conventional manufacturing techniques produce machining blanks with excess wall thicknesses (frequently 8 times the wall thicknesses in the finished part) so that there will be enough material for subsequent preprogrammed machining operations. Near net forming produces machining blanks with little excess material. On-line inspection would allow adjustment of the subsequent machining operations to compensate for irregularities in the forming process without requiring excess wall thickness of the machining blank.

Technology Development: A major need for sensors in the automation of the Nuclear Weapons Complex (NWC) is in in-process inspection. While the development of sensor technology for ensuring the safe control of robotic automation systems is discussed in Section 7, inspection sensors for high-tolerance process control is unique to this waste minimization task. The study of NWC production processes in

FY 1991 is expected to produce a clear understanding of the sensor technology development needed for waste minimization through automation.

6.5 DECONTAMINATION AND DECOMMISSIONING

Decontamination and decommissioning (D&D) of old facilities represents a significant problem throughout the DOE complex. While the RTDP team has visited only three sites (Hanford, INEL and SRS) with significant D&D needs, it is recognized that many other sites (e.g., Oak Ridge, Los Alamos, etc.) also have D&D problems.

6.5.1 Description of the Need

There is a large number of highly contaminated hot cell, canyon, glove box, and reactor facilities at DOE sites that must eventually undergo some form of D&D. Most DOE sites have these facilities. The objective of a D&D activity can range from removing old process equipment and replacing it with new equipment to full restoration of the landscape. All of the facilities requiring D&D are currently carefully contained, and none are known to present an immediate environmental threat. There are no current regulatory agreements in place driving the start of D&D activities at this time.

D&D operations include disassembly of process equipment, cutting of pipes, size reduction of equipment to be removed, transport of pipe and equipment out of the hot cells, decontamination of some equipment before removal from a facility, and decontamination of walls and remaining equipment in facilities to be refurbished. Hazards associated with D&D of these facilities are radiation, radiological contamination of the equipment to be removed, and hazardous chemicals associated with the processes performed at the facilities. Due to these hazards, many of the facilities requiring D&D are remotely operated. Many of the anticipated D&D activities will also have to be performed remotely. Hardened robotic systems for facility D&D can provide capabilities to allow safe accomplishment of these operations with workers in a safe environment away from the work site. Programmable, sensor-based robots can reduce the time required for performing repetitive remote D&D operations. In addition, human-supervised computer-controlled robots can help ensure safety by assisting human operators in difficult remote manual operations.

The Hanford site has a near-term D&D need at the B-Plant. Thirteen canyon hot cells are scheduled to be refurbished and used to pretreat waste from the double-shelled storage tanks (DSTs) using the TRUEX process as part of the Hanford ER&WM activities. Current plans are to remove equipment from the cells, decontaminate the cells, line the cells with stainless steel, and install new equipment for the TRUEX process using remote manual technologies. Removal of equipment and decontamination of the cells is scheduled to start in FY 1995. Removed equipment will be reduced in size to fit into standard disposal containers.

Similarly, the INEL staff has identified various hot cell areas (ROVER and FAST) that are to undergo D&D prior to reuse or closure. Disassembly and removal of piping and process equipment will be more difficult in facilities such as the ROVER and FAST hot cells at INEL that were not designed for remote disassembly and are more cluttered and unstructured than the B-Plant process canyon cells.

6.5.2 Planned D&D Tasks

D&D of a facility can involve disassembly and removal of equipment, size reduction of removed equipment, decontamination and/or disposal of removed equipment, contamination surveys and mapping, and decontamination of the facility and remaining equipment. Figure 6.5.1 illustrates a concept of the general types of remote technologies that may be required for D&D. Refurbishing or dismantling of the facility itself would normally occur after decontamination and, thus, may not involve the exposure of workers to hazardous chemical and radiological environments. Thus, remote operations may not be required for these final operations. More study of the hazards associated with these operations is needed.

Remote change-out of equipment and removal of process piping at hot cell facilities such as B-Plant are expected to be relatively straightforward. Lifting fixtures are provided for all removable equipment and piping, and connections were designed for remote operation. Facilities without such design features will require work in a less structured environment, with needs for grasping, remote cutting of pipes and equipment, and, in some cases, remote attachment of lifting fixtures to components or pieces of components. Size reduction of removed components can involve cutting or compaction and will require a means to transport the resulting pieces.

Decontamination technologies range from soaking and washing techniques for surface contamination to chemical and/or material removal techniques for embedded contamination. Decontamination requires remote delivery of the selected decontamination technology and removal of the resulting waste. Similarly, survey sensors must be remotely delivered for contamination mapping tasks. Desired characteristics of remote systems for D&D include reliability, ruggedness, remote maintainability, safety of all remote (both programmed and manual) operations, safe automation of repetitive operations such as contamination surveys, and decontamination operations.

6.5.3 Technology Development Plan

The initial application of robotics technologies to the broad areas of D&D may most likely begin with the relatively near-term needs at the SRS and the Hanford B-Plant. The SRS has a series of D&D demonstrations planned, starting in FY 1992 while the B-Plant D&D is scheduled to start in FY 1995. Although the near-term RTDP thrust will be to augment projects through focused technology development, the results of the RTDP activity will be broadly applicable to future D&D needs. The objective is to reduce the time,

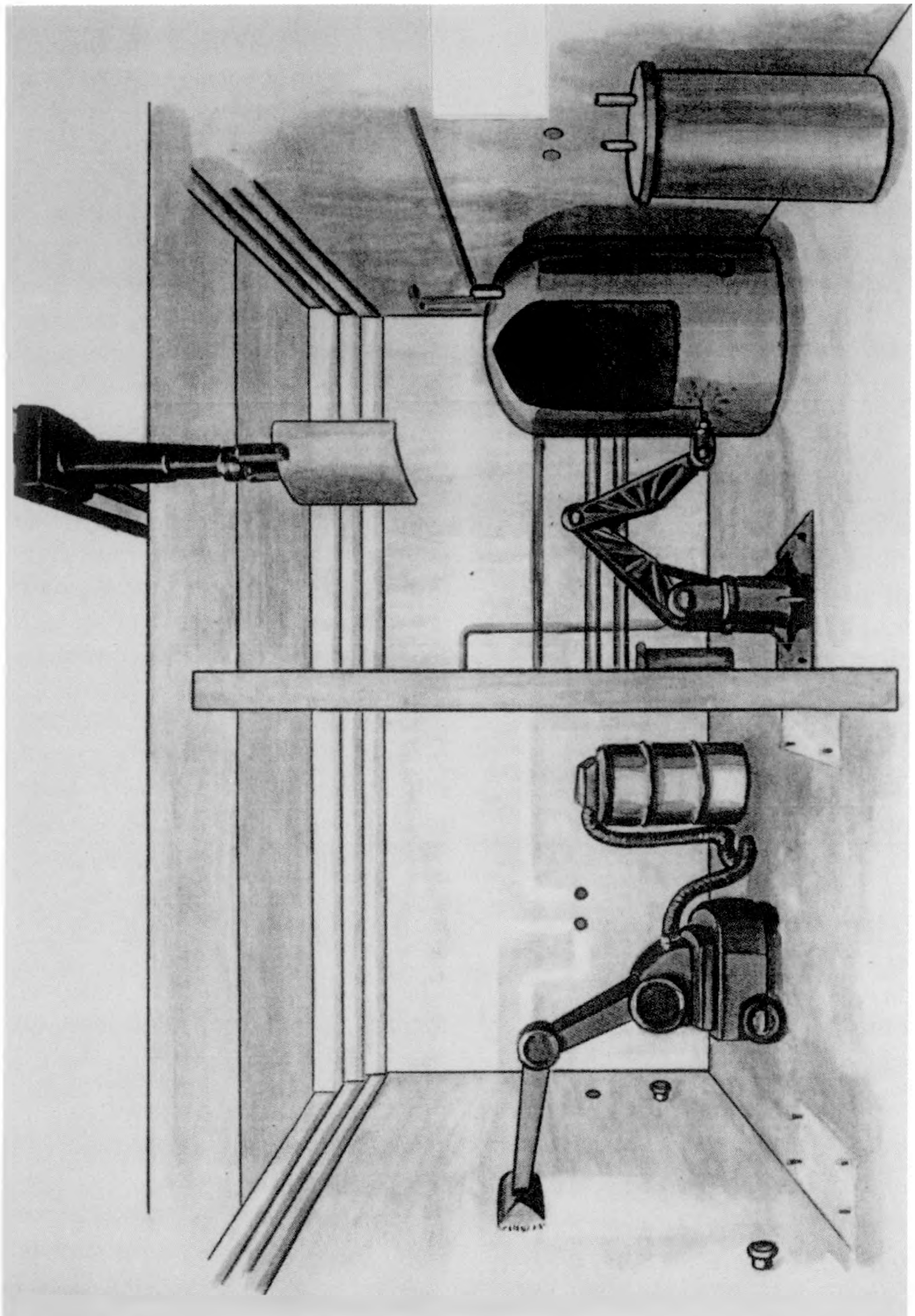


Figure 6.5.1 Robotic System Concept - Decontamination and Decommissioning

costs, hazards, and additional waste generation associated with D&D.

As part of the RTDP, technology to support implementation of two remote mechanical manipulation systems will be developed to assist in the eventual refurbishing of B-Plant as part of an integrated technology demonstration. One robot system would perform the decontamination operations in the hot cells after process equipment and piping have been removed. The other would perform any required size reduction operations. An existing single gantry system services all 40 hot cells in B-Plant and scheduling problems would cause significant delays if the manipulator systems were attached to the gantry. Thus, both systems would be delivered to a cell by the gantry but would use existing utilities available in the cells in order to free the gantry for other tasks. While it is not anticipated that B-Plant D&D will require mobility, mobile robots will be incorporated into the SRS technology demonstrations. SRS experience has indicated that mobile systems are critical to D&D activities.

The 5-Year Plan for robotics RDDT&E to support the D&D work is illustrated in Figure 6.5.2. This logic chart shows the major elements of technology development in ER&WM projects at DOE sites. Results from technology development activities are shown by the arrows. These results are keyed to specific needs at DOE sites, which are shown on the lines for each site. Significant dates for the site projects are shown in the ovals.

The principal thrust of the technology development plan is robotics support initially for D&D of the B-Plant at Hanford. The technology development is influenced by the complexity of the facilities to be decontaminated. The Plan is oriented toward integrating robotics technology into project-related demonstrations. The key date driving the schedule is the start of D&D at the Hanford B-Plant in FY 1995.

6.5.3.1 Mechanical Subsystems

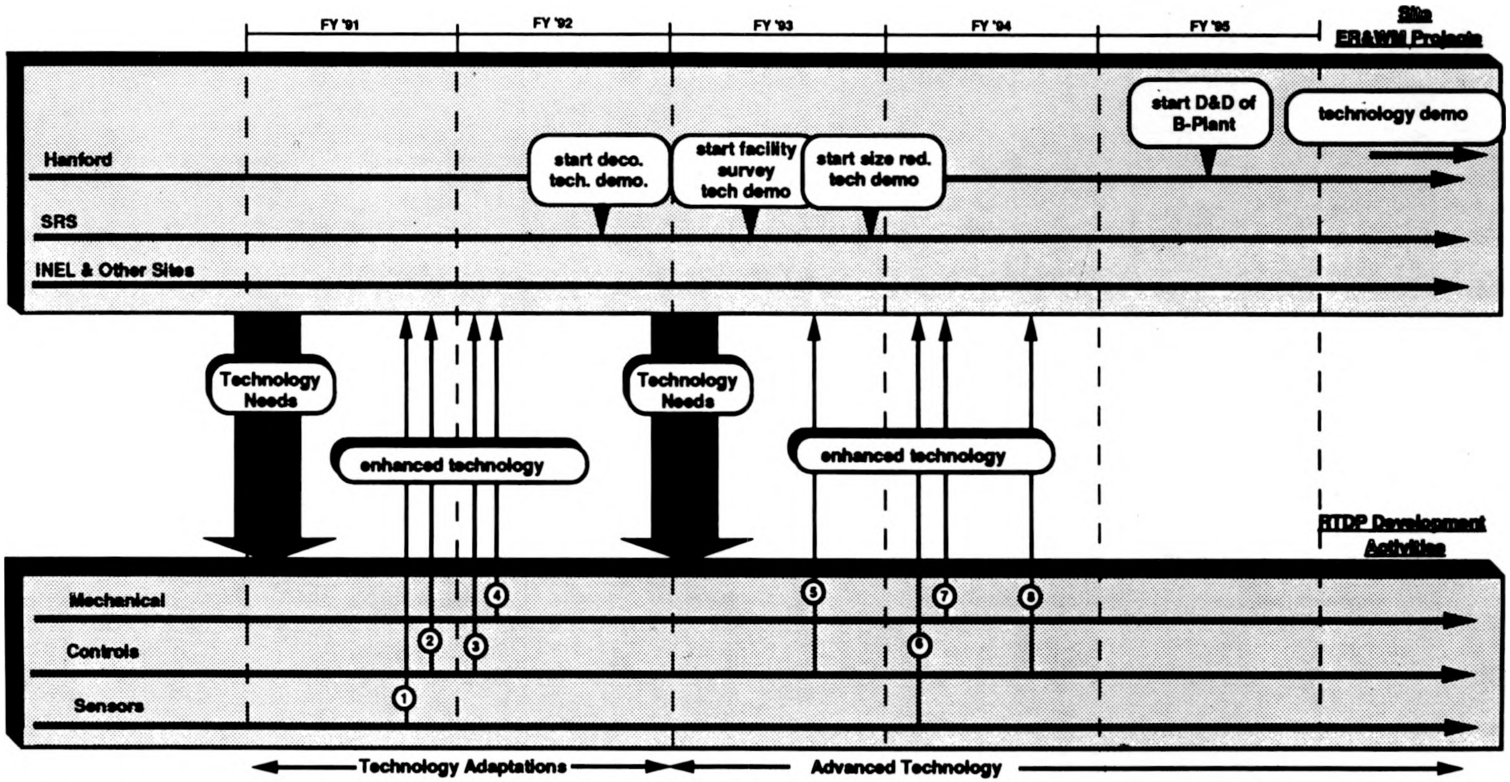
Many of the technology development issues associated with robotic D&D systems are similar to those for storage tank remediation and buried waste. While these issues are discussed here, more detail is presented in Sections 6.1 and 6.2.

Near-Term Technology Adaptations: A current schedule driver for the decontamination and size reduction systems is the refurbishment of the B-Plant for the TRUEX process. While independent, the technology demonstrations at the SRS scheduled for FY 1992 and FY 1993 provide an opportunity to evaluate and demonstrate advanced technology concepts potentially applicable to B-Plant D&D. The goal would be to design, implement, and test under cold conditions both decontamination and size reduction systems by early FY 1993 in order to impact specification and procurement of the B-Plant D&D system. The cold test facilities would have to supply utilities similar to those available in the B-Plant canyon cells.

Figure 6.5.2 Robotics Technology Development - Decontamination and Decommissioning

Figure 6.5.2

ROBOTICS TECHNOLOGY DEVELOPMENT - DECONTAMINATION AND DECOMMISSIONING



1 - proximity, force/torque sensors

2 - modular, structured software and system control concepts

3 - model based control, sensor based control

4 - decontam. and size reduction robot ready for cold test, mobile systems

5 - force reflection teleoperation control, error detection/recovery

6 - hardened sensors

7 - high dexterity end-effectors, hardened systems, mobile manipulation

8 - multiple robot/end-effector control

It is expected that enhanced decontamination and size reduction technologies can be developed by modifying existing end-effector and mobile robot manipulator technologies.

Much of the technology to accomplish this has been developed and demonstrated in research laboratories. High dexterity may be required for systems that require contact with the environment (e.g., a shearing tool for size reduction).

Technology Development: Refinement of the prototypes for the B-Plant size reduction and decontamination systems, together with the needs at INEL, SRS, and other DOE sites, will focus advanced technology development. Environmental hardening of the systems will be a major goal. The size reduction system will form the technology base for systems that are used to disassemble and remove equipment from facilities. These systems will require additional dexterity and coordination between subsystems for disassembly, stabilization and removal of components in an unstructured environment. Grasping of odd-shaped objects is anticipated to be required in less structured environments such as the ROVER and FAST hot cells at INEL. Development of dexterous end-effectors should lead to technology which can be deployed by early FY 1994. Since no single end-effector is expected to perform all anticipated operations for a subsystem, technologies for high-reliability end-effector changing will be required. Advanced passive and active vibration damping technologies will be required for the control of robots manipulating high-energy cutting systems and for the remote systems (e.g., swing free cranes) that transport heavy components. Vibration damping technologies should also be ready by FY 1994.

Much of the technology development required for long reach, high strength robot arms hardened for harsh environments has been discussed in Section 6.1 and is applicable here. Mobile robotic systems incorporating robot manipulators will be required for D&D of large facilities. Such advanced mobile manipulators are expected to be available in FY 1994.

Modular mechanical subsystems need development to facilitate remote maintenance. Due to their entry into hazardous environments, mechanical designs that facilitate decontamination will be very important.

6.5.3.2 Control Subsystems

The system controllers for robots deployed in the D&D of DOE facilities will have the technology attributes discussed in Section 7, Cross-Cutting and Advanced Robotic Technology Development. To obtain these characteristics, the remote systems will have to use models and sensors to automate operations and monitor operator actions. The basic technology needs are generic and similar across a wide variety of applications.

Near-Term Technology Adaptations: As with other ER&WM tasks (such as the remediation of waste storage tanks), system control technology development is expected to support D&D programs.

The technologies for preparing highly structured software architectures functioning in multi-processor, real-time control systems can be merged with commercial robot-control technologies to produce early model-based, sensor-directed robot system controllers in early FY 1992. These near-term technology developments will impact the prototype systems developed for the refurbishing of B-Plant. The focus will be on adapting structured software programming techniques to existing computing and operating systems. Here also, newly emerging animated graphic modeling technologies can be used to automate the programming of repetitive robot operations and allow graphic programming of robot actions by the operator. Early model-based control concepts would allow whole arm collision detection and warning and could be incorporated into trajectory planning, as well as both computer and manual control of robot movements.

Technology Development: There will be a continuing development of new modeling technologies for use in world model construction and real-time control, including monitoring and preventing operator mistakes. Technology to allow real-time error detection and recovery will be an important focus of these advanced technology development efforts.

Of particular importance in disassembly and removal operations, and in size reduction operations, will be the development of planning algorithms for sequencing the operations while ensuring stability of the components being disassembled and transported. Computer controlled coordinated motions of several end-effectors may sometimes be required to stabilize components, attach lifting fixtures, and transport components. Robot controllers capable of higher speed servo controlled robot motions will be very important for safe, efficient operations in these situations.

Improved viewing systems and models will likely be required to reliably and safely plan and execute these operations. Development of force-reflecting tele-robotic control technology is expected to be difficult, but extremely useful, especially in the complex environments of many facilities that will undergo D&D operations. Force-reflection telerobotic control is expected to be available in late FY 1993, potentially supporting robotics systems for the B-Plant D&D.

6.5.3.3 Sensor Subsystems

As with the other applications, sensors will play several major roles in the systems developed for D&D of DOE facilities. The sensors will be used to assess the environment to provide mapping of contamination and help develop and update models used by the robot control systems. In addition, sensors such as force and proximity will be used to provide real-time servo control of the robot systems. Such sensing technology should be available in FY 1991. Real-time control will be required for contact operations and for active damping of arm movements during transport of heavy objects and operation of energetic end-effectors.

Near-term technology adaptation efforts will focus on the modification of existing sensor technologies and algorithms for use in D&D systems. Longer-term technology development will focus on the refinement of sensors and hardening them to the harsh environmental conditions expected during decontamination and decommissioning operations.

6.6 WASTE FACILITIES OPERATIONS

A critical element in DOE's ER&WM Program is the storage of radioactive waste. Handling operations associated with loading and unloading waste shipping containers, placement of waste in storage facilities, and performance of EPA mandated inspections can result in significant operator radiation exposure. Evaluation of needs at DOE sites has indicated two potential robotics applications to support waste facilities operations; visual inspection of interim stored waste and unloading of Transuranic Package Transporter (TRUPACT) shipping containers. Adaptation of technology existing in research laboratories can provide functioning systems for near-term needs. In addition, while the applications appear quite different, similar robotics technology supports both applications providing a synergism which fosters fast system implementation.

6.6.1 DESCRIPTION OF THE NEED

Robots and automated remote handling technologies offer the potential to greatly reduce the radiation exposure of operators unloading TRUPACT shipping containers and performing EPA mandated visual inspections of stored waste containers. Life cycle costs can be reduced by decreasing the time for these operations and allowing more dense storage configurations. In addition, automated TRUPACT unloading and inspection of interim stored waste containers improves quality assurance by automatically generating the required audit trails.

6.6.1.1 TRUPACT Unloading at WIPP

The WIPP low-level waste storage facility has developed handling procedures for TRUPACT shipping containers when they arrive at the WIPP site. A major task is opening the TRUPACT shipping containers and removing the waste containers. After the waste containers are removed, the TRUPACT shipping containers are inspected and closed for reshipment back to a waste generating site.

WIPP currently has two TRUPACT unloading stations in which all the operations are performed using contact handling methods. It has been determined that, under normal conditions, radiation exposure to at least some of the operators can approach one rad/yr depending on the contents of the TRUPACT. Due to the potential radiation exposure hazard, personnel and materials are extensively monitored for contaminants. This monitoring requirement has contributed to reducing throughput of the TRUPACT unloading stations. Health Physics operations can require as much time as actual unloading operations.

DOE has several hundred thousand low-level TRU waste containers awaiting shipment to WIPP when it opens. WIPP operations personnel anticipate that the existing two unloading stations will be unable to handle expected shipments in a timely manner. Thus, WIPP personnel are planning to construct a third TRUPACT unloading station for use in FY 1993. Use of robotic automation technology has the potential to increase the facility throughput, reduce operator exposure, and automate the Quality Assurance record keeping and data management required for the unloading station.

Finally, WIPP is responsible for certifying TRUPACT containers and the loading and unloading practices at the waste generating sites. An automated system for unloading the TRUPACTs could also be placed at the waste generating sites to support implementation of uniform TRUPACT loading procedures.

6.6.1.2 Inspection of Interim Stored Waste

Inspection of interim stored waste is another area where significant operator dose is anticipated. RCRA requires that waste containers in interim storage be visually inspected weekly for indications of gross deterioration or leakage. Presently, all waste is considered to be in interim storage. INEL has received a notice of noncompliance from the EPA. INEL has estimated that the RCRA requirements, if met by operators walking through the storage facility once a week, could result in cumulative operator doses of up to 60 rads/yr per 20,000 containers. INEL has approximately 47,000 containers subject to the RCRA interim storage regulations. Interim waste storage facilities at other DOE sites, such as Fernald, Ohio, potentially face similar inspection requirements.

Inspection requirements not only result in operator exposure to radiation, but may also result in very large storage facilities. Typically, 4-ft walkways are required on all sides of the waste containers to allow human access. RCRA also recommends, for example, that barrels be stacked 2 by 2 by 3 high to provide access needed for visual inspection. In addition to reducing operator exposure, the use of robots may allow more dense packing of waste containers. Dexterous robot inspection system may be able to reach into densely packed arrays of waste containers to perform the required inspections.

In addition, there is significant concern about a human's ability to inspect large numbers of waste containers and recognize week-to-week signs of degradation. Automated robotic systems in which week-to-week inspection data bases are automatically compared for signs of degradation, hold promise for significantly improving the quality of the inspection process.

6.6.2 PLANNED WASTE FACILITY OPERATIONS

6.6.2.1 TRUPACT Unloading at WIPP

An automated TRUPACT unloading station at WIPP would utilize robotics technology to accomplish all of the major waste container unloading operations such as:

TRUPACT lid removal and replacement,

lid storage,

radiological swiping of the TRUPACT and contained waste packages,

waste container removal,

TRUPACT inspection, and

radiation monitoring of the unloading station.

Since radiation levels may not preclude all contact handling, some contact-handling operations may be safe and cost effective. Engineering studies to determine the level of contact handling, if any, would be conducted.

An automated TRUPACT unloading system would be designed so that it could be operated as a contact-handled facility in the advent of failure of the automated system.

6.6.2.2 Inspection of Interim Stored Waste

Although engineering design studies are still in the early stages, it has been determined that an automated waste container inspection system should be able to uniquely identify each container, and visually inspect and log the container's condition.

These basic tasks allow an automated inventory of the interim stored waste to be performed, evaluation of the individual waste containers condition over time, and automated recording of inspection results in a data base.

6.6.3 TECHNOLOGY DEVELOPMENT PLAN

Since the needs and milestones identified in this areas are near-term, robotics would be limited to technology that has been at least demonstrated in the laboratory. As a result, this entire activity falls within the areas of near-term technology adaptation. However, this technology is generic in nature and would be useful to many problems within the ER&WM areas. Limited development activities to further develop existing laboratory technologies so that they could be used in a production application would be performed.

Plans, schedules, and road maps for this technology adaptation and application will be prepared based on need dates and milestones at DOE sites.

6.6.3.1 Mechanical Subsystems

TRUPACT Unloading - One robotic concept under preliminary study for unloading of TRUPACTs is the automated movement of TRUPACT components and waste containers. This would require development of a gantry-type robot with a multi-ton lift capacity. Several options exist for accomplishing this. An evaluation of the cost/performance tradeoffs would be performed to contrast heavy lift capacity rigid mast gantry cranes with more conventional bridge cranes for heavy load lifting. Technology for implementing a bridge crane controller capable of moving large payloads with minimum swing has been demonstrated in DOE laboratories.

Dexterous movements, such as obtaining radiological contamination swipes would require modification of a commercial robot system to provide a real-time sensor control capability. Such dexterous motions could be accomplished either with the above mentioned gantry robot or with a separate pedestal mounted robot. Use of a separate pedestal mounted robot manipulator might result in significant cost savings if the large gantry robot were not required to perform high dexterity operations. If a pedestal robot manipulator were used in the system, the TRUPACTs would be mounted on a large turntable so that they could be rotated to allow the pedestal robot to access all sides of the TRUPACTs.

Inspection of Interim Stored Waste - Two basic engineering concepts have been proposed for automating the inspection of interim stored waste containers. One concept employs a mobile robot platform while the other employs an overhead gantry robot. Both concepts deliver inspection systems to all pertinent locations in the storage facility. Technology to support both approaches exists and could be adapted to the waste inspection task.

One advantage of a gantry robot would be that, since it operates on overhead rails, pathways on the floor need not be provided. In addition, the repeatability and accuracy of such gantry systems would allow fast movement to stored waste locations. However, due to the large areas proposed for interim waste storage facilities, gantry robot systems may prove to have higher capital and life cycle costs than equivalent mobile robot systems. Facility studies may indicate that combined use of both concepts is most cost effective.

A dexterous manipulator subsystem would be required for both gantry and mobile robot concepts in order to position sensors at appropriate locations near the waste containers. A dexterous manipulator would probably be an integral part of the gantry robot as is typical in most commercial gantry robot systems. If a mobile robot were employed, a dexterous arm manipulator would need to be integrated into the mobile robot system to allow placement of sensors. If dense packed storage concepts were employed, long-reach mobile robot manipulators might be required to reach the interior containers. In either case, adaptation of existing manipulator and mobile robot technologies could provide early systems in the early FY 1992 time frame.

6.6.3.2 System Control

Control systems for robotic systems tend to be general in nature and it is anticipated that the control technology for both the TRUPACT Unloading and the Inspection of Interim Stored Waste would be quite similar. Therefore, a single discussion of required controls technologies is presented here with the understanding that this technology is applicable to both areas with some modifications.

Robot control system with many of the technical attributes discussed in Section 7.0 would be required. Only those control technology attributes which have been fully laboratory demonstrated would be considered to be ready for use at WIPP and for Inspection of Interim Stored Waste. Human control of the robots, when required, would be through a man-machine interface with computer monitoring of all operator commands to ensure safety and adherence to procedures as discussed in Section 7.0. All programming of robot motions would be through a graphics interface to simplify the operator's interactions with the robot and minimize operator error. Computer control of the robots for swing free movement of heavy loads would be utilized if needed.

The control system would include extensive error detection and recovery from off-normal conditions. Automatic generation of audit trails for quality assurance would be an integral feature of the control software. This software would record all movements of the robot(s) as well as all sensor readings even when the system were operated in a telerobot mode.

Technologies utilized in the system control could include:

off line graphical programming,

geometric modeling of the robot and its environment for safer and faster robotic operations,

human assisted computer control for automatic collision avoidance and sensor-based operations during manual control,

use of highly structured, modular software programming environments,

sensor-based force, torque, and proximity servo control algorithms, and

graphical augmentation of direct viewing systems to assist the operator during any manual control operations.

All of these technical capabilities, while not available in commercial robot systems, have been demonstrated in research laboratories.

6.6.3.3 Sensors

TRUPACT Unloading - Robots used in the TRUPACT automated unloading station would require real-time sensor-based control. The sensors would include force, torque, and proximity. These sensors are typically commercial devices which could be modified for use in this application. Large-capacity (multiple ton) force/torque sensors for use with robot systems are not currently available commercially and would be developed if needed. Such large-capacity force/torque sensors would be required if the gantry robot is used both for heavy lifting and dexterous, sensor-directed manipulations.

Radiological swipe operations would require development of automated swipe dispensers. Modifications of commercial automatic swipe reading machines for operation with robotic loaders would be required. Radiation monitoring equipment adapted for use with robotic survey systems would be required.

Inspection of Interim Stored Waste - The same basic robot control sensors required for the control of TRUPACT unloading robot systems would be required for control of the robot manipulator associated with inspection of interim stored waste. Proximity sensors for servo controlled positioning of inspection technologies with respect to the surface of the waste containers as well as preventing inadvertent collisions are expected to be important.

Waste container inspection sensors would be required for container identification (e.g., bar code readers) and evaluation. Evaluation sensors include vision and radiation sensors, chemical detectors, and eddy-current detectors. The design of these integrated sensor packages for use with robot systems will be very important. Much of the technology adaptation efforts in the sensor area will be directed at providing the most appropriate sensor packages.

7.0

CROSS-CUTTING AND ADVANCED ROBOTIC TECHNOLOGY DEVELOPMENT

7.0 CROSS-CUTTING AND ADVANCED ROBOTIC TECHNOLOGY DEVELOPMENT

Cross-cutting robotic technology development is that technology development which can be applied to more than one ER&WM need area, for example, waste storage tanks and buried waste. Advanced robotic technology development is technology development which will sustain long-range development directed at needs and potential applications beyond a three- to five-year time frame. Advanced robotic technology development can also be cross-cutting.

One role of robotic technologies is to deliver waste characterization, treatment, and removal technologies to waste sites to eliminate the exposure of humans to the hazards present. In addition to reducing human risk, robotics technology offers potential for efficiency and quality improvements in highly repetitive tasks. Initially, robotic applications in site cleanup activities will necessarily be focused on existing technologies that can be readily adapted to the specific cleanup tasks and environments. As the DOE cleanup activities progress and evolve, a larger body of robotic technology will be suitable for application to environmental restoration and waste management projects. A technology development program targeted at relevant cross-cutting and advanced technology developments will make possible a more rapid insertion of beneficial technology into these activities. This technology development will be focused on high payback projects that clearly offer safer, faster, and cheaper approaches to cleanup goals.

Although much robotics technology exists that could be applied to environmental restoration and waste management projects, little of this technology has been developed specifically for the environments and applications inherent in DOE facilities. Adaptation and environmental hardening will be required for robotic systems to function reliably and for extended periods in cleanup operations. As described in Section 6.0, Application-Specific Technology Development, existing robotics technology is not sufficiently developed to be immediately applied. The potential payback from development of applicable advanced robotics technology is quite large because of the long duration and magnitude of the planned DOE remediation activities.

Much of the robotics technology required for safer, faster, cheaper ER&WM systems is cross-cutting in nature. Review of the site needs and the technology development road maps developed to meet those needs shows that similar technology development satisfies needs for diverse applications. Examples include telerobotic control in which systems control is shared between a human operator and computing system, man-machine interfacing, sensor based (force, proximity, etc.) servo control of robot manipulators, mobile manipulation, generalized computing and structured programming environments, geometric world modeling for overall system control, passive and active damping of oscillations in large structures, graphical programming, three-dimensional viewing systems, environmental hardening, environmental sensing, and high speed computer vision.

Cross-cutting and advanced technology developments can be focused on near-term, mid-term, and long-term implementations. Investment in a sustained and balanced long-range development program will assure steady progress toward the technology required for the safer, faster, and cheaper completion of the complex and demanding ER&WM tasks of the decades to come.

A goal of the ER&WM program is to utilize efficiently and effectively all applicable existing technology resources. Basic R&D will feed industry the enabling technologies needed to provide robotic devices and systems to site cleanup activities. A cross-cutting and advanced technology development program, including a long term R&D component, is a means to effectively incorporate the expertise of the universities, national laboratories and other basic research organizations into the nation's cleanup projects. Also, this offers educational training opportunities consistent with the DOE emphasis on developing the next generation technical work force.

Technology Areas: Areas where cross-cutting and/or advanced technology development would be highly beneficial to application of robotics in ER&WM activities will be described within the context of Mechanical Subsystems, Control Subsystems, and Sensor Subsystems as listed as follows:

MECHANICAL SUBSYSTEMS
- Manipulators
- End-Effectors
- Mobile Systems

CONTROL SUBSYSTEMS
- Computing, Graphics, and Modeling
- Man-Machine Interfaces
- Communications
- Teleoperations
- Motion Planning and Control

SENSOR SUBSYSTEMS
- Environmental Sensors
- Servomechanical Control Sensors
- Imaging & Vision Systems
- Multi-Sensor Integration

Mechanical Subsystems: A characteristic of most of the waste remediation application areas is that manipulation systems will be required to have a significantly larger work space volume and higher payload capacity than currently available. While adaptation of existing robotics technology will allow early attention to selected remediation tasks, significant advanced technology development will be required to address some engineering problems (e.g., reducing the structural vibrations and deflections of such manipulators) associated with long manipulators with large payload requirements.

Development of advanced technology for segmented, extendable, long-reach manipulator arms (or positioners) is needed to support applications such as retrieval of wastes from waste storage tanks. One concept illustrated in Section 6.1 shows a long-reach boom device with a small dexterous manipulator on the end. These long-reach manipulator arms must be capable of accessing work areas through small existing openings and must be able to maneuver special end-effectors weighing on the order of five hundred pounds over a large work space volume. While some existing technology can be adapted for these manipulator arms, advanced technology development is needed for:

- compact, high-strength joints,
- light weight, small cross section, stiff, high-strength structural segments,
- compact, high load drive systems, and
- seals for mechanical components.

Characteristics of these components must be integrated so that a complete assembly meets objectives for size, strength, and stiffness. Also the characteristics of the manipulator arm assembly must be compatible with the control system technology developed for these arms.

In some waste cleanup activities, dexterous manipulators will be needed to position and control remediation end-effectors. New manipulator designs and control systems will be needed for the more complicated tasks, although existing technology can be adapted to some applications. The mechanical manipulator task is to position an end-effector accurately and provide a stable position for the end-effector. The end-effector task is to interact with the environment and manipulate objects. Present manipulators used in most industrial applications are limited in interacting and manipulating objects. Even the simplest assembly operations such as "getting" and "putting" involve a complex sequence of mechanical motions and sensory information. Greater dexterity and control along with high load capacity will likely be required, for example, for decontaminating and decommissioning cluttered hot cells or sorting through debris excavated from a buried waste site.

Mobile vehicles are envisioned for remote buried waste site characterization, removal of excavated buried wastes, retrieval of wastes from storage tanks and silos, and decommissioning and decontamination activities. The primary development issues for mobile vehicles in these applications are mobility, maneuverability, reliability, and control. Some applications will require transport of heavy loads while others may require minimum vehicle weight because of terrain subsidence or other surface loading constraints. Some applications will require delivery of simple subsystems while others may require transport of multi-armed robotic systems with extensive on-board instrumentation and computers. Each application will require specific dynamics, reliability, and control technology developments.

Robotic systems applied to ER&WM tasks will often operate in harsh, hostile environments and may become contaminated. Reliable operation under these circumstances is a prime requirement for robotic system performance. There is a large technology base of radiation hardened and chemically hardened components which has been developed for hot cell operations. This can be adapted and incorporated in manipulation, end-effector, and mobile robot system designs. Many of the anticipated remediation operations are expected to generate significant levels of abrasive dust. Mechanical and electromechanical system designs will need to accommodate operation in this abrasive dust environment. Additional development of hardened components for robotic systems in ER&WM applications is needed to support performance objectives for robotic systems.

Mechanical systems operating in cleanup activities must be reliable and either remotely maintainable or remotely recoverable in case of system failure. These systems must be easily decontaminated to allow for repairs, maintenance, upgrades, or redeployment at other sites. Failure mode risk analysis will be needed to identify the critical mechanical and control components that are most likely to fail and design features/technology must be developed to support reliability and maintainability objectives.

Control Subsystems: The operation of robots used to clean up waste sites is dependent upon the development of advanced control technologies. For most industrial robots, the dynamics of the manipulator and its environment are neglected by means of simple joint servomechanisms. The servomechanism approach neglects the motion and configuration of the whole manipulator and ignores the varying dynamics of a manipulator. The result is sluggishness, poor damping, limited precision, noticeable vibrations, and poor interaction with the environment. Task requirements for typical waste remediation manipulation tasks dictate more advanced control techniques.

Motion planning of a manipulator is an extremely difficult problem. It entails moving a manipulator to perform a specific task while avoiding obstacles with minimum (or no) human intervention. A sufficiently accurate working environment model must be built by a combination of sensor information and previously defined world models of the work space geometry. A model of manipulator dynamics and kinematics needs to be developed to avoid overshoot conditions and collisions of each of the linkages. Environment models and manipulator models will be developed for simulation and training exercises. Manipulator control based on multi-sensor fusion (i.e., joint position and velocity, proximity, actuator position and velocity, drive train torque, and end-effector force/torque sensing) will be crucial to provide the necessary tracking, precision, damping, back-drivability, and force control required to meet the performance needed for waste remediation.

In order to execute remediation tasks, control systems for mobile vehicles must gather data from multiple sensors and integrate this data to generate world models. Therefore, multi-sensor integration is also a priority development area. In the D&D tasks mobile vehicles may be operating in very cluttered areas, whereas buried waste site activities may involve traversal of highly irregular terrain. These vehicles will need to accommodate the physical environment demand while maintaining control of the vehicle and safely executing the characterization or delivery tasks.

Because of the unstructured environments and need to ensure safe operation, mobile vehicle control systems will need to rapidly adapt to unexpected circumstances. For characterization applications, vehicles will need to accommodate a wide variety of sensors including some that are sensitive to the presence of ferrous materials or liquid fuel vapors.

Many current approaches to robot motion programming would require extended access to the hazardous environments for manual programming (teaching) purposes. Since this access will be limited, off-line programming of the robots using both computer models and operator assistance will be required. This relatively new approach to robotic system control has already been demonstrated in limited laboratory experiments. It requires:

- Integration of advanced computer and graphics technology,
- Computer models of the robotic work environment,
- Sophisticated actuator control algorithms,
- Reliable sensors,
- Development of rapid reassigning and task planning,
- Development of control strategies for recovery from fault and error detection,
- Development of fast reliable integration methods for data from several sensors, and
- Decision control methodology for meaningful data presentation to the human interface.

In some applications multiple robot systems will be deployed. Effective communications between different systems and a coordinated control approach must be developed to ensure safe and efficient operations.

In robotic system operations, the man-machine interface providing communication between the operator and the system is extremely important for safe and efficient operation. Perhaps the most important sensory feedback is remote viewing. While significant advances have been made in providing remote viewing to robot operators, additional technology development is needed. Placement of cameras and monitors is an important issue not completely understood at this time. Three-dimensional-viewing systems represent an emerging technology which needs to be focused on issues of robot control. Techniques for automatically determining and generating appropriate viewing angles for specific robot tasks and for providing nonvisual sensory feedback to the operator need to be developed. An example of an important nonvisual sensing modality is force reflection to inform the operator of the robot's interactions with the environment. Such operator sensory feedback technologies must be integrated into the overall robot control system so that the operator and sensor-based servo control systems do not counteract one another.

Generalized computer modeling technologies need to be developed to further facilitate the operator's interactions with the robot system. Those modeling environments must efficiently capture the geometrics of the robot system and its environment for use in real-time control of the robot system. Advanced input technologies (beyond keyboards and joysticks) will be required for easy control of complex robot systems especially in remediation areas requiring control of multiple robot systems. Development of telerobotic systems rather than master/slave robotic systems will be pursued to incorporate advances in teleoperations, multi-sensor feedback, and supervisory control.

Computing environments which incorporate user-friendly, menu-driven operator interfaces with high-speed real-time computing have been demonstrated to be successful in controlling complex robot systems operating in unstructured environments. To meet near-term waste clean up needs, currently available computing environments will be integrated with existing robot controllers to provide the computing environment needed for robot system control. As advanced computing environments become available, they will be integrated into the control architectures for robotic systems. Of particular importance are parallel computing environments and neural-network-based computing environments which allow increasing levels of modeling and sensor interpretation within the real-time computing constraints of robots.

New or emerging communications technologies such as fiber optics will be adapted to the needs of robotic systems. Remotely operated or supervised systems require substantial communication with the central computer control station. Technology development leading to higher bandwidth communication in chemically corrosive and radiation environments will be required. Noise suppression and signal degradation due to long communication cabling must be addressed. Typically, current commercial robots require that the robot controller be located within 100 feet of the robot to eliminate concerns of excessive signal losses. Many waste remediation activities will necessarily exceed this limitation.

Advanced software programming environments impact robotics technology in the broadest sense by improving the way in which the software which controls the robot system is constructed. Programming environments which stress structured software concepts facilitate the development of highly modular software which can be reused in multiple projects addressing widely differing applications. Reusability reduces software development time and improves reliability. Recent development of highly structured software technologies within the computer science community will be adapted for early use in remediation, laboratory automation, and waste minimization projects. These structured software concepts assist in the development of modular system control software. Experiments within robotics research laboratories have shown that the adaptations of structured software concepts, such as object-oriented programming to the control of robot systems, lead to significant increases in system reliability. Such newly emerging structured software technologies will be applied to early remediation systems.

A generalized robotic system programming environment, specially adapted to the efficient programming of model-based, sensor-directed robot systems, will be developed. A specific feature of this robot system programming environment will be the development of extensive libraries of reusable software for use with multiple projects. Thus, system programmers will use extensively tested software modules and develop only those modules specific to their particular project. In addition, software which translates generalized robot programming commands into specific robot control commands will be developed to control the system programming. A goal is to develop a single general purpose robot programming environment and language to be used throughout the DOE on site remediation projects. The reliability of this programming technology will be continuously improved through the development and incorporation of advanced software safety concepts.

Sensor Subsystems: Robotic systems use sensors to locate objects and obstacles, gather data about object characteristics, and to feed back to the control system information about the physical and functional status of each system component. Most of the required sensors exist at present but need adaptation to the ER&WM environments and applications. Sensor development is required in three broad categories: (1) sensors for the machine/work space interface, (2) sensors for internal components of the robotic system, and (3) environmental sensors.

Sensors for the machine/work space interface typically provide data required for modeling the work space so that robot tasks can be planned and executed. Once a model is developed, the sensors are used to locate the robot and objects of interest within the work space and also to verify or update the model to account for unexpected circumstances. Camera systems, three-dimensional laser scanners, and ultrasonic or infrared range sensors are examples of sensors used to construct and update work space models. These are also the kind of sensors required for navigation of mobile vehicles and path-planning for robot task execution.

Sensors are required for internal components of robotic systems to provide inputs to servo control algorithms controlling robot fine motion. These sensors provide processed information at a high rate to provide stable control. Servo control sensors such as encoders, resolvers, proximity, and force and torque sensors allow rapid movement in ill-defined environments and provide collision avoidance. In addition, force and tactile sensors allow controlled contact with objects in the environment for manipulation. The unstructured environments associated with many site cleanup activities will require a wide variety of servo control sensors to ensure safe operations.

Environmental sensors may be divided into two groups: mapping sensors and sampling sensors. Environmental mapping sensors are typically used to help develop the models of the work environment required by the robot system controller to automatically plan and execute robot actions as well as assist the operator during manual operation. Significant analysis and interpretation of the sensor data is required to extract the desired information. Examples of mapping sensors include computer vision, ground penetrating radar, and seismic sensing. Environmental sampling sensors will be used to characterize the waste. These sensors provide the information required to formulate the most effective remediation approach with minimal environmental risk. Examples of sampling sensors include chemical, radiological, and physical properties sensors. Such sensors will also be used to analyze the waste during retrieval operations to provide data required for acceptable repackaging, storage, and disposal.

Robust and reliable methods to integrate information from multiple sensors must be developed for both robotic control and for interpreting data from environmental sensors, especially subsurface mapping sensors.

Technology Development Plan: Within each of these three technology areas are numerous examples of technology development that would be beneficial for cleanup activities. This technology development program will focus on a subset of priority projects identified as those with the broadest applicability and/or highest impact on the successful use of robotic technology in environmental restoration and waste management activities. The development road maps in Section 6 illustrate the cross-cutting nature of technology development in several key areas as well as the technology required for specific cleanup applications. Large complex operations like buried waste retrieval where multiple robotic systems may be applied require both cross-cutting and advanced technology development in all three technology areas. Although the bulk of this technology development program will initially focus on near-term adaptations of existing technology, long-term/high impact technology development will be initiated and sustained to provide the safer, faster, cheaper systems required in future years.

Acronyms and Initialisms

ACRONYMS AND INITIALISMS

AGV	Automatic guided vehicle
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
D&D	decontamination and decommissioning
DIM	data interpretation module
DOD	Department of Defense
DOE	Department of Energy
DP	Defense Programs
EM	Office of Environmental Restoration and Waste Management
EPA	Environmental Protection Agency
ER&WM	Environmental Restoration and Waste Management
FFCA	Federal Facility Compliance Agreement
FI	Facility Investigation
FS	feasibility study
HACC	Human-Assisted Computer Control
HLW	high-level waste
INEL	Idaho National Engineering Laboratory
NWC	Nuclear Weapons Complex
ORNL	Oak Ridge National Laboratory
OTD	Office of Technology Development
Pu	plutonium
QA	quality assurance
R&D	research and development
RCRA	Resource Conservation and Recovery Act
RDDT&E	Research, Development, Demonstration, Testing, and Evaluation
RH-TRU	remote handled transuranic

RI	remedial investigation
RPM	Robotics Program Manager
RTDP	Robotics Technology Development Program
SAM	Standard Analysis Method
SDA	Subsurface Disposal Area
SLM	Standardized Laboratory Modules
SNL	Sandia National Laboratories
SNM	special nuclear material
SRS	Savannah River Site
SST	single-shell storage tank
TPO RG	Technical Program Officer Review Group
TRG	Technical Review Group
TRU	transuranic(s)
TSA	transuranic(s) storage area
U	uranium
UST	underground storage tank
VOCs	volatile organic compounds
WIPP	Waste Isolation Pilot Plant
WMMG	Waste Management Minimization Group
Y-12	Oak Ridge Y-12 Plant

Glossary

GLOSSARY

Caissons. A large buried heavy walled vessel used to hold and isolate extremely radioactive and dangerous debris, components, and small equipment. Personnel access is not possible. Debris entry is through a chute convoluted to prevent radiation "shine".

Characterization. Facility or site sampling, monitoring, and analysis activities to determine the extent and nature of the release. Characterization provides the basis for acquiring the necessary technical information to develop, screen, analyze, and select appropriate cleanup techniques.

Chemometrics. The application of statistical methods to chemical analysis data.

Compliance Agreements. Legally binding agreements between regulators and regulated entities that set standards and schedules for compliance with environmental statutes. Includes Consent Order and Compliance Agreements, Federal Facilities Agreements, and Federal Facilities Compliance Agreements.

Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). Federal statue (also known as Superfund) enacted in 1980 and reauthorized in 1986, that provides the statutory authority for cleanup of hazardous substances that could endanger public health, welfare, or the environment.

Decommissioning. The process of removing a facility from operation, followed by decontamination, entombment, dismantlement, or conversion to another use.

Decontamination. The removal of unwanted material (typically radioactive material) from facilities, soils, or equipment by washing, chemical action, mechanical cleaning, or other techniques.

Disposal. Waste emplacement designed to ensure isolation of waste from the biosphere, with no intention of retrieval for the foreseeable future, and that requires deliberate action to regain access to the waste.

End-Effectors. The apparatus on the end of an arm or support which performs a function, i.e., manipulator, sensor, camera, shovel, etc.

Feasibility Study (FS). A step in the environmental restoration process specified by CERCLA. The objectives of the feasibility study are to identify the alternatives for remediation and to select and describe a remedial action that satisfies the applicable or relevant and appropriate requirements for mitigating confirmed environmental contamination. Successful completion of the feasibility study should result in unimpeded subsequent development of a remedial design for implementation of the selected remedial actions.

Hazardous Waste. As defined in the Resource Conservation and Recovery Act, a solid waste, or combination of solid wastes, that because of its quantity, concentration, or physical, chemical, or infectious characteristics, may cause or significantly contribute to an increase in mortality or an increase in serious, irreversible, or incapacitating reversible illness or pose a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported, or disposed of, or otherwise managed. Hazardous wastes may be listed or characterized.

High-Level Waste. The highly radioactive waste material that results from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid waste derived from the liquid, that contains a combination of transuranic waste and fission products in concentrations requiring permanent isolation.

Intelligent Machine. See robot.

Low-Level Waste. Radioactive waste not classified as high-level waste, transuranic waste, spent nuclear fuel, or by-product material.

Mast. Structure for boom support and vertical position location as well as power and signal cable supply. Part of the mechanical subsystem.

Master/Slave. Any remote device (e.g., mobile vehicle, manipulator arm) which directly executes the commands of an operator. There is no computer-based intelligence to assist the operator by automating all or part of a task's execution (see robot).

Mixed Waste. Mixed waste contains both radioactive and hazardous components, as defined by the Atomic Energy Act and the Resource Conservation and Recovery Act, respectively.

Radioactive Waste. A solid, liquid, or gaseous material of negligible economic value that contains radionuclides in excess of threshold quantities. Does not include material contaminated by radionuclides from nuclear weapons testing.

Real-Time Control. Control as a function is being performed, as opposed to delay or time lag between command and subsequent action.

Remedial Investigation (RI). The Comprehensive Environmental Response, Compensation, and Liability Act process of determining the extent of hazardous substance contamination and, as appropriate, conducting treatability investigations. The RI provides the site specific information for the Feasibility Study.

Robot. Electromechanical device which incorporates sensors and computer control to operate intelligently in remote environments. Typically, Human Assisted Computer Control (HACC) is used for robot control. Thus, a robot possesses sufficient intelligence to automatically execute selected tasks and is guided in the execution of these tasks by a human operator. If the environment is well defined and as the technology matures, system control responsibilities shift from the human operator to the computing system leading to more autonomous robot systems.

Silo. Waste storage tank.

Special Nuclear Material (SNM). Special Nuclear Material (SNM) is defined in 10 CFR Ch 1., Paragraph 70.4 "Definitions" as follows: "'Special Nuclear Material' means (1) plutonium, uranium 233, uranium enriched in the isotope 233 or in the isotope 235, and any other material which the Commission, pursuant to the Section 51 of the act, determines to be special nuclear material, but does not include source material; or (2) any material artificially enriched by any of the foregoing but does not include source material".

Spent Fuel. Irradiated nuclear reactor fuel before reprocessing. Contains uranium, fission products, and transuranic elements.

Storage. Retention and monitoring of waste in a retrievable manner pending final disposal. (All stored waste is considered to be in interim storage.)

Subsurface Disposal Area. Burial ground.

Teleoperation. Control by a human operator with no computer involvement.

Telerobotic Control. Control shared by the human operator and a computer.

Transuranic (TRU) Waste. Waste that is contaminated with alpha-emitting transuranium nuclides with half-lives greater than 20 years and concentrations greater than 100 nanocuries per gram of waste.

Treatment. Any activity that alters the chemical or physical nature of a hazardous waste to reduce its toxicity, volume, mobility, or render it amenable for transport, storage, or disposal.

World-models. An algorithm defined volume of space which is interpreted by a computer for the control of a robotic system or device within that space. The volume definition includes all obstacles and environments which may effect the robotic systems and devices.